FEDERAL UNIVERSITY OF CEARÁ
CENTER OF AGRARIAN SCIENCES
SOIL SCIENCE DEPARTMENT
POST-GRADUATE PROGRAM IN SOIL SCIENCE

ANTONIO YAN VIANA LIMA

SOIL HEALTH ASSESSMENT IN THE BRAZILIAN DRYLAND REGION (CAATINGA BIOME)

FORTALEZA

2022

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Dissertation presented to the Post-Graduate Program in Soil Science of the Federal University of Ceará, as a partial requirement to obtain Master's degree in Soil Science.
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2022

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

L696s Lima, Antonio Yan Viana.
Soil health assessment in the Brazilian dryland region (Caatinga biome) / Antonio Yan Viana Lima. – 2022.
57 f. : il. color.

Dissertação (mestrado) – Universidade Federal do Ceará, Centro de Ciências Agrárias, Programa de Pós-Graduação em Ciência do Solo, Fortaleza, 2022.
Orientação: Prof. Dr. Arthur Prudêncio de Araujo Pereira.

1. Drylands. 2. Bibliometric review. 3. Desertification. 4. Grazing exclusion. 5. Soil Management Assessment Framework. I. Título.

CDD 631.4

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Approved in: 21/10/2022.

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ACKNOWLEDGMENTS

I thank God for all the support throughout this journey.

I thank my parents José Pereira Lima *(in memoriam)* and Maria Fátima Viana for all the love and extreme care they have always taken for me.

I thank my advisor, Professor Arthur Prudêncio de Araujo Pereira for all the teachings on soil science, feedback, and insights on this dissertation. I thank you for encouraging my interest in studying soil health in the Caatinga biome and for the partnership in publications throughout the master's degree.

I thank Professor Maurício Roberto Cherubin for agreeing to participate in this project and cooperating with his extensive experience in soil health. I thank you for your teachings and receptivity in SOHMA.

I thank Soil Microbiology and Biotechnology Study Group (GEMBioS) and Soil Health & Management Research Group (SOHMA) for the possibility of developing and discussing the results of this work. I thank the friends and colleagues of both groups for all the support and companionship received in Fortaleza/CE and Piracicaba/SP.

I thank the Microbiology Laboratory (Kaio Gráculo), and Physics Laboratory (Professor Jaedson Mota and Franzé) for the monitoring during the execution of the analyses in their respective laboratories, and the secretary Edilson Dote for always being requested and willing to help with academic bureaucracies.

I thank the friends I made throughout my master's degree in Fortaleza: Fernanda Abreu and Lucas Simões, and in Piracicaba: Mateus Marcon, Gabriela Cardoso, Beatriz Vanolli, Bruna Schiebelbein, and Martha Lustosa.

I thank the Federal University of Ceará for the opportunity to become an Agronomist, and now, a Master's in Soil Science. I thank the Post-Graduate Program in Soil Science for the structure that allowed me to do this work, beyond the excellent staff of professors linked to the program. Eternal gratitude for this important institution. I thank "Luiz de Queiroz" College of Agriculture – ESALQ/USP for the partnership during the academic mobility held in Piracicaba/SP. I thank FUNCAP for the promotion of the research grant (process nº BMD-0008-01847.01.04/20).

ABSTRACT

The Caatinga is an exclusively Brazilian biome present in the semiarid northeast, the most populated dryland worldwide, where more than 28 million people live. Climate factors (e.g., long periods of drought), and deleterious anthropic activities contribute to the soil degradation in the Caatinga biome. Overgrazing is the main cause of soil loss in this region, reducing soil health (SH), agricultural productivity, and soil functioning. However, the effects of soil degradation in SH remain poorly understood in the Caatinga biome. This study aimed to i) evaluate how SH has been studied in the Caatinga biome through bibliometric analyses, ii) evaluate chemical, physical, and biological parameters of the soil, and iii) validate the SMAF (Soil Management Assessment Framework) tool for the assessment of the effects of overgrazing and the grazing-exclusion on the health of soils affected by desertification processes in the Caatinga biome. The number of publications by year, most cited articles, main institutions, major journals, most used keywords, and international scientific collaboration among countries and authors were cataloged, through the search for the terms “soil quality" OR "soil health" AND "Caatinga" OR "Brazilian semiarid" in the Scopus® database. The assessment of the impact of management practices on SH was carried out in an experimental area of the effects of degradation on the Irauçuba Desertification Nucleus, Ceará State, where 3 areas with different managements were evaluated: i) Native vegetation (NV), ii) in advanced degradation process by overgrazing (DE), and iii) Restored (RE – grazing-exclusion for 21 years). Soil samples were collected (0-10 cm) in February/2020 (S1) and October/2021 (S2), totaling 54 samples (3 areas x 3 managements x 3 blocks x 2 seasons). Chemical (pH, sodium adsorption ratio, extractable K, and P), physical (bulk density), and biological (soil organic carbon, microbial biomass carbon, and β-glucosidase activity) indicators were analyzed. The results showed that SH research in the Caatinga biome is fragmented and incipient (only 39 publications were found), limited to studies of soil processes, and with low connectivity among institutions and researchers. The restored area (RE) increased soil health indicators, as follows: RE = NV > DE. The SH assessment showed bulk density and sodium adsorption ratio as limiting indicator to SH in DE, while soil organic carbon, microbial biomass carbon and β-glucosidase activity showed a significant increase in RE.

Keywords: drylands; bibliometric review; SMAF; desertification; grazing-exclusion.

