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Grazing exclusion restores soil health in Brazilian drylands under desertification process

Antonio Yan Viana Lima [a,b], Maurício Roberto Cherubin [b], Danilo Ferreira da Silva [a,b], Jaedson Cláudio Anunciato Mota [a], Francisco Gilcivan Moreira Silva [a], Ademir Sérgio Ferreira de Araujo [c], Vania Maria Maciel Melo [d], Jay Prakash Verma [e], Arthur Prudêncio de Araujo Pereira [a,*]

[a] Department of Soil Science, Federal University of Ceará, Fortaleza, CE, Brazil
[b] Department of Soil Science, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil
[c] Federal University of Piauí, Teresina, Piauí, Brazil
[d] Department of Biological Science, Federal University of Ceará, Fortaleza, CE, Brazil
[e] Banaras Hindu University, Varanasi, Uttar Pradesh, India

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ABSTRACT

The Brazilian drylands (Caatinga biome) are facing accelerated soil desertification due to human activities (e.g., overgrazing). However, restoration practices (e.g., grazing exclusion), are promising to curb soil desertification and, eventually, increase soil functioning. However, the understanding of soil health (SH) changes, induced by desertification and restoration in the Caatinga biome remains, poorly understood. Here, the SMAF (Soil Management Assessment Framework) was applied to assess the impact of desertification and long-term grazing exclusion on the SH in the Caatinga biome. Three conditions were assessed: i) native vegetation (NV), ii) degraded soil by overgrazing (DE) and iii) restored soil by grazing exclusion (RE). Soil samples (0–10 cm) were collected in both rainy and dry seasons, and chemical (pH, sodium adsorption ratio (SAR), K^+, and P), physical (bulk soil density), and biological (soil organic carbon (SOC), microbial biomass carbon (MBC), and β-glucosidase activity) indicators were analyzed. Then, integrated soil health indexes (SHI) were calculated using the SMAF algorithms. Briefly, DE reduced (0.44 and 0.47 in rainy and dry seasons, respectively) the SHI compared to NV (0.72 and 0.82 in rainy and dry seasons, respectively). Importantly, RE recovered SH after two decades of implantation (0.65 and 0.79 in rainy and dry seasons, respectively). Bulk soil density and SAR were the indicators that presented a higher negative correlation with SH, mainly in DE, while SOC, MBC, and β-glucosidase activity correlated with SH in NV and RE soils. Biological soil health indicators increased in dry season, which may be due to the deciduous behavior of Caatinga vegetation, which could intensify microbial activity. We provided novel evidence that SMAF can be a user-friendly tool to monitor changes in SH under Brazilian drylands soils. In addition, long-term grazing exclusion can restore SH, contributing to curbing the desertification process in the region.

1. Introduction

Drylands comprise approximately 41 % of Earth's surface, of which 10–20 % are degraded, affecting around 250 million people worldwide (Huang et al., 2020; IPCC, 2021). In particular, the Brazilian drylands compose the most populated semiarid region in the world, with approximately 28 million people (da Silva et al., 2017). This region is covered by the Caatinga dry forest, an exclusive Brazilian biome that covers 844,000 km^2, which is approximately 10 % of the national territory.

The Caatinga climate is characterized by semiarid conditions, with low annual rainfall (Pereira et al., 2021a). The plant life in this region has metabolic adjusted to the challenges of high temperatures, prominently featuring xerophytic species like cacti and thorny shrubs. The economic pulse of Caatinga is driven by subsistence agriculture, bustling intensive livestock activities, and extraction of nonrenewable natural

* Corresponding author.
E-mail address: arthur.prudencio@ufc.br (A.P. de Araujo Pereira).

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resources (Oliveira-Filho et al., 2019). Additionally, due to climate instability associated with these intensive human activities, the Caatinga biome has lost 45 % of its native vegetation (Brasil, 2005, 2021). Recent land use change mapping confirmed that about 11 million hectares were converted from Caatinga native vegetation to pasture from 1985 to 2020 (MapBiomas, 2021).

Importantly, the capacity of dryland soils to support pasture growth is low (Jiang et al., 2022), leading consequently to overgrazing of animals (i.e., cattle, goats, and cheeps), that are raised extensively in this region. Overgrazing reduces vegetation cover and accelerates the degradation process, which mainly impacts soil functioning (Schulz et al., 2016; Marengo et al., 2022). Those processes of degradation are the main drives of an accelerated desertification process that has affected the Caatinga biome. Conversely, restoration practices are needed to mitigate the consequences of degradation in Brazilian drylands (Amorim et al., 2020). To address the negative effects of overgrazing, grazing exclusion has been applied to restore degraded soils and has had positive effects on soil chemical and microbial properties (Oliveira-Filho et al., 2019; Oliveira et al., 2021; Pereira et al., 2021a, 2021b). For instance, Pereira et al. (2021a, 2021b) and Oliveira et al. (2021) demonstrated that overgrazing reduced soil microbial diversity, while grazing exclusion increased enzyme activity in the Caatinga biome. Other studies have also corroborated that grazing exclusion is an important restoration practice not only in Brazil (Pereira et al., 2022) but worldwide (Hu et al., 2016; Listopad et al., 2018; Wilson et al., 2018). However, although previous studies have assessed individual soil chemical and microbial properties under overgrazing and grazing exclusion, little is known about the impacts of those processes (degradation and restoration) on soil health (SH) changes in the Brazilian Caatinga biome (Simon et al., 2022).

Soil health (SH) is defined as the continued soil's capacity (as a living ecosystem) to sustain plant and animal productivity, support environmental quality (air and water), and promote human health (U.S. Department of Agriculture). Additionally, Doran and Parkin (1994) define SH as the ability of soil to perform functions of biological production, environmental conservation, and promotion of plant and animal health in a sustainable manner. Integrated approaches have been proposed to assess SH in different ecosystems around the world (Bünemann et al., 2018; Karlen et al., 2019; Rinot et al., 2019; Lehmann et al., 2020). Primarily, those approaches are based on assessing multiple soil chemical, physical, and biological indicators that are directly related to critical soil ecological functions (Andrews et al., 2004; Karlen et al., 2008; Cherubin et al., 2021). Here, we propose using the Soil Management Assessment Framework (SMAF) as a powerful method developed by Andrews et al. (2004) for U.S soils, and then successfully applied worldwide (i.e., Gura and Mnkeni, 2019; Karlen et al., 2019; Çelik et al., 2021; Cherubin et al., 2021; Chavarro-Bermeo et al., 2022) to assess SH in Brazilian desertified hotspots. Previous studies have reported that SMAF is sensitive to detecting SH changes in Brazilian tropical soils (e.g., Cherubin et al., 2016a, 2021; Matos et al., 2022), but there is no information about the SMAF performance in the soils of Brazilian drylands.

Therefore, this study is the first to apply SMAF to evaluate the effects of degradation caused by overgrazing and a long-term restoration practice (21 years of grazing exclusion) in Brazilian drylands (Caatinga biome). Thus, we hypothesized that (i) SMAF is efficient in quantifying SH scores using chemical, physical, and biological indicators in both degraded and restored soils and (ii) continuous overgrazing significantly degraded SH, while long-term grazing exclusion can recover SH scores to similar levels of those found in native vegetation soils of Brazilian drylands (Caatinga biome).

2. Material and methods

2.1. Site description and soil sampling

The study was conducted in the Irauçuba municipality, located in the state of Ceará, Brazil (3°44′46" S and 39°47′00" W), within the "Irauçuba Desertification Nucleus" (IDN) experimental research area. The region is characterized by low annual precipitation (~540 mm), primarily occurring between January and April (Pereira et al., 2021a, 2021b). The climate is classified as tropical hot semiarid according to the Köppen-Geiger classification system, with average annual temperatures ranging from 26 to 28 °C over the last 20 years and, an altitude of 152 m above sea level (IPECE, 2017). Soils at the experimental sites are predominantly Planosols (FAO system).

Livestock activity in the region over the past 150 years has resulted in the removal of soil cover, preventing the renewal of native vegetation (Oliveira-Filho et al., 2019). In addition, soil degradation has been caused by high soil compaction due to animal grazing and natural environmental conditions such as high temperatures and water shortage (Oliveira-Filho et al., 2019). Irauçuba municipality has an aridity index of 0.26, one of the lowest in the Brazilian semiarid region (Fig. 1).

The experimental areas were established in 2000 to study the effects of desertification on soil properties (Oliveira-Filho et al., 2019). Degraded areas (overgrazed) were mapped, fenced to prevent animal access, and left fallow. Each experimental unit measures 50 m × 50 m (2500 m^2) (Pereira et al., 2021a, 2021b), and grazing exclusion was used to promote natural (passive) soil restoration.

The study was conducted at three sites (site 1, site 2, and site 3) with three land use and management scenarios: 1) native Caatinga vegetation (NV) – fragments of dry forest mainly composed of *Mimosa tenuiflora*, *Auxemma oncocalyx*, *Caesalpinia bracteosa*, *Cereus jamacaru* and *Copernicia* spp.; 2) degraded (DE) – plots subjected to intensive animal (over) grazing, particularly during the rainy season. Natural vegetation is the main feed source for animals (e.g., goats, cattle, and sheep) of local smallholders that lives in the region, and 3) grazing exclusion (RE) – plots with grazing exclusion for 21 years. In those plots, spontaneous vegetation recovery, with a predominance of *Mimosa tenuiflora*, *Anthephora hermaphrodita*, and small cactus plants (Fig. 2). In the RE areas, plots measuring 40 m × 40 m (1600 m^2) were used to avoid border effects.

Two soil samplings were conducted in February/2020 (S1) – rainy season – and October/2021 (S2) – dry season. In each plot, three replicates were established. Samples were collected at 0–10 cm depth, and nine subsamples were collected and mixed into a composite sample. Thus, a total of 54 soil samples were collected (3 sites × 3 soil managements x 3 field replicates and 2 seasons). Later, composite samples were sieved (2 mm) and stored at 4 °C for biological analyses, and another portion was air-dried for chemical analyses. Undisturbed samples were stored for physical analyses.

2.2. Soil characterization

Soil pH was determined using a $CaCl_2$ solution (0.01 mol L^{-1}), while available phosphorus (P) and potassium (K^+) were extracted via ion exchange resin. Sodium (Na^+) was extracted via Mehlich 1 solution, and calcium (Ca^{2+}), and magnesium (Mg^{2+}) contents in the water extract from saturated soil paste. The sodium absorption ratio (SAR) was calculated by the amount of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the water extracted from a saturated soil paste. All the above-mentioned methods were applied following Raij et al. (2001).

Bulk soil density (BD) was measured using the Beaker method and the paraffin-embedded clod, following the methods of Blake and Hartge (1986) and Teixeira et al. (2017). Soil organic carbon (SOC) was extracted using potassium dichromate and determined via colorimetry (Nelson and Sommers, 1983). Microbial biomass carbon (MBC) was quantified using the fumigation-extraction method described by Vance

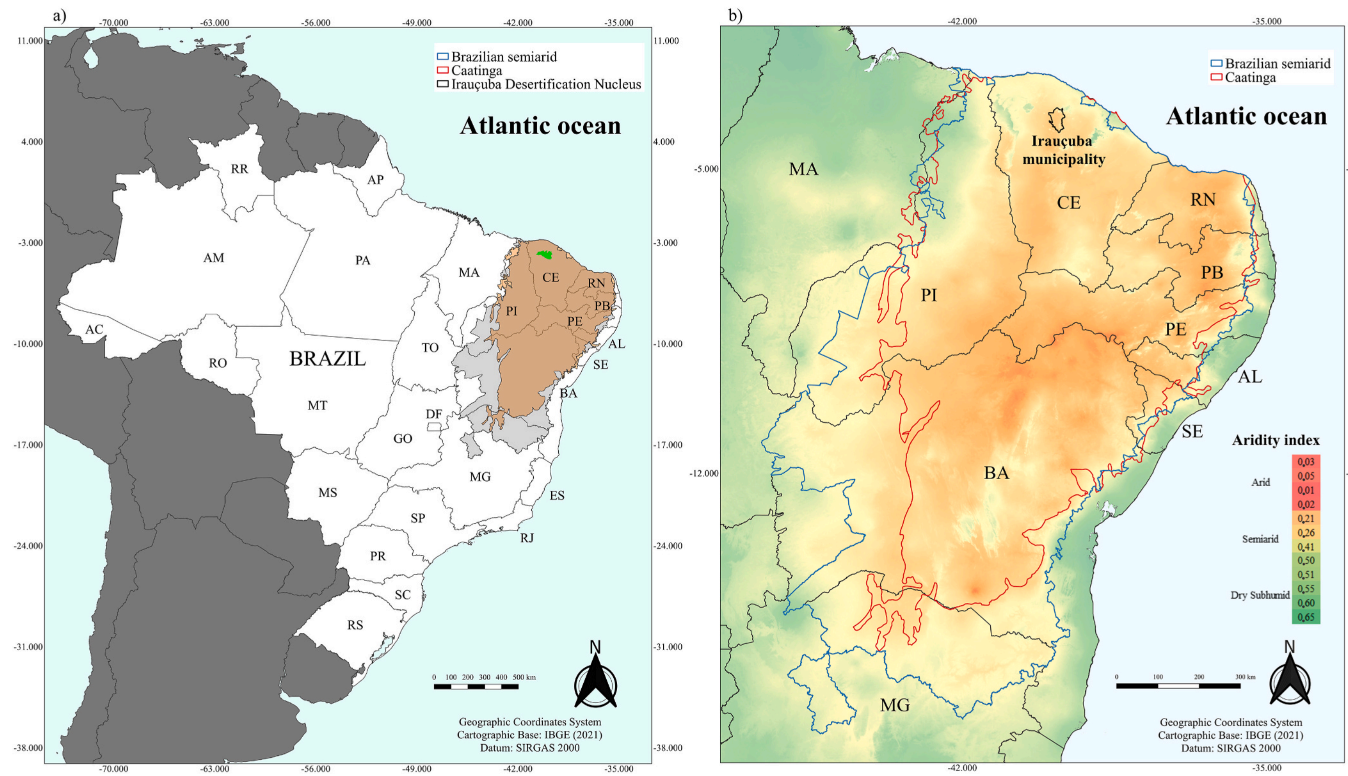

Fig. 1. Geographic location of study area. a) Desertification Nuclei of Irauçuba (green), b) Aridity index of Brazilians drylands. The map was drawn with QGIS (v. 3.16.16).

et al. (1987) and Polli and Guerra (1997). The potential activity of β-glucosidase (BG) (EC 3.2.1.21) was determined by incubating the soil (1 g) with ρ-nitrophenyl β-glucopyranoside substrate (pH 6.0) at 37 °C for 1 h and measuring the released ρ-nitrophenol via spectrophotometry (410 nm) (Tabatabai, 1994).

2.3. Soil management assessment framework tool

The Soil Management Assessment Framework (SMAF) includes algorithms for 13 indicators that encompass chemical, physical, and biological. In this study, a total of eight SH indicators were utilized, including pH, sodium adsorption ratio (SAR), P, K^+ (chemical), BD (physical), SOC, MBC, and BG (biological). These specific parameters were selected due to their significance in soil functioning (Cherubin et al., 2016a) and representation of at least one indicator from each of the three SH components (i.e., chemical, physical, and biological) (Karlen et al., 2008; Wienhold et al., 2009; Cherubin et al., 2017). These indicators are listed among the most frequently used in soil health studies in Brazil (Matos et al., 2022; Simon et al., 2022) and in the world (Bünemann et al., 2018; Gura and Mnkeni, 2019; Basak et al., 2022).

The measured SH indicators were transformed into a score ranging from 0 to 1, using non-linear scoring curves previously published and incorporated in the SMAF spreadsheet (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2013). For SOC, MBC, and BG, a factor of 4 was employed for organic matter class (low, suborder Argids). For treatments with clay content <8 %, a texture factor class of 1 was used to score BD, SOC, MBC, and BG, while a class of 2 was applied to treatments with clay content >8 %. A climate factor of 2 (≥170 °C and ≤ 550 mm average annual precipitation) was used for all treatments to score SOC, MBC, and BG, while a season factor of 2 (summer) was used for all treatments to score MBC. A factor of 2 (other) was used for Fe oxide content for all treatments. For BD scoring, a mineralogy factor class of 3 (other) was utilized, while a slope factor of 2 (2–5 % slope) and a weathering class factor of 3 (little weathering) was employed for P scoring for all treatments. Resin methodology (class 5) was used to measure extractable P. Thresholds for P and pH were established according to Fernandes (1993) with optimum values for P and pH set at 10 mg dm^{-3} and 5.5, respectively.