RESUMO

A Caatinga é um bioma exclusivamente brasileiro presente no semiárido nordestino, a área seca mais populosa do mundo, onde vivem mais de 28 milhões de pessoas. Os fatores climáticos e as atividades antrópicas prejudiciais contribuem para a degradação do solo no bioma Caatinga. O sobrepastejo é a principal causa da perda de solo nesta região, reduzindo a saúde do solo (SS), a produtividade agrícola e o funcionamento do solo. Entretanto, os efeitos da degradação do solo na SS permanecem mal compreendidos no bioma Caatinga. Este estudo visou i) avaliar como a SS foi estudada no bioma Caatinga através de análises bibliométricas, ii) avaliar parâmetros químicos, físicos e biológicos do solo, e iii) validar a ferramenta SMAF (Soil Management Assessment Framework) para a avaliação dos efeitos do sobrepastejo e da exclusão do pastoreio na saúde dos solos afetados por processos de desertificação. O número de publicações por ano, os artigos mais citados, as principais instituições, as principais revistas, as palavras-chave mais utilizadas e a colaboração científica internacional entre países e autores foram catalogadas, através da busca dos termos "soil quality" ou "soil health" e "Caatinga" ou "brazilian semiarid" no banco de dados Scopus®. A avaliação do impacto das práticas de manejo na SS foi realizada em uma área experimental dos efeitos da degradação no Núcleo de Desertificação de Irauçuba, estado do Ceará, onde foram avaliadas 3 áreas com diferentes manejos: i) vegetação nativa (NV), ii) restaurada (RE - exclusão de pastoreio por 21 anos) e iii) em processo avançado de degradação por sobrepastoreio (DE). Foram coletadas amostras de solo (0-10 cm) em fevereiro/2020 (S1) e outubro/2021 (S2), totalizando 54 amostras (3 áreas x 3 manejos x 3 blocos x 2 estações). Foram analisados indicadores químicos (pH, taxa de adsorção de sódio, K extraível e P), físico (densidade do solo) e biológicos (carbono orgânico do solo, carbono de biomassa microbiana, e atividade da β-glicosidase). As pesquisas em SS no bioma Caatinga são fragmentadas, incipientes e com baixa conectividade entre instituições e pesquisadores. A área restaurada (RE) aumentou os indicadores de saúde do solo: RE = NV > DE. A avaliação de SS mostrou que a densidade do solo como o indicador mais limitante à SS em DE, enquanto carbono da biomassa microbiana e a atividade da enzima β-glicosidase apresentaram um aumento significativo em RE.

Palavras-chave: semiárido; bibliometria; SMAF; desertificação; exclusão de pastoreio.

CONTENTS

1 INTRODUCTION

The Caatinga biome is inserted in the Brazilian semiarid, the most densely populated dryland on the world, where 28.6 million people live. Drylands comprise about 41% of the globe. It is estimated that between 10 – 20 % of these areas are affected by soil degradation, with negative effects of billions of dollars on agribusiness and the loss of sustainability and biodiversity of ecosystems. Brazilian drylands are marked by historical poverty, presenting the lowest rates of human development in Latin America. Importantly, the Caatinga biome presents high degradation of its natural ecosystems, caused by anthropic activities such as excessive withdrawal of natural resources, overgrazing, fire, climate-related factors and others. Water scarcity caused by long periods of drought has been intensified by increased climate change through phenomena such as El Niño and La Niña, contributing to the deterioration of the biome's natural resources.

In the semiarid northeast, soil degradation reached very high levels, triggering the so called "Soil Desertification Processes". This phenomenon has a direct influence on the resilience and agricultural production of the Caatinga biome, limiting the supply of ecosystem services essential to the functioning of ecological systems and agricultural productivity on a small and large scale. In Brazil, there are currently four desertification nuclei: Irauçuba (CE), Gilbués (PI), Cabrobó (PE), and Seridó (RN/PB). In these locations, desertification processes have significantly affected agricultural productivity, besides directly influencing soil health (SH), bringing negative effects on human and animal life quality. The Irauçuba Desertification Nucleus, Ceará State, is, among the four, the one that is in the most advanced stage of degradation. Soil degradation through agricultural activities in Irauçuba has been reported for more than 150 years, while livestock has intensified its activity in the last 50 years, which is a decisive factor in reducing the resilience of the Caatinga biome in Irauçuba.

Techniques for the recovery of degraded areas have been studied in drylands worldwide. Among them, grazing-exclusion has obtained positive results in the evaluation of soil indicators and processes in areas restored by the technique. This technique consists of the adoption of fallow in highly degraded areas, seeking the recovery of environmental quality through the natural regeneration of vegetation. In the Caatinga, this technique has been used in the Irauçuba Desertification Nucleus, where positive results such as the recovery of soil fertility and greater microbial and enzymatic activity are already reported, indicating that this may be a promising technique for the SH restoration in degraded areas of Caatinga.

SH refers to the capacity that the soil has to function, aiming at maintaining productivity and environmental quality, beyond promoting human health and animal welfare. However, few studies evaluating SH in the Caatinga biome, and the use of robust tools such as the SMAF (Soil Management Assessment Framework), which through the integration of chemical, physical and biological indicators generate SH index in areas under different types of management. SH metrics remains poorly understood in the Caatinga, as well as metrics on scientific production focused on the SH of the biome. Thus, the validation of tools for the SH evaluation, such as SMAF, in the Brazilian semiarid and the use of systematic research as a bibliometric review may help researchers, producers, extensionists, and government agencies in monitoring and decision-making on the degradation of the Caatinga biome. They may also bring encouraging data on the recovery of degraded areas by desertification processes, fostering sustainable practices for the restoration of ecosystems, beyond areas of research little studied on SH in the Caatinga biome.

2 HYPOTHESES

There are few publications on SH in the Caatinga, confirming that this is a research area still incipient in Brazil.

The use of SMAF (Soil Management Assessment Framework) allows the evaluation of chemical, physical and biological indicators of soil health in degraded areas of the Caatinga.

The adoption of the grazing-exclusion technique recovers soil health in degraded areas by overgrazing at levels equal to or similar to those found in areas of native vegetation of the Caatinga.

3 OBJECTIVES

3.1 General

Evaluate soil health in the Brazilian dryland region (Caatinga biome).

3.2 Specific

Investigate how soil health has been addressed in research in the Caatinga biome through bibliometric analyses.

Evaluate chemical, physical, and biological parameters of the soil in native, degraded, and restored areas in the Caatinga.

Use and validate the SMAF tool to evaluate the effects of overgrazing and grazing-exclusion on the health of Caatinga soils affected by the desertification process.