The scores for each indicator were integrated using a weighted additive approach through Eq. (1) to generate an overall soil health index (SHI).

$$SHI = \sum_{i=1}^{n} SiWi \quad (1)$$

where Si is the indicator score, and Wi is the indicator weight. Each group (chemical, physical, and biological) had an equal weight (33.33 %) in the final index (Cherubin et al., 2016a). The use of weighted additive was applied to equally combine chemical, physical, and biological components in a soil health index, reflecting the contribution, and enabling a more comprehensive and balanced assessment of each indicator group.

2.4. Statistical analyses

Homogeneity and normality of variance were examined by Levene and Shapiro-Wilks tests, respectively. Following these preliminary tests, a pooled analysis was performed using Nested-ANOVA. This analysis helps to understand the sources of variability within and between groups. To determine significant mean differences between groups, Tukey's test at 5 % analyses were performed using RStudio® (Version 1.3.1093). Redundancy analysis (RDA) was performed to explore relationships between multiple responses (soil properties) variables and explanatory variables (soil health indicators). Multivariate analysis was applied using Canoco for Windows v. 4.5 packages (Braak and Šmilauer, 2002).

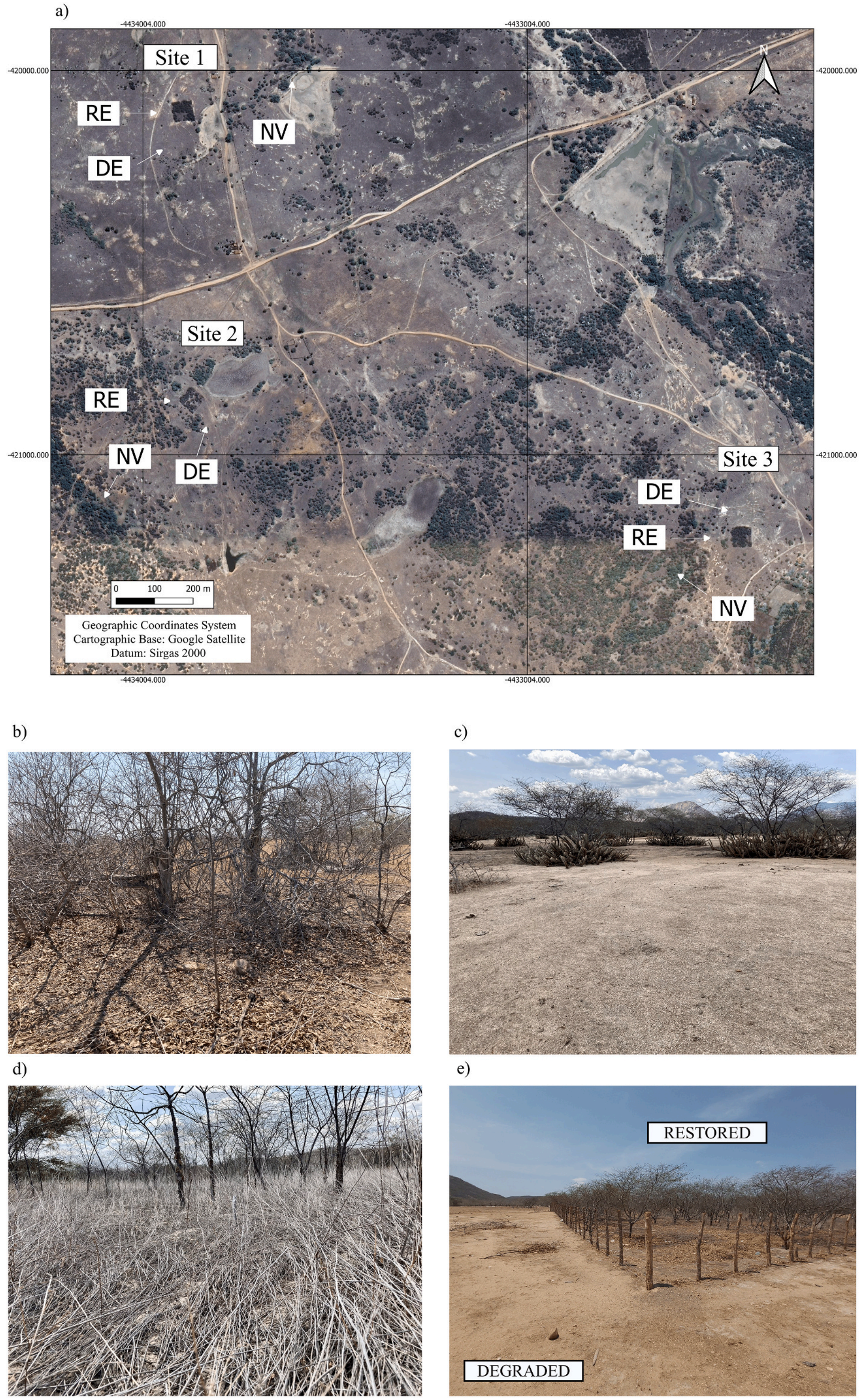

Fig. 2. Geographic location of study sites (1, 2, and 3) (a). NV = Caatinga's native vegetation, RE = restored (grazing-exclusion), DE = degraded area; b) Caatinga seasonally dry tropical forest, c) degraded dryland, d) restored dryland, and e) subdivision of DE and the RE areas. The map was drawn with QGIS (v. 3.16.16) software.

3. Results

The highest soil pH values were found in native vegetation (NV), regardless of the sampling period, while the lowest values were found in degraded (DE) (Table 1). On the other hand, the highest SAR values were observed in DE, while restored (grazing exclusion) (RE) and NV had the lowest values. The available *P* values were significantly higher in NV and lower in DE, especially during the rainy season. During the dry season, the values of P were higher in DE and RE. The highest values of BD were observed in DE, independent of the sampling period. The highest values of SOC were found in NV and RE in both seasons. The values of MBC were higher in RE compared to NV and DE, and the values of β-glucosidase were higher in RE and NV than in DE in both seasons (Table 1).

Table 1
Mean values of soil health indicators from Caatinga's native (NV), degraded (DE), and restored (RE) vegetation in Brazilian desertification hotspot (0–10 cm).

Land use	Chemical			Physical			Biological	
	[1]pH	[2]SAR	[3]P mg dm^{-3}	[4]K mmol dm^{-3}	[5]BD g cm^{-3}	[6]SOC g dm^{-3}	[7]MBC mg kg^{-1}	[8]BG mg p-nitrophenol kg^{-1} solo^{-1}
				S1				
NV	5.59 ± 0.1^{a}	0.20 ± 0.1^{b}	37.61 ± 7.9^{a*}	106.26 ± 0.6^{a}	1.51 ± 0.04^{b*}	13.41 ± 2.2^{a}	77.71 ± 3.9^{b}	114.11 ± 6.7^{a}
DE	5.02 ± 0.1^{b}	0.89 ± 0.1^{a}	7.73 ± 1.8^{b}	115.12 ± 0.4^{b}	1.62 ± 0.05^{a}	6.69 ± 1.8^{b}	48.08 ± 3.6^{c}	37.12 ± 15.8^{b}
RE	5.48 ± 0.1^{a*}	0.39 ± 0.3^{b}	13.41 ± 3.2^{b}	69.86 ± 0.5^{a}	1.52 ± 0.04^{b}	16.17 ± 1.4^{a}	92.63 ± 7.6^{a}	102.72 ± 6.8^{a}
				S2				
NV	6.08 ± 0.5^{a}	0.17 ± 0.09^{b}	12.10 ± 0.6^{b}	114.23 ± 0.7^{a}	1.41 ± 0.06^{b}	21.02 ± 5.0^{a*}	130.36 ± 9.9^{b*}	175.62 ± 5.8^{a}
DE	5.14 ± 0.2^{b}	0.63 ± 0.29^{a}	10.06 ± 0.6^{b*}	84.69 ± 0.5^{b}	1.85 ± 0.16^{a*}	8.61 ± 2.7^{b}	84.01 ± 5.1^{b*}	83.09 ± 4.1^{b*}
RE	5.04 ± 0.1^{b}	0.31 ± 0.11^{b}	19.21 ± 2.7^{a*}	132.75 ± 0.2^{a*}	1.41 ± 0.09^{b}	26.77 ± 5.7^{a*}	285.21 ± 26.1^{a*}	197.43 ± 15.7^{a*}

[1] Hydrogenionic potential.
[2] Sodium adsorption ratio.
[3] Available phosphorus.
[4] Potassium.
[5] Bulk density.
[6] Soil organic carbon.
[7] Microbial biomass carbon.
[8] β-glucosidase activity. Soils were sampled in February/2020 (S1) and October/2021 (S2). Lower-case letters compared soil management (NV, DE, and RE) within each period and *compared periods within each treatment by the Tukey test (5 %)($P < 0.05$), $n = 9$ and ± standard deviation.

During the rainy season, there were no significant differences in SMAF scores for soil pH between the areas (Table 2). However, in the dry season, NV and RE had the highest SMAF scores for soil pH. The highest SMAF scores for P were found in RE in both seasons, while DE had the lowest SMAF scores for K. NV had higher SMAF scores for BD, while the scores decreased in DE during the dry season. For SOC, MBC, and BG, the higher SMAF scores were found in NV and RE (Table 2).

The soil health index (SHI) was highest in NV (0.73 in S1 and 0.82 in S2) and RE (0.65 in S1 and 0.79 in S2), while DE had the lowest SHI (0.44 in S1 and 0.47 in S2) (Fig. 3). The SHI was higher in S2 (0.69) than in S1 (0.60), but there were no seasonal effects observed for chemical and physical indicators. However, there was an increase in the biological component from S1 to S2 (Fig. S1). The soil chemical score decreased in S2, especially in NV (from 0.76 to 0.66) (Fig. 3). The physical score showed a reduction in S2, specifically in DE (from 0.42 to 0.26), while the biological score showed an improvement in all areas evaluated in S2. Overall SHI increased in NV and RE in both S1 and S2, whereas no significant variation was observed in DE (Fig. 4).

A redundancy analysis (RDA) was conducted to correlate SH indicators with SMAF scores (Fig. 5). In S1, axis 1 and 2 explained 80 % of variance. The RDA showed a positive correlation of MBC, BG, and SOC with the biological component of SH, as well as its interaction with NV and RE. In addition, BD and SAR were negatively correlated with the physical component and SHI and were important indicators for distinguishing DE in a separate cluster (Fig. 5a). In S2, axis 1 and 2 explained 79 % of data variance. RDA showed a positive correlation between MBC, P, K^{+}, BG, and SOC, mainly in RE. Soil pH showed a close correlation with NV. BD and SAR showed a positive correlation with DE and a negative correlation with the physical component of SH and SHI. The areas with NV and DE were clearly separated (Fig. 5b).

4. Discussion

This study provides novel insights into soil health (SH) changes/assessment in degraded and restored soils in the Brazilian drylands (Caatinga biome). Our findings support both initial hypotheses, showing that SMAF was efficient to evaluate SH based on chemical, physical, and biological indicators in both degraded and restored soils; overgrazing led to a reduction in SH scores compared to native vegetation, whereas grazing exclusion increased SH after two decades of restoration to similar levels of native Caatinga vegetation. Our results provide valuable insights to understand the resilience of the Caatinga biome and

Table 2
SMAF scores of soil health indicators from Caatinga's native (NV), degraded (DE), and restored (RE) vegetation in Brazilian desertification hotspot.

Land use	Chemical			Physical			Biological	
	[1]pH	[2]SAR	[3]P	[4]K	[5]BD	[6]SOC	[7]MBC	[8]BG
S1								
NV	0.96*	0.25^{a}	0.99^{a*}	0.93^{a}	0.75^{a}	0.93^{a}	0.48^{b}	0.51^{a}
DE	0.87	0.21^{b}	0.93^{b}	0.80^{b}	0.42^{b*}	0.42^{b}	0.17^{c}	0.07^{b}
RE	0.93	0.24^{c}	0.98^{a}	0.95^{a}	0.56^{b}	0.98^{a}	0.58^{a}	0.38^{a}
S2								
NV	0.91^{a}	0.25^{a}	0.96^{b}	0.95^{a}	0.89^{a*}	1.00	0.81^{a*}	0.91^{a*}
DE	0.56^{b}	0.23^{b}	0.97^{ab}	0.87^{b}	0.25^{c}	0.62^{b*}	0.43^{b*}	0.27^{b*}
RE	0.89^{a}	0.24^{c}	0.99^{a}	0.99^{a*}	0.65^{b}	1.00	1.00^{a*}	0.87^{a*}

[1] Hydrogenionic potential.
[2] Sodium adsorption ratio.
[3] Available phosphorus.
[4] Potassium.
[5] Bulk density.
[6] Soil organic carbon.
[7] Microbial biomass carbon.
[8] β-glucosidase activity. Soils were sampled in February/2020 (S1) and October/2021 (S2). Lower-case letters compared soil management (NV, DE, and RE) within each period and *compared periods within each treatment by the Tukey test (5 %)($P < 0.05$), $n = 9$.

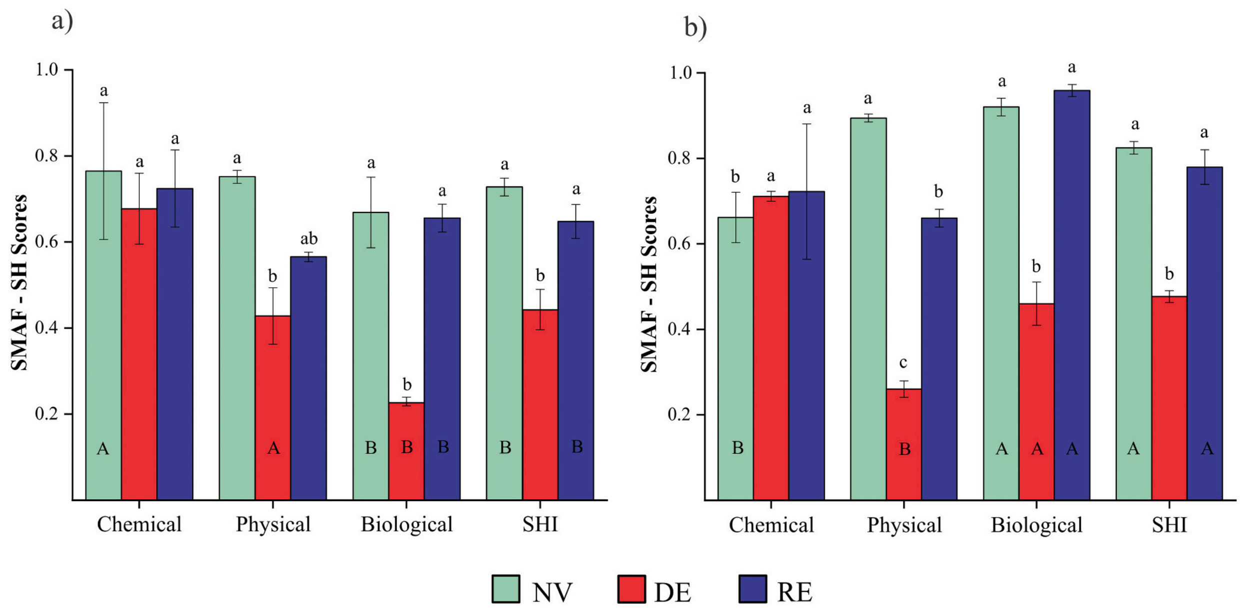

Fig. 3. SMAF - SHI and chemical, physical, and biological components. Means followed by the same letter do not differ by Tukey's test at a significance level of 5 % ($P < 0.05$). Lower-case letters compared soil management (NV, DE, and RE) within each period, and, upper-case letters, compared periods within each treatment. Absence of letters indicates no differences. Error bars indicate standard deviation ($n = 9$). (a) sampling 1 and (b) sampling 2.