4 SOIL HEALTH RESEARCH IN BRAZILIAN DRYLANDS (CAATINGA BIOME): AN OVERVIEW.

ABSTRACT

Soil health (SH) in the Brazilian drylands (Caatinga biome) is highly threated by poor management, land overuse (e.g., overgrazing) and climate changes. Therefore, understand the research profile in this vulnerable region that cover ~11% of Brazil's territory is critical to support the soil health research agenda in the next decades. In this context, we aimed to evaluate how SH research has been addressed in the Caatinga, Brazil. The terms "soil quality" or "soil health" and "Caatinga" or "Brazilian semiarid" were searched in the Scopus® database, between 1992 and 2022, and the results obtained were cataloged by the number of publications by year, most cited papers, main institutions, main journals, frequency of keywords, international scientific collaboration network among countries, and authors. SH research in Caatinga represented only 5 % of all papers published on soil health in Brazil with 39 papers published in the last two decades. In the years 2011, 2017, and 2021, 4 papers/year were published, the highest number for the evaluated period. Most of the research focused on SH changes induced by land use change from native Caatinga vegetation to agricultural systems. Beyond Brazil and Caatinga, Soil quality (17), Land use (4) and Forestry (3) are the most used keywords. The Brazilian Agricultural Research Corporation (EMBRAPA) that has 8 units into the Caatinga biome contributed with 23.1% of the publications, followed by the Federal Rural University of Pernambuco (15.4%). Papers were predominantly published in regional and national journals, such as Revista Caatinga (17.9%) and Revista Brasileira de Ciência do Solo (10.3%), respectively. Only 44% of papers were published in international journals. The network of international collaboration was limited, especially partnerships with institutions in Germany, the United States, and Canada. Our results also revealed a poor scientific network among the researcher groups from different institutions and countries. The study shows that knowledge of SH is still incipient in the Caatinga biome, and part of this is due to the lack of a scientific cooperation network dedicated to this theme in the region. The advances in knowledge of SH will be essential to understand the processes of SH degradation that occur in the region, and thus generate scientific support to establish more sustainable use and management.

Keywords: Bibliometric review, International network, Brazilian semiarid, Desertification.

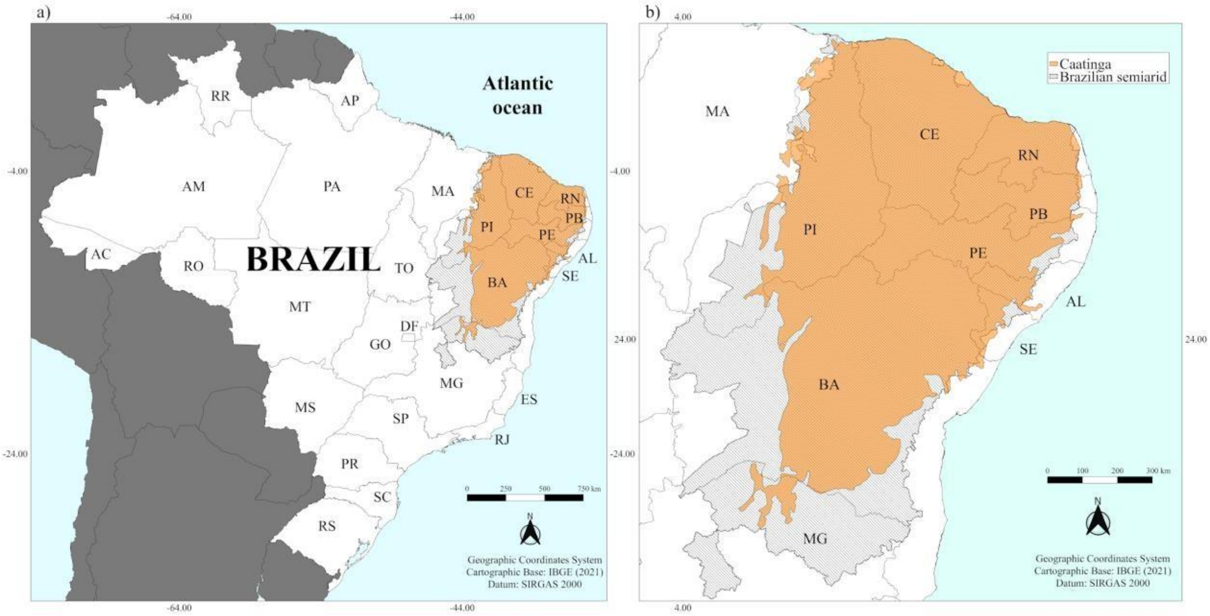
1. INTRODUCTION

Soil Health (SH) can be defined as the soil capacity to function (Andrews et al 2004), within the limits of the ecosystem, to sustain biological (plant and animal) production, maintain or enhance water and air quality and promote human health (DORAN; PARKIN 1994). Soi health is an important element in the search for sustainable agricultural systems since the demand for inputs (agricultural and industrial) tends to increase with the growth of the world population (CHERUBIN et al., 2016). Therefore, the study of SH goes beyond what concerns the increase of agricultural productivity, being essential in the survival of future generations, contributing to the most different ecosystem services, such as water quality, human health, and reduction of impacts caused by climate change (LEHMANN et al., 2020; CHERUBIN et al. 2021).

Historically, drylands are characterized by climatic conditions and anthropic activities that contribute to soil degradation, such as overgrazing and land use changes. Thus, the research seeks to employ technologies in drylands, such as the use of reflectance spectroscopy (LEVI et al., 2020) and imaging spectroscopy in Israel semiarid (LEVI et al., 2022), the study of arbuscular mycorrhizae in Tunisia semiarid (MAHMOUDI et al., 2021), among others. Soil health assessment is based on an integrated approach, including chemical, physical, and biological indicators (CHERUBIN et al., 2016; KARLEN et al., 2019; LISBOA et al., 2019; RUIZ et al., 2020; CHERUBIN et al., 2021), which provide data on SH and fertility (ABDEL-FATTAH et al., 2021) and can be used in dryland monitoring.

In Brazil, the Caatinga biome comprises about 11% of the national territory and is inserted within the northeastern semiarid region (Figure 1) - the most densely populated semiarid region worldwide. This region is susceptible to degradation due to climatic factors (*i.e.*, high temperatures and low rainfall throughout the year (PEREIRA et al., 2021) and accentuated by unsustainable anthropic activities, such as animal overgrazing and excessive vegetation removal for use as firewood (PEREIRA et al., 2022). In the last decades, land use change from natural vegetation to agricultural use has increased in Caatinga biome (BEUCHLE et al., 2015), reinforcing the need for greater monitoring of native areas of the semiarid susceptible to soil health degradation processes. In addition, Caatinga biome is one of most vulnerable regions to global warming and climate changes, intensifying the desertification process and socio-economic constraints as the migration of people from degraded areas to the large Brazilian urban centers. (BRAZIL, 2021; IPCC, 2021).

Figure 1. Representation of Brazilian territory (a) and Caatinga biome (orange) and Brazilian semiarid delimitation (grey) (b). The map was drawn with QGIS (v. 3.16.16).



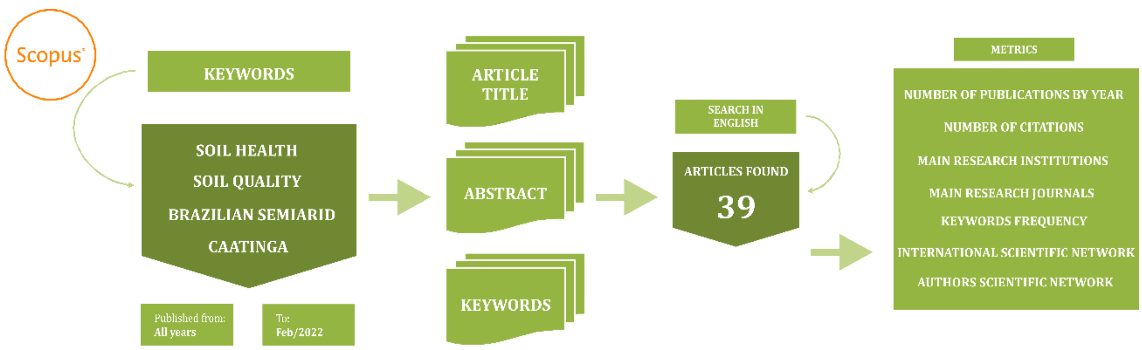
SH is a concept that has gained notoriety over the last 20 – 30 years (LEHMANN et al., 2020; GUO 2021), but studies on SH in the Brazilian drylands are still scarce. Therefore, we believe that the use of bibliometric research techniques to produce an integrated systematic analysis of scientific publications, related to the Caatinga biome and SH, is characterized as an encouraging strategy, and can serve as a starting point for research to be carried out in areas that have been little explored. Globally, Liu et al. (2020) mapped SH research (1999-2018), indicating an evolution of research, expanding from basic studies in agricultural production systems to studies aimed at understanding the soil ecosystem. In contrast, the mapping of soil science research in global drylands conducted by Oliveira Filho and Pereira (2021), indicated soil quality as a research trend in the dry ecosystems of the planet, but with little contribution to the Brazilian semiarid. More detailed surveys on SH research in the Caatinga biome are needed, which will allow us to follow the evolution and map the current and future trends of research in this area of knowledge.

This bibliometric study aims to investigate how SH has been addressed in research on the Caatinga biome. The information generated through the Scopus® database will allow the deepening of studies on SH in the Brazilian drylands, in addition identifying research trends on SH in the Caatinga to be considered in future perspectives.

2 MATERIAL AND METHODS

The bibliographic search was performed using a combination of search terms considering all the databases of the Scopus® platform (https://www.scopus.com/), conducted in February 2022. The search was performed using the "Documents" field, which considers the "Article title", "Abstract" and "Keywords" of a record. The advanced search for papers selection was done through using the following terms/keywords and Boolean operators in the enter query string: ("soil quality" OR "soil health" AND "Brazilian semiarid" OR "caatinga"). There were no limitations in the searches, as only articles and book chapters were identified in the previous analysis, and these represent robust research data. Only publications in English were considered (Figure 2).

Figure 2. Main steps used for screening and evaluation of Soil Health manuscripts in Caatinga biome and Brazilian dryland.



The files were downloaded in .csv and processed in the field “Analyse search results" in the Scopus® platform, being later exported to Microsoft Office Excel (v. 2021) and VOSviewer (v. 1.6.17) software (VAN ECK; WALTMAN, 2010) available at (https://www.vosviewer.com/). The following parameters were analyzed: i) number of publications by year, ii) most cited articles, iii) main institutions, iv) main journals, v) frequency of keywords, vi) international scientific collaboration network among countries, and viii) authors. The search did not limit the number of publications per author, as well as the number of citations. Subsequently, a new screening was performed for the metrics: i) keyword frequency, ii) international scientific collaboration network among countries, and iii) authors, to refine the search for terms with greater strength.

The maps obtained from VOSviewer are based on co-occurrence matrices, this being a three-step process: i) a co-occurrence matrix is used to calculate a similarity matrix, which ii) will be applied VOS mapping technique to construct a map, and finally, iii) this map is translated, rotated, and reflected, thus giving rise to the VOSviewer maps (VAN ECK; WALTMAN, 2010).

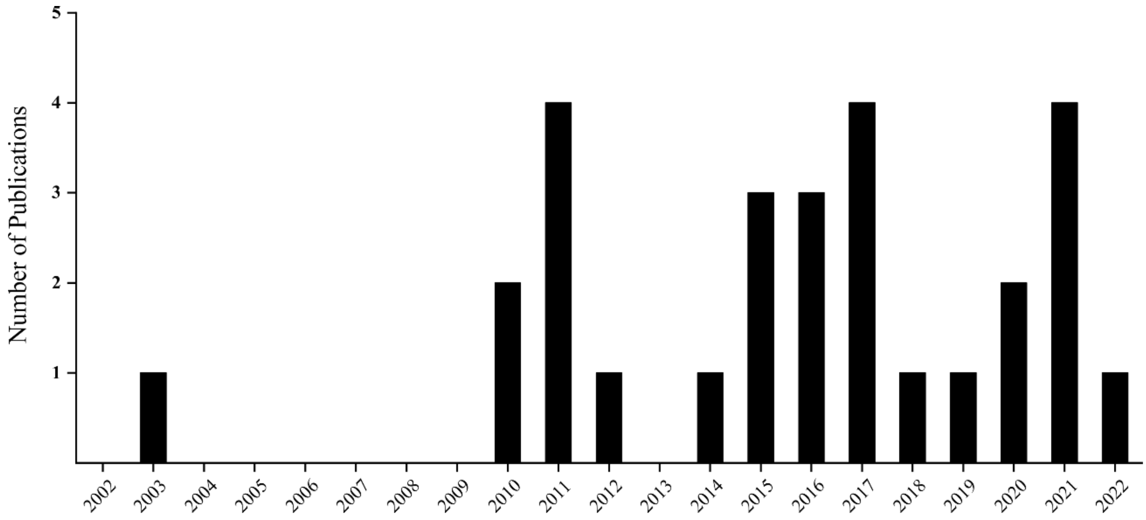
In this study, maps were formed representing the linkage among i) keywords, ii) countries and iii) authors who contribute the most research, showing the existing relationship within each group by forming individual clusters. Each group of clusters represented by the same color shows the strongest network of cooperation between them. In the clustering maps, each word is identified by a rectangle, where the size of the rectangle represents the frequency of the record of that word. Words with more frequency have a larger size than words registered with less frequency. In the case of the map of countries, the group of countries that present coauthored publications have the same color.