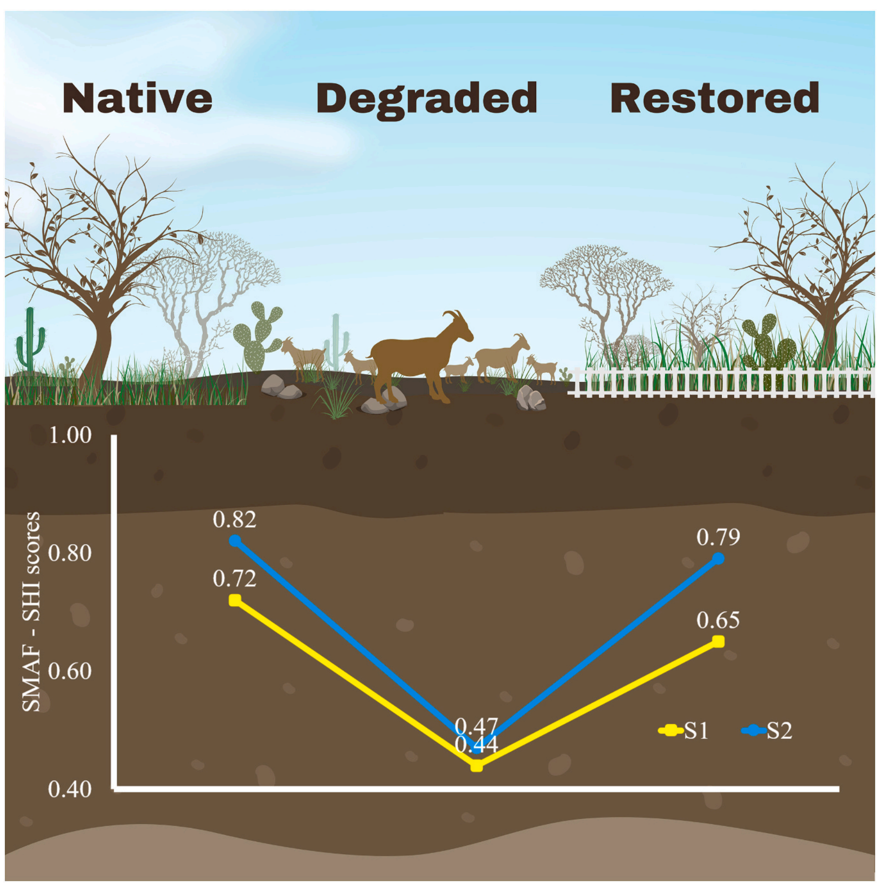

Fig. 4. SMAF - SHI in Caatinga's native (NV), degraded (DE), and restored (RE) vegetation in Brazilian desertification hotspot. (S1) sampling 1 and (S2) sampling 2.

important strategies to restore/monitor soil functioning in semiarid regions under desertification.

We showed that grazing exclusion led to significant improvements in soil health indicators, mainly in biological component. The restored areas, which were subjected to grazing exclusion for 21 years, had higher soil health index (SHI) scores compared to the degraded areas. Additionally, the restored and native areas showed similar SHI scores, indicating that grazing exclusion is an effective approach for restoring

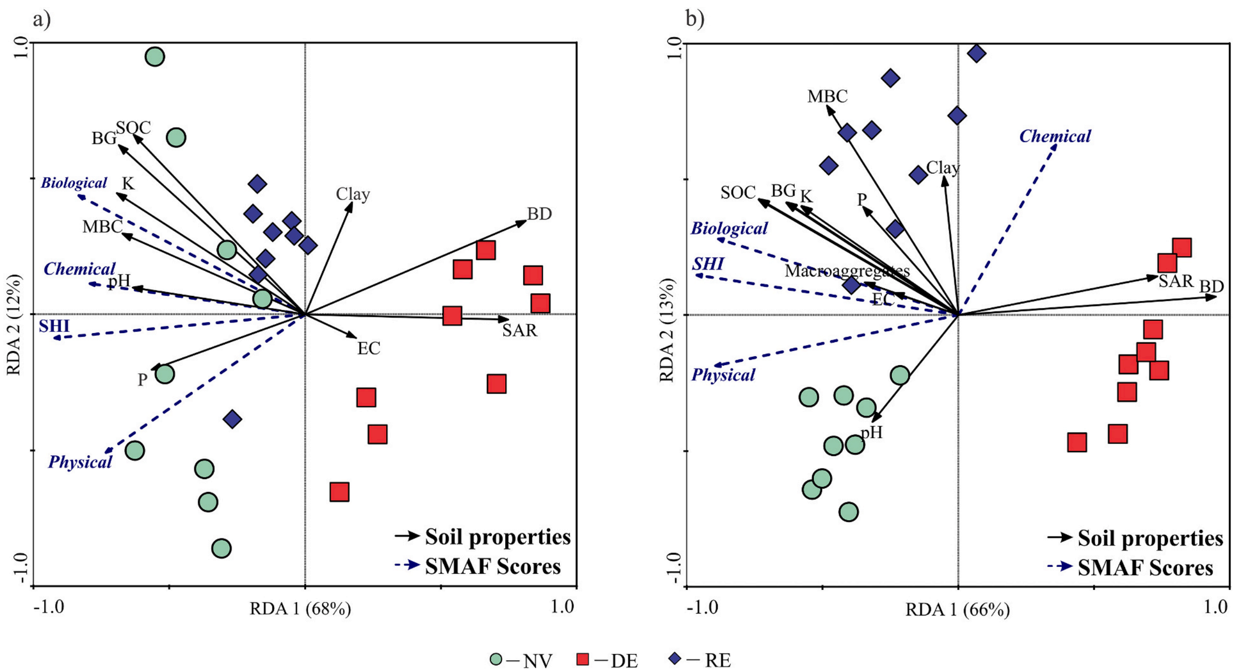

Fig. 5. Redundancy analysis (RDA) with the relationship between soil health scores (SHI and components) and NV = natural vegetation of Caatinga biome, DE = degraded and, RE = restored (by grazing-exclusion) treatments and soil properties. In (a) sampling 1 and (b) sampling 2.

soil functioning in degraded lands affected by overgrazing. Oliveira-Filho et al. (2019), in the same experimental area, evaluated the effects of 19 years of grazing exclusion on soil stoichiometry and demonstrated that particulate soil organic fractions (C and N contents, specifically) increased with grazing exclusion. Also, Pereira et al. (2021a, 2021b) demonstrated a positive correlation between bacterial diversity and SOC in the same area in subsequent years.

Thus, soil recovery strategies such as grazing exclusion could be an important strategy to increase soil health indicators. Importantly, these effects seem to occur in different eco-regions. For example, Dong et al. (2021) evaluating Chinese grasslands of a semiarid region, demonstrated that medium-term grazing exclusion increased labile C fractions and mineralization rate compared with continuous grazing. Interestingly, the climatic conditions observed in the region studied by Dong et al. (2021) resemble the Brazilian semiarid environment, characterized by remarkably low annual precipitation rates and an approximately 21-year period of grazing exclusion treatments. This parallel suggests that soil management techniques, like the implementation of grazing exclusion, hold promising potential for enhancing soil health across diverse contexts.

Soil organic carbon plays a crucial role in soil fertility, structural stability, and promotes microbial traits (Hoffland et al., 2020). Our results suggested that biological indicators, such as SOC, MBC, and BG, play a crucial role in restoring SH. The higher SHI scores in the restored areas were largely driven by these biological indicators since we found a positive correlation of SOC, MBC, and BG, with the biological component of SH, mainly at NV and RE. Its interaction indicates that the improvement in soil biological properties can be achieved through grazing exclusion and vegetation cover. These findings are consistent with those of Pereira et al. (2021a, 2021b), Oliveira et al. (2021), and Silva et al. (2022), who reported that grazing exclusion improved microbial properties (i.e., bacterial, and fungal communities, and enzyme activity). Specifically, Oliveira et al. (2021) demonstrated that grazing exclusion (18 years) had the highest β-glucosidase and arylsulfatase activities. Importantly, restored areas showed 20 % more phosphate solubilizers bacteria, indicating that grazing exclusion improved soil biological functioning such as enzyme activity (C and S cycles) and phosphorus contents.

Thus, the increase in SHI in the restored areas may be attributed to the increased richness of bacteria and fungi associated with higher enzyme activity, which are in turn driven by higher SOC content (Oliveira-Filho et al., 2019; Pereira et al., 2021a; Oliveira et al., 2021; Silva et al., 2022). Importantly, the increase in SOC may have contributed to the improvement of SH and the potential for C sequestration, which could have important implications for climate change mitigation. It reinforces the sensitivity of grazing exclusion and biological indicators to assess SH Caatinga biome areas, as well as they can provide valuable insights into the effectiveness of restoration practices (Bhaduri et al., 2022). Beyond the implementation of grazing exclusion, other methodologies, including the establishment of terraces and the use of cover crops, have emerged as noteworthy contributors to the restoration of degraded regions within the Brazilian semiarid (Araujo et al., 2023). These techniques have exhibited favorable outcomes on both the diversity and abundance of soil microorganisms. Nonetheless, the comprehensive quantification of soil health across all these systems within the Brazilian semiarid zone demands concerted endeavors, being crucial to its sustainability.