The data extracted by VOSviewer allows reflecting on the state of the art of a given subject by generating knowledge maps from co-occurrence and co-citation analyses, allowing, for example, identification of gaps in knowledge as well as critical points in a research area (VAN ECK; WALTMAN, 2010).

3 RESULTS AND DISCUSSION

A total of 39 publications were found during the search, which 37 were published as research papers and 2 as book chapters, representing ~5% of the papers published on SH in Brazil in the last 7 years (SIMON et al., 2022). These numbers are considerably small given the large proportion of area (11%) that the Caatinga biome occupies in the northeastern semiarid region (where ~29 million people live). Until the year 2010, there were only 4 publications in the years 1992, 1997, 2000, and 2003, going through a period of 6 years without publications on the subject (Figure 3).

Figure 3. The number of publications by year in which Soil Health was mentioned in research in the Caatinga biome and Brazilian dryland.



The first paper where the term "soil quality" was used in research in the Caatinga and Northeastern semiarid region was published by Queiroz and Norton (1992). In this, the classification of indigenous soils used in agriculture in the Caatinga was carried out, evaluating morphological characteristics, moisture, and pH for pedogenetic classification. Years later, papers were published evaluating nutrient availability in weathered Oxisol in the Chapada do Araripe (SALCEDO et al., 1997), and SH in areas where native Caatinga was converted into silvopastoral systems (WICK et al., 2000), with emphasis on the evaluation of biological indicators such as organic matter, microbial biomass, and enzyme activity. The low quantity of papers produced on the theme in the region can be attributed, probably, the low interest in this area of knowledge by researchers, who for a long time considered soil only as a supplier of nutrients and water for plant growth (OLIVEIRA FILHO, 2020). With increasing knowledge related to soil ecosystem services in other Brazilian regions (VEZZANI, 2015), the number of studies related to health and soil quality has been intensified in the Brazilian semiarid.

Since 2010, in every year (except 2011), there were publications about SH, and the period between 2012 and 2022 is where we find more than 70% of the published papers. The same growth pattern is seen at the national level, where more than 74% of the published papers are in the period between 2012 and 2022 (SIMON et al. 2022). Although publications of journal articles are recorded almost every year in this period, the number of publications by year is still very low, with 4 being the maximum number of articles published by year.

The paper “Land-use type effects on soil organic carbon and microbial properties in a semi-arid region of Northeast Brazil" published by Ferreira et al. (2016) in the journal Land Degradation and Development, presented the highest number of citations, 76 in total, as well as the highest citation rate per year (11) (Table 1). This paper evaluated the impact of land use changes on soil processes and microbial properties in native Caatinga areas converted to agricultural soils. Land use change is among the most evaluated topics, especially because of the modifications that have occurred in the Caatinga throughout history when agriculture intensified in the region and can cause serious problems to the SH and ecosystems.

The paper "Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: Inferences to improve soil quality", published by Kashuk et al. (2011) – 56 citations – presents SH as a key factor in maintaining the sustainability of agricultural activities and brings as a focus a meta-analysis on soil microbial activity and its important role in the quality of soils in areas where there was land use change.

Table 1. Top 10 articles on Soil Health ranked by the number of citations – Caatinga biome and Brazilian dryland.

Ranking	Article	Journal	1º Author	Citations	Citations/year
1	Land-use type effects on soil organic carbon and microbial properties in a semi-arid region of Northeast Brazil (2016)	Land Degradation and Development	Ferreira *et al*.	71	11
2	Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: Inferences to improve soil quality (2011)	Plant and Soil	Kaschuk *et al.*	55	5
3	Land quality changes following the conversion of the natural vegetation into silvo-pastoral systems in semi-arid NE Brazil (2000)	Plant and Soil	Wick *et al.*	46	2
4	Soil biochemistry and microbial activity in vineyards under conventional and organic management at Northeast Brazil (2011)	Scientia Agricola	Freitas *et al.*	29	2
5	Plant-type dependent changes in arbuscular mycorrhizal communities as soil quality indicator in semi-arid Brazil (2011)	Ecological Indicators	Pagano *et al*.	26	2
6	Nutrient availability in soil samples from shifting cultivation sites in the semi-arid Caatinga of NE Brazil (1997)	Agriculture, Ecosystems and Environment	Salcedo *et al*.	26	1
7	An assessment of an indigenous soil classification used in the caatinga region of Ceara State, Northeast Brazil (1992)	Agricultural Systems	Queiroz *et al.*	24	1
8	Feeding habits, sexual dimorphism and size at maturity of the lizard *Cnemidophorus ocellifer* (Spix, 1825) (Teiidae) in a reforested restinga habitat in northeastern Brazil (2010)	Brazilian Journal of Biology	Santana *et al.*	12	1
9	Estimating potential soil sheet Erosion in a Brazilian semiarid county using USLE, GIS, and remote sensing data (2019)	Environmental Monitoring and Assessment	Falcão *et al.*	10	5
10	Soil fauna as bioindicator of recovery of degraded areas in the caatinga biome (2017)	Revista Caatinga	Lima *et al.*	10	2

The Brazilian Agricultural Research Corporation (EMBRAPA) was the research institution that most contributed with publications (Table 2), being present in 23.1% of the published papers, followed by the Federal Rural University of Pernambuco (15.4%) and the Federal Rural University of the Semi-Arid Region (12.8%). These institutions are in the Brazilian northeast, with direct action in research in the Caatinga. EMBRAPA represents a major center for the development of agricultural technologies for the country, having a long history of contributions to Brazilian society through patents registered by the agency throughout its history. Eight EMBRAPA units are in the Brazilian northeast: Tropical Agro-industry, Cotton, Goats and Sheep, Cocais, Cassava and Fruits, Mid-North, Semi-arid, and Coastal Tablelands.

Table 2. Institutions responsible for the highest number of publications on Soil Health – Caatinga biome and Brazilian dryland.

Ranking	Institution (Country)	Publications	%
1	Brazilian Agricultural Research Corporation (EMBRAPA/ Brazil)	9	23.1
2	Federal Rural University of Pernambuco (UFRPE/Brazil)	6	15.4
3	Federal University of the Semi-Arid Region (UFERSA/Brazil)	5	12.8
4	Federal University of the São Francisco Valley (Univasf/Brazil)	4	10.2
5	University of Saskatchewan (USask/Canada)	3	7.7
6	University of Pernambuco (UPE/Brazil)	3	7.7
7	Federal University of Rio Grande do Norte (UFRN/Brazil)	3	7.7
8	São Paulo State University (Unesp/Brazil)	2	5.1
9	University of Florence (UniFl/Italy)	2	5.1
10	University of Brasilia (UnB/Brazil)	2	5.1

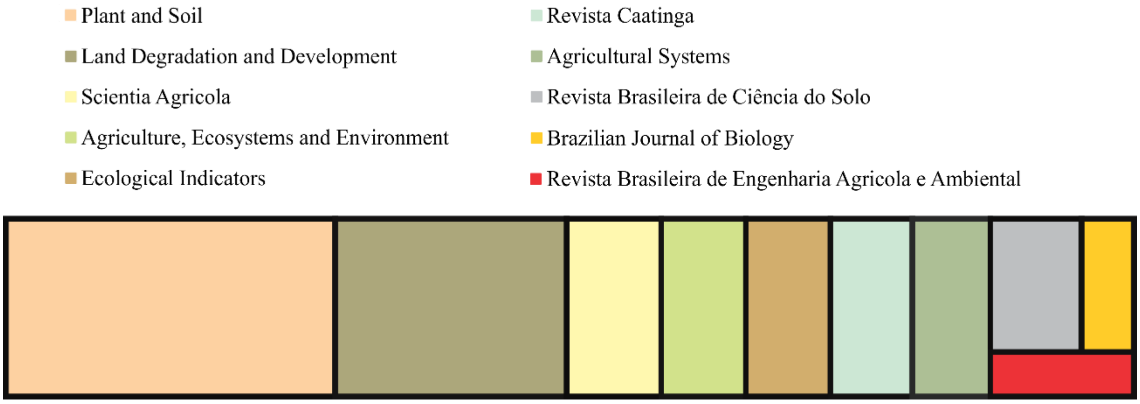
Twenty-five journals and one book were cataloged as responsible for the SH publications. Most of papers are published in regional and national journals, among them, the "Revista Caatinga" (Table 3), was responsible for 17.9% of the publications. Revista Caatinga is a traditional journal of agricultural sciences, edited by the Federal University of the SemiArid Region (UFERSA), which brings publications on research related to engineering, plant and animal production, sustainable development, natural resources, and the environment, is the destination of many works carried out in the Caatinga biome. Revista Caatinga was followed by the "Revista Brasileira de Ciência do Solo", with 10.3% and the Revista Brasileira de Engenharia Agrícola e Ambiental, with 7.7% of the publications. Publications on the Caatinga biome and the Northeastern semiarid region represent ~ 5% of the number of papers released on SH by the Revista Brasileira de Ciência do Solo, which is surprising because it is a journal specialized in research related to the study of soil science, reinforcing the low amount of research in the Brazilian dryland region. Internationally, the journal Plant and Soil was highlighted with 5.1% of the publications.

Table 3. Top 10 journals ranked by the number of publications on Soil Health – Caatinga biome and Brazilian dryland.

Ranking	Journal	Publications	%
1	Revista Caatinga (Brazil)	7	17.9
2	Revista Brasileira de Ciência Do Solo (Brazil)	4	10.3
3	Revista Brasileira de Engenharia Agrícola e Ambiental (Brazil)	3	7.7
4	Handbook On Agroforestry Management Practices and Environmental Impact (USA)	2	5.1
5	Plant and Soil (Netherlands)	2	5.1
6	Agricultural Systems (United Kingdom)	1	2.6
7	Agriculture Ecosystems and Environment (Netherlands)	1	2.6
8	Applied Soil Ecology (Netherlands)	1	2.6
9	Brazilian Journal of Biology (Brazil)	1	2.6
10	Ciencia del Suelo (Argentina)	1	2.6

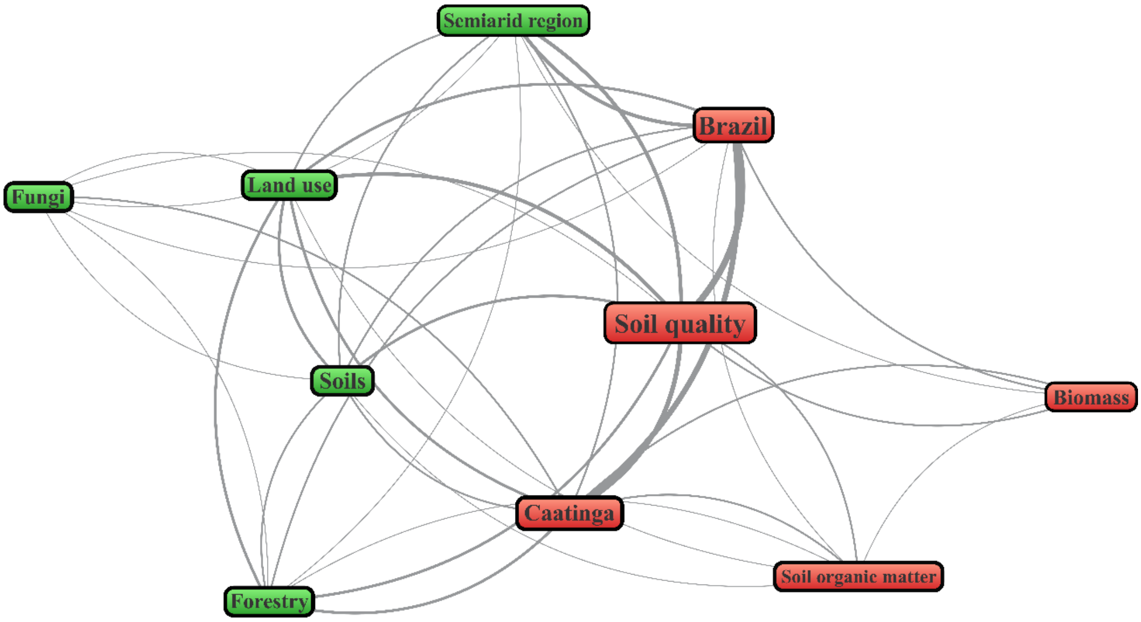
The ranking of journals with the highest number of citations highlights the low potential to reach wider audience of the Brazilian journals and, particularly when published in Portuguese. Of the three journals with the highest number of citations: Plant and Soil, Land Degradation and Development, and Scientia Agricola (Figure 4), only Plant and Soil appears among the best ranked in the number of publications, which shows that journals that publish exclusively in English have greater reach, consequently they will be more cited. International journals with a high impact factor also amplify the range of the published material, this helps to explain why publications on SH in the Caatinga are not cited as much, since most publications are in journals of national, and often even regional.