Globally, bulk soil density (BD) is the most physical property affected by overgrazing (Byrnes et al., 2018). BD is an important SH indicator, as it affects several soil functions, including physical stability, water relations, and filtering and oxygen diffusion (Andrews et al., 2004). Our results showed a higher BD in degraded areas, probably due to the long-term effect of overgrazing and trampling by animals, which contribute to soil compaction and degradation (Pulido et al., 2017). Importantly, we found a negative correlation of BD with soil health indexes, which contributed to distinguishing DE in a separate cluster (Fig. 5). It suggests that overgrazing and soil compaction are important contributors to the degradation of soil's physical properties in Brazilian drylands.

Increased BD reduces pore space and soil water storage (Oliveira-Filho et al., 2019), which can adversely affect plant root development (Matos et al., 2022). Previous studies have reported negative effects of increased BD on soil functionality, including soil degradation, and reduced nutrient availability (Cherubin et al., 2016a; Luz et al., 2019). On the other hand, grazing exclusion practices can help to restore SH by allowing vegetation recovery and improving soil structure, which reduces BD and maintains soil functionality (Cherubin et al., 2016b; Luz et al., 2022). Recently, Gamboa et al. (2023) demonstrated that active plant biomass inputs increased the soil pore system and improved functionality under no-till soils. Also, soil cover can contribute to increasing biogenic aggregates and, consequently, reduce BD (Pereira et al., 2021b).

Interestingly, degraded areas showed the highest sodium absorption ratio (SAR). Soil bulk density can increase due to the Na^+ contents, reducing pore-size distribution, permeability, drainage rate, and root development (Shakir et al., 2002; Hussain et al., 2022). Thus, soil health enhancement induced by grazing exclusion could be attributed to increased vegetation cover, which reduces soil erosion and provides organic matter that contributes to improved soil structure and porosity (Gamboa et al., 2023; Oliveira-Filho et al., 2019).

Biological soil health indicators quickly change due to soil management practices (Cardoso et al., 2013) and widely respond as per climate season. Interestingly, our results showed that SHI was higher during dry season. In addition, these changes were boosted by biological components since, together, there were no significant changes in chemical or physical components over time (Fig. S1). It highlights the importance of biological indicators to SH assessment in soils under desertification. These results are in line with Matos et al. (2022) that demonstrated higher BG and MBC activity during the dry season in agroforest systems in southeast Brazil. The Caatinga vegetation is mainly composed of deciduous botanical tree species (de Queiroz et al., 2017). Thus, its vegetation promotes intensive litter fall at the end of the rainy season. In fact, the origin of "Caatinga" term (i.e., "whitish forest" in the indigenous "Tupi" language) is mainly due to the aspect of its seasonally deciduous vegetation.

Probably, during the dry season, the higher liter deposition improves biological activity (mainly extracellular enzymes) to promote nutrient cycling (Matos et al., 2022). Furthermore, the enzyme activity during the dry season is an important driver for the transformation and decomposition of soil organic matter since β-glucosidase is involved in the hydrolytic breakdown of C-rich compounds in soil, which explained a positive correlation with SOC and MBC contents. In contrast, degraded areas showed the lowest scores for BG and MBC, indicating a deterioration of microbial properties (Veum et al., 2014), independently of season. Thus, our results confirm that BG and MBC are important indicators for assessing the biological component of SH (Nunes et al., 2020), especially during the dry season.

Soil health assessment requires robust tools which can be quickly applied and provide relevant information about soil functioning. SMAF scores were able to detect loss of SH among land use management in Caatinga biome and biological components were more sensitive than physical and chemical components. Thus, our results suggested that biological manipulation (e.g., the use of efficient plant growth-promoting microorganisms, organic inputs, crop diversification, etc.) could be an important strategy for accelerating SH recovery in Brazilian drylands. The use of SMAF to assess SH in this ecosystem is particularly significant given the unique characteristics of the Caatinga biome, which is characterized by a semiarid climate and is vulnerable to land degradation caused by human activities (Oliveira et al., 2021; Oliveira-Filho et al., 2019; Pereira et al., 2021a). Thus, we encourage the use of SMAF as a useful tool for a feasible strategy for monitoring SH under desertification hotspots in Brazilian drylands. SMAF results can detect strategic/priority areas for restoration based on soil functioning. Finally, future studies, including different ecoregions, soil types, and, more importantly, different strategies for soil recovery in Caatinga (e.g., integrating livestock systems) are urgently needed.

5. Conclusions

This study has successfully assessed soil health using the SMAF in both degraded and restored lands within the Brazilian semiarid region. Notably, the SMAF scores (encompassing chemical, physical, and biological aspects) displayed elevated values in both native vegetation and restored lands. This outcome led to higher soil health index values, effectively corroborating the initial hypothesis and highlighting the SMAF's efficacy in generating soil health scores in Brazil's drylands. It is crucial to underline that soil health scores experienced a decline in degraded areas due to overgrazing. Nevertheless, the grazing exclusion facilitated the recovery of soil health following two decades of restoration efforts. In alignment with the restoration areas, the native Caatinga vegetation emerges as a pivotal factor in influencing soil health, with its presence yielding notably higher soil health values, particularly evident in biological indicators such as SOC, MBC, and BG. The distinctive seasonality of the Caatinga deciduous vegetation, characterized by substantial leaf shedding during the dry season, intensifies biological activity within this timeframe. This emphasizes the pivotal role of native vegetation in stimulating microbial processes and nutrient cycling in arid environments. The study underscores the significance of implementing grazing exclusion as a strategic measure to augment vegetation cover and enhance soil health in dryland regions. Furthermore, it elucidates the sensitivity and rapid responsiveness of biological properties as effective indicators to discern the impacts of detrimental practices on soil health.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2023.105107.

References

Amorim, H.C.S., Ashworth, A.J., Moore, P.A., Wienhold, B.J., Savin, M.C., Owens, P.R., Jagadamma, S., Carvalho, T.S., Xu, S., 2020. Soil quality indices following long-term conservation pasture management practices. Agric. Ecosyst. Environ. 301, e107060 https://doi.org/10.1016/j.agee.2020.107060.

Andrews, S., Karlen, D.L., Cambardella, C.A., 2004. The Soil Management Assessment Framework. Soil Sci. Soc. Am. J. 68 (6), 1945–1962. https://doi.org/10.2136/sssaj2004.1945.

Araujo, A.S.F., Pereira, A.P.A., Costa, D.P., Lima, A.Y.V., Melo, V.M.M., Medeiros, E.V., Mendes, L.W., 2023. A desertificação e a saúde do solo no bioma Caatinga. In: Nogueira, T.A.S., Cherubin, M.R., Pereira, A.P.A., Tiecher, T. (Eds.), Tópicos em Ciência do Solo (XII). Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 7–23.

Basak, N., Mandal, B., Biswas, S., Basak, P., Mitran, T., Saha, B., Rai, A.K., Alam, M.K., Yadav, A.K., Datta, A., 2022. Impact of long term nutrient management on soil quality indices in rice-wheat system of lower Indo-Gangetic plain. Sustainability 14, 6533. https://doi.org/10.3390/su14116533.

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B.C., Munda, S., Dari, B., 2022. A review on effective soil health bio-indicators for ecosystem restoration and sustainability. Front. Microbiol. 13, 938481 https://doi.org/10.3389/fmicb.2022.938481.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis: Physical and Mineralogical Methods. Part. 1. American Society of Agronomy. Madison, pp. 363–375. https://doi.org/10.1002/gea.3340050110.