Figure 4. Top 10 journals ranked by the number of citations of Soil Health in research in the Caatinga biome and Brazilian dryland.



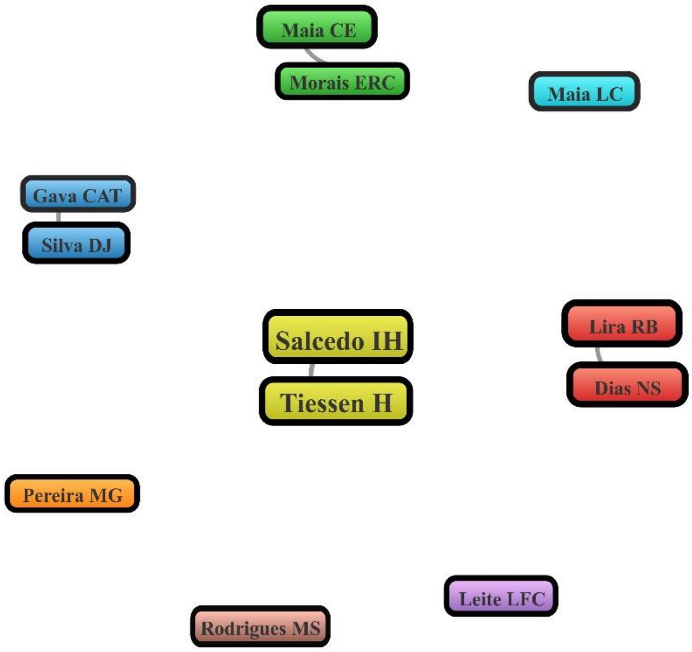
Forty keywords were found in this work, 10 of these being reported with a frequency greater than or equal to three (Figure 5), with emphasis on the 2 main clusters. The low number of keywords reveals the reduced amplitude of research, mainly focused on land use change in soils of the semiarid region, as well as the evaluation of SH indicators in the Caatinga biome (WICK et al., 2000; KASHUK et al., 2011; FERREIRA et al., 2016). An interesting aspect is the research involving soil microbiology, and of the 10 most cited articles, the first 4 have terms like "microbial properties", "microbial biomass", "microbial activity" and "arbuscular mycorrhizal communities" in their titles, which reinforces a trend in the use of bioanalysis in the SH evaluation. In fact, recent review papers have point out the advance in soil (micro)biology is one of research priority for the near future in SH topic (e.g., BUNEMANN et al., 2018; KARLEN et al., 2019) Despite that, there was a low frequency of the use of enzymatic analyses such as phosphatases, arylsulfatase, urease, and β-glucosidase. However, there is a growing trend to increase the evaluation of SH through enzymatic analysis, especially with the launch of "BioAS - Soil Bioanalysis Technology", created by EMBRAPA (2020), where the biological component (arylsulfatase and β-glucosidase enzymes) is added to chemical indicators in the evaluation of SH (MENDES et al., 2021).

Figure 5. Bibliometric map of the frequency of keywords used in research on Soil Health in the Caatinga biome and Brazilian dryland.



Twelve authors were cataloged (Figure 6) and the researchers who contributed the most research were H. Tiessen, from the University of Saskatchewan, Canada, and I.H. Salcedo, from the National Institute of the Semiarid (INSA), Brazil. The high number of clusters for only 12 results represents weak interaction in the co-authorship of the papers, limiting papers to research groups within the same institution. The low interaction among authors and, consequently, among research groups represents a serious problem, as it results in less scientific production and integrated studies between national and international bodies, making the drylands of the Caatinga biome unknown even to renowned researchers on the subject worldwide. Since more than 26 million people live in the semiarid region of the Northeast, where the Caatinga biome is located, and make use of the Caatinga's natural resources (ANTONGIOVANNI et al., 2022), the low quantity of research reinforces the need for monitoring the SH of the Caatinga biome, especially in degraded areas.

Figure 6. Bibliometric map of authors scientific network on Soil Health in Caatinga biome and Brazilian dryland.



SH assesses the functioning of soil and its interaction with animals and humans, as well as providing them with the means and inputs to maintain life on Earth (CHERUBIN et al. 2016). However, there is a lack of studies that address the relationship of soil with human and animal health, in addition studies that associates soil health with climate change, as recently reported by LEHMANN et al. (2020) and tested by QIAO et al. (2022).. Another little explored field that may represent an enormous potential for conducting research is metagenomic studies (ARAUJO et al., 2022) since the Caatinga biome still presents little known data about the structure and function of the microorganisms that inhabit it. The use of bioanalysis in the evaluation of SH may also represent a great advance in the understanding of soil enzyme activity, such as arylsulfatase and β-glucosidase. The latter plays a key role in the evaluation of soil carbon cycling and can be crucial for decision-making for the implementation of techniques that increase carbon sequestration and its maintenance for a longer period in the soil. However, there are still no reference values for enzyme activity in Caatinga soils, even with the recent implementation of EMBRAPA's BioAs in other areas of Brazil. The change in the understanding of the integration between soil chemistry, physics, and biology plays a key role in the advancement of studies on SH, looking mainly at the interaction of processes and indicators with the role ecosystem.