Braak, C.T., Šmilauer, P., 2002. CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (version 4.5).
Brasil, 2005. Ministério do Meio Ambiente. In: Programa de Ação Nacional de Combate à Desertificação e Mitigação dos Efeitos da Seca, PAN-Brasil. Secretaria de Recursos Hídricos, Brasília. https://antigo.mma.gov.br/estruturas/sedr_desertif/_arquivos/pan_brasil_portugues.pdf. (Accessed 12 April 2022).
Brasil, 2021. Quarta Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Setor Uso da Terra, Mudança do Uso da Terra e Florestas. MCT, Brasília. https://www.gov.br/mcti/pt-br/centrais-de-conteudo/publicacoes-mcti/quarta-comunicacao-nacional-do-brasil-a-unfccc/sumario_executivo_4cn_brasil_web.pdf. (Accessed 29 July 2022).
Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030.
Byrnes, R.C., Eastburn, D.J., Tate, K.W., Roche, L.M., 2018. A global meta-analysis of grazing impacts on soil health indicators. J. Environ. Qual. 47, 758–765. https://doi.org/10.2134/jeq2017.08.0313.
Cardoso, E.J.B.N., Vasconcellos, R.L.F., Bini, D., Miyauchi, M.Y.H., dos Santos, C.A., Alves, P.R.L., de Paula, A.M., Nakatani, A.S., Pereira, J. de M., Nogueira, M.A., 2013. Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? Sci. Agric. 70, 274–289. https://doi.org/10.1590/S0103-90162013000400009.
Çelik, İ., Günal, H., Acir, N., Barut, Z.B., Budak, M., 2021. Soil quality assessment to compare tillage systems in Cukurova Plain, Turkey. Soil Tillage Res. 208 https://doi.org/10.1016/j.still.2020.104892.
Chavarro-Bermeo, J.P., Hincapie, K.L.P., Cherubin, M.R., Morea, F.A.O., Olaya, A.M.S., 2022. Evaluating soil quality in silvopastoral systems by the Soil Management Assessment Framework (SMAF) in the Colombian Amazon. Rev. Ciênc. Agron. 53, 1–11. https://doi.org/10.5935/1806-6690.20220060.
Cherubin, M.R., Karlen, D.L., Franco, A.L.C., Cerri, C.E.P., Tormena, C.A., Cerri, C.C., 2016a. A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane Expansion on soil quality. Soil Sci. Soc. Am. J. 80 (1), 215–226. https://doi.org/10.2136/sssaj2015.09.0328.
Cherubin, M.R., Karlen, D.L., Cerri, C.E.P., Franco, A.L.C., Tormena, C.A., Davies, C.A., Cerri, C.C., 2016b. Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. PLoS One 11 (3), e0150860. https://doi.org/10.1371/journal.pone.0150860.
Cherubin, M.R., Tormena, C.A., Karlen, D.L., 2017. Soil quality evaluation using the Soil Management Assessment Framework (SMAF) in Brazilian oxisols with contrasting texture. Rev. Bras. Cienc. Solo 41, 1–18. https://doi.org/10.1590/18069657rbcs20160148.
Cherubin, M.R., Bordonal, R.O., Castioni, G.A., Guimarães, E.M., Lisboa, I.P., Moraes, L.A.A., Menandro, L.M.S., Tenelli, S., Cerri, C.E.P., Karlen, D.L., Carvalho, J.L.N., 2021. Soil health response to sugarcane straw removal in Brazil. Ind. Crop. Prod. 163, e113315 https://doi.org/10.1016/j.indcrop.2021.113315.
da Silva, J.M.C., Barbosa, L.C.F., Leal, I.R., Tabarelli, M., 2017. The Caatinga: understanding the challenges. In: Silva, J.M.C., Leal, I.R., Tabarelli, M. (Eds.), Caatinga: The Largest Tropical Dry Forest Region in South America. Springer, pp. 3–19. https://doi.org/10.1007/978-3-319-68339-3_1.
de Queiroz, L.P., Cardoso, D., Fernandes, M.F., Moro, M.F., 2017. Diversity and evolution of flowering plants of the Caatinga domain. In: Silva, J.M.C., Leal, I.R., Tabarelli, M. (Eds.), Caatinga: The Largest Tropical Dry Forest Region in South America. Springer, pp. 23–63. https://doi.org/10.1007/978-3-319-68339-3_2.
Dong, L., Martinsen, V., Wu, Y., Zheng, Y., Liang, C., Liu, Z., Mulder, J., 2021. Effect of grazing exclusion and rotational grazing on labile soil organic carbon in north China. Eur. J. Soil Sci. 72, 372–384. https://doi.org/10.1111/ejss.12952.
Doran, J.W., Parkin, T.B., 1994. Defining and Assessing Soil Quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment, Soil Sci. Soc. Am. J. Madison. https://doi.org/10.2136/sssaspecpub35.c1.
Fernandes, V.L.B., 1993. Recomendações de Adubação e Calagem para o Estado do Ceará. Universidade Federal do Ceará – UFC, Fortaleza, p. 248.
Gamboa, C.H., Figueiredo, Getulio C., Vezzani, F.M., Ferreira, F.C., Bayer, C., 2023. Active plant biomass inputs influence pore system functioning in no-till soils. Geoderma 434, 116477. https://doi.org/10.1016/j.geoderma.2023.116477.
Gura, I., Mnkeni, P.N.S., 2019. Dataset on the use of the Soil Management Assessment Framework (SMAF) in evaluating the impact of conservation agriculture strategies on soil quality. Data Brief 22, 578–582. https://doi.org/10.1016/j.dib.2018.12.044.
Hoffland, E., Kuyper, T.W., Comans, R.N.J., Creamer, R.E., 2020. Eco-functionality of organic matter in soils. Plant Soil 455, 1–22. https://doi.org/10.1007/s11104-020-04651-9.
Hu, Z., Li, S., Guo, Q., Niu, S., He, N., Li, L., Yu, G., 2016. A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China. Glob. Chang. Biol. 22, 1385–1393. https://doi.org/10.1111/gcb.13133.
Huang, J., Zhang, G., Zhang, Y., Guan, X., Wei, Y., Guo, R., 2020. Global desertification vulnerability to climate change and human activities. Land Degrad. Dev. 31 (11), 1380–1391. https://doi.org/10.1002/ldr.3556.
Hussain, R., Sharma, S., Geetika, Ahmed, M., Kumari, I., 2022. Plant microbiome: modulation of plant defense and ecological dynamics under stressed environment. In: Mitigation of Plant Abiotic Stress by Microorganisms: Applicability and Future Directions. Elsevier Inc. https://doi.org/10.1016/B978-0-323-90568-8.00002-X.
IPCC, 2021. The Intergovernmental Panel on Climate Change. Special Report on Climate Change and Land. https://www.ipcc.ch/srccl/chapter/chapter-3/. (Accessed 21 August 2021).
IPECE, 2017. Instituto de Pesquisa e Estratégia Econômica do Ceará. Perfil municipal, Irauçuba-CE, p. 18. https://www.ipece.ce.gov.br/wpcontent/uploads/sites/45/2018/09/Iraucuba_2017.pdf. (Accessed 13 July 2021).
Jiang, R., Li, T., Jia, Z., Dong, Y., 2022. Determining soil available water capacity and reasonable irrigation volume in dryland pasture. Water (Switzerland) 14. https://doi.org/10.3390/w14172760.
Karlen, D.L., Andrews, S.S., Wienhold, B.J., Zobeck, T.M., 2008. Soil quality assessment: past, present, and future. J. Integr. Biosc. 6 (1), 3–14. https://digitalcommons.unl.edu/usdaarsfacpub/1203/. (Accessed 24 August 2022).
Karlen, D.L., Veum, K.S., Sudduth, K.A., Obrycki, J.F., Nunes, M.R., 2019. Soil health assessment: past accomplishments, current activities, and future opportunities. Soil Tillage Res. 195, 104365 https://doi.org/10.1016/j.still.2019.104365.
Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nat. Rev. Earth Environ. 1, 544–553. https://doi.org/10.1038/s43017-020-0080-8.
Listopad, C.M.C.S., Köbel, M., Príncipe, A., Gonçalves, P., Branquinho, C., 2018. The effect of grazing exclusion over time on structure, biodiversity, and regeneration of high nature value farmland ecosystems in Europe. Sci. Total Environ. 610–611, 926–936. https://doi.org/10.1016/j.scitotenv.2017.08.018.
Luz, F.B., Silva, V.R., Mallmann, F.J.K., Pires, C.A.B., Debiasi, H., Franchini, J.C., Cherubin, M.R., 2019. Monitoring soil quality changes in diversified agricultural cropping systems by the Soil Management Assessment Framework (SMAF) in southern Brazil. Agric. Ecosyst. Environ. 281, 100–110. https://doi.org/10.1016/j.agee.2019.05.006.
Luz, F.B., Carvalho, M.L., Castioni, G.A.F., de Oliveira Bordonal, R., Cooper, M., Carvalho, J.L.N., Cherubin, M.R., 2022. Soil structure changes induced by tillage and reduction of machinery traffic on sugarcane – a diversity of assessment scales. Soil Tillage Res. 223 https://doi.org/10.1016/j.still.2022.105469.
MapBiomas, 2021. Caatinga – Desmatamento, queimadas e retração da superfície da água aumentam o risco de desertificação da Caatinga. https://mapbiomas.org/desmatamento-queimadas-e-retracao-da-superficie-da-agua–aumentam-o-risco-de-desertificacao-da-caatinga. (Accessed 20 April 2023).
Marengo, J.A., Galdos, M.V., Challinor, A., Cunha, A.P., Marin, F.R., Vianna, M.D.S., Alvala, R.C.S., Alves, L.M., Moraes, O.L., Bender, F., 2022. Drought in Northeast Brazil: a review of agricultural and policy adaptation options for food security. Clim. Resil. Sustain. 1, e17 https://doi.org/10.1002/cli2.17.
Matos, P.S., Cherubin, M.R., Damian, J.M., Rocha, F.I., Pereira, M.G., Zonta, E., 2022. Short-term effects of agroforestry systems on soil health in Southeastern Brazil. Agrofor. Syst. 96 (5-6), 897–908. https://doi.org/10.1007/s10457-022-00749-4.
Nelson, D.W., Sommers, L.E., 1983. Total Carbon, Organic Carbon, and Organic Matter. In: Page, A.L. (Ed.), Methods of Soil Analysis, Soil Sci. Soc. Am. J. Madison. https://doi.org/10.2134/agronmonogr9.2.2ed.c29.
Nunes, M.R., Karlen, D., Veum, K.S., Moorman, T.B., Cambardella, C.A., 2020. Biological soil health indicators respond to tillage intensity: a US meta-analysis. Geoderma 369, 114335. https://doi.org/10.1016/j.geoderma.2020.114335.
Oliveira, A.F.N., Sousa, L.I.S., Costa, V.A.S., de Andrade, J.V.T., Lima, L.A.L., de Sales, P.A.F., da Silva, D.F., Pereira, A.P.A., Melo, V.M.M., 2021. Long-term effects of grazing on the biological, chemical, and physical soil properties of the Caatinga biome. Microbiol. Res. 253 https://doi.org/10.1016/j.micres.2021.126893.
Oliveira-Filho, J.D.S., Vieira, J.N., Silva, E.M.R., Oliveira, J.G.B., Pereira, M.G., Brasileiro, F.G., 2019. Assessing the effects of 17 years of grazing exclusion in 33 degraded semi-arid soils: evaluation of soil fertility, nutrients pools, and stoichiometry. J. Arid Environ. 166, 1–10. https://doi.org/10.1016/j.jaridenv.2019.03.006.
Pereira, A.P.A., Lima, L.A.L., Bezerra, W.M., Pereira, M.L., Normando, L.R.O., Mendes, L.W., Oliveira, J.G.B., Araújo, A.S.F., Melo, V.M.M., 2021a. Grazing exclusion regulates bacterial community in highly degraded semiarid soils from the Brazilian Caatinga biome. Land Degrad. Dev. 32 (6), 2210–2225. https://doi.org/10.1002/ldr.3893.
Pereira, A.P.A., Mendes, L.W., Oliveira, F.A.S., Antunes, J.E.L., Melo, V.M.M., Araujo, A.S.F., 2022. Land degradation affects the microbial communities in the Brazilian Caatinga biome. Catena 211, e105961. https://doi.org/10.1016/j.catena.2021.105961.
Pereira, M.G., Loss, A., Batista, I., de Melo, T.R., da Silva Neto, E.C., Rodrigues Pinto, L.A. da S., 2021b. Biogenic and physicogenic aggregates: formation pathways, assessment techniques, and influence on soil properties. Ver. Bras. Cienc. Solo 45, 1–23. https://doi.org/10.36783/18069657rbcs20210108.
Polli, H., Guerra, J.G.M., 1997. Determinação do carbono da biomassa microbiana do solo: método de fumigação-extração. Embrapa-CNPAB, Seropédica., p. 10
Pulido, M., Schnabel, S., Contador, J.F.L., Lozano-Parra, J., Gómez-Gutiérrez, Á., Brevik, E.C., Cerdà, A., 2017. Reduction of the frequency of herbaceous roots as an effect of soil compaction induced by heavy grazing in rangelands of SW Spain. Catena 158, 381–389. https://doi.org/10.1016/j.catena.2017.07.019.
Raij, B., Andrade, J.C., Cantarella, H., Quaggio, J.A., 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico, Campinas, p. 285.
Rinot, O., Levy, G.J., Steinberger, Y., Svoray, T., Eshel, G., 2019. Soil health assessment: a critical review of current methodologies and a proposed new approach. Sci. Total Environ. 648, 1484–1491. https://doi.org/10.1016/j.scitotenv.2018.08.259.
Schulz, K., Voigt, K., Beusch, C., Almeida-Cortez, J.S., Kowarik, I., Walz, A., Cierjacks, A., 2016. Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. For. Ecol. Manag. 367, 62–70. https://doi.org/10.1016/j.foreco.2016.02.011.
Shakir, M.S., Hassan, A., Razzaq, A., 2002. Effect of salts on bulk density, particle density and porosity of different soil series. Asian J. Plant Sci. 1, 5–6. https://doi.org/10.3923/ajps.2002.5.6.

Silva, D.F., Moreira, J.V., Sousa, L.I.S., Santana, M.C., Mota, J.C.A., Queiroz, A.S., Nascimento, I.V., Silva, A.M.M., Araújo, A.S.F., Melo, V.M.M., Medeiros, E.V., Cardoso, E.J.B.N., Pereira, A.P.A., 2022. Arbuscular mycorrhizal fungi community in soils under desertification and restoration in the Brazilian semiarid. Microbiol. Res. 264, e127161 https://doi.org/10.1016/j.micres.2022.127161.

Simon, C.P., Gomes, T.F., Pessoa, T.N., Soltangheisi, A., Bieluczyk, W., Camargo, P.B., Martinelli, L.A., Cherubin, M.R., 2022. Soil quality literature in Brazil – a systematic review. Rev. Bras. Cienc. Solo 4, e0210103. https://doi.org/10.36783/18069657rbcs20210103.

Stott, D.E., Karlen, D.L., Cambardella, C.A., Harmel, R.D., 2013. A soil quality and metabolic activity assessment after fifty-seven years of agricultural management. Soil Sci. Soc. Am. J. 77, 903–913. https://doi.org/10.2136/sssaj2012.0355.

Tabatabai, M.A., 1994. Soil Enzymes. In: Weaver, R.W., Angle, J.S., Botttomley, P.S. (Eds.), Methods of Soil Analysis: Microbiological and Biochemical Properties, Soil Sci. Soc. Am. J. Madison, pp. 775–833. https://doi.org/10.2136/sssabookser5.2.

Teixeira, P.C., Donagema, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de Métodos de Análise de Solo. Embrapa. Distrito Federal, Distrito Federal, p. 573.

U.S. Department of Agriculture, Natural Resources Conservation Service. Technical Soil Services Handbook. Available online (https://www.nrcs.usda.gov/resources/guides-and-instructions/technical-soil-services-handbook). Accessed [08/12/2023].

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707. https://doi.org/10.1016/0038-0717(87)90052-6.

Veum, K.S., Goyne, K.W., Kremer, R.J., Miles, R.J., Sudduth, K.A., 2014. Biological indicators of soil quality and soil organic matter characteristics in an agricultural management continuum. Biogeochemistry 117, 81–99. https://doi.org/10.1007/s10533-013-9868-7.

Wienhold, B.J., Karlen, D.L., Andrews, S.S., Stott, D.E., 2009. Protocol for indicator scoring in the soil management assessment framework (SMAF). Renew. Agric. Food Syst. 24 (4), 260–266. https://doi.org/10.1017/S1742170509990093.

Wilson, C.H., Strickland, M.S., Hutchings, J.A., Bianchi, T.S., Flory, S.L., 2018. Grazing enhances belowground carbon allocation, microbial biomass, and soil carbon in a subtropical grassland. Glob. Chang. Biol. 24, 2997–3009. https://doi.org/10.1111/gcb.14070.