Tools that evaluate SH may represent an important means for farmers, researchers, and policymakers to monitor the Caatinga biome, providing for the maintenance of environmental quality, recovery of degraded areas, planning of land use changes, and improvement of the quality of animal and human life.

Although all the documents found contain the terms used in the search, not all present SH as the main theme of the research, often mentioning SH through the isolated study of soil attributes. The need for comprehensive studies on the evaluation of SH in drylands of the Caatinga biome should be further promoted, by integrating chemical, physical, and biological indicators into an overall SH index. National and international partnerships should be pursued for establishing research networking focused on assessing and monitoring the Caatinga biome, especially in areas more vulnerable to degradation by agriculture and livestock activities, and climate changes.

4 CONCLUSIONS

Our study revealed that soil health research in the Caatinga biome is still incipient and fragmented. Soil health is “new” thematic, and therefore, a more robust research network needs to be developed to connect local research groups with other national and international partners. The scientific production is restricted to the study of soil attributes or processes. The number of papers published on SH in the Caatinga remains ≤ 4 articles/year, representing ~5% of the research on SH in Brazil, a very low number when compared to the richness in terms of fauna and flora that the Caatinga biome presents and size of the territory, and the population that lives in and depends on this biome.

This bibliometric review also showed that important SH research topics are still unexplored, such as integrated SH approach and adapted tool to assess and monitor degraded and under restoration areas. The increase in climate change and growing soil degradation through anthropic activities tends to accentuate the reduction of the typical vegetation cover of the biome. These factors contribute to the increase of social differences in the world's most populous dryland, such as the reduction of human development indexes and the increase in rural exodus. Studies on SH in the Caatinga will allow the evaluation and monitoring of areas at risk of degradation and accelerated desertification process, fostering public policies for the mitigation of damage caused by climate change and anthropic activities. National and international partnerships through more SH integrated studies are essential for the consolidation of the Caatinga as an important research area, as well as for monitoring one of the drylands most susceptible to degradation in the world.

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5 SOIL HEALTH ASSESSMENT IN BRAZILIAN DESERTIFICATION HOTSPOT (CAATINGA BIOME)

ABSTRACT

The Caatinga is an exclusively Brazilian biome and the most densely populated semiarid region worldwide, where ~28 million people live. Factors such as climate changes and human activities (e.g., overgrazing), accelerated soil degradation, promoting Caatinga soils highly susceptible to desertification. However, the soil health (SH) assessment in Caatinga biome remain poorly understood and this is the first tentative to quantity SH indexes in a long-term field experiment. Thus, we aimed to use the SMAF (Soil Management Assessment Framework) platform to assess the impact of management practices on the health of Caatinga soils inserted in the Irauçuba Desertification Nucleus, Ceará State (Brazil). The study evaluated three sites with three land use and management scenarios each: i) Native Caatinga vegetation (NV), ii) in advanced desertification process by overgrazing (DE) and iii) Restored (RE – grazing-exclusion for 21 years). Soil samples (0-10 cm) were collected in February/2020 (S1) and October/2021 (S2), totaling 54 samples (i.e., 3 sites x 3 managements x 3 blocks x 2 sampling periods). Chemical (pH, sodium adsorption ratio, K^+, and P), physical (bulk density), and biological (soil organic carbon, microbial biomass carbon, and β-glucosidase activity) indicators were analyzed. Overgrazing significantly reduces SH in the Caatinga biome, reaching SHI values of DE (SMAF-scores = 0.44 in S1 and 0.47 in S2). However, grazing-exclusion management proved to be an efficient strategy for SH recovery, increasing SHI values to RE (SMAF-scores = 0.65 in S1 and 0.79 in S2), similar to that verified in NV (SMAF-scores = 0.72 in S1 and 0.82 in S2). Bulk density and sodium adsorption ratio are the indicators that most negatively correlated with SH in DE, while soil organic carbon, microbial biomass carbon and β-glucosidase activity were the biological indicators that most contributed to increased SH in RE. Thus, we provide novel evidence that SMAF can be a user-friendly tool to monitor changes in SH under soil desertification and sustainable practices in Caatinga biome. Finally, our results highlighted the importance of grazing-exclusion technique to improve SH at similar levels those find in native Caatinga vegetation.

Keywords: SMAF, Drylands, Desertification, Brazilian semiarid, Grazing-exclusion.

1. INTRODUCTION

Drylands represent ~41% of Earth's surface, where10-20% are degraded, affecting life quality of more than ~250 million people (HUANG et al., 2020). The Caatinga is an exclusively Brazilian biome and the most populated dryland region worldwide (~29 million people) (DA SILVA et al., 2017). Brazilian drylands have the lowest human development indices in South American, where local communities live in extreme poverty and depend on Caatinga's natural resources for food, fiber, and energy (ANTONGIOVANNI et al., 2022). The Caatinga degradation has caused the loss of 45% of the biome's native vegetation (BRASIL, 2005), which tends to be intensified with climate changes (IPCC, 2021). Present in 10.1% of the national territory and with an estimated area of 844,000 km^2, the Caatinga is characterized by low average annual precipitation, mainly concentrated in a short period (Jan-May) (BRASIL, 2021; PEREIRA et al, 2022). The climatic instability and, consequently, soil degradation, make the Caatinga biome highly vulnerable to the impacts of desertification (MARENGO et al., 2022).

In Caatinga, the areas susceptible to desertification correspond to ~ 70,500 km^2. Thus, natural resources are scarce, which negatively reflect on the human being health and environmental sustainability (BRASIL, 2021). Sustainable land management (e.g., restoration, rehabilitation practices, and others) are needed to adapt to and mitigate the effects of climate change and reduce/reverse the consequences caused by desertification (IPCC, 2021). In the Caatinga, the adoption of conservationist practices can promote soil recovery of desertified-affected areas (PEREIRA et al., 2021; AMORIM et al., 2020), mainly it's functioning and nutrient contents (ARAUJO et al., 2022). Grazing-exclusion has been successfully adopted worldwide, with studies conducted in China (LI et al., 2022), Tunisia (MSADEK et al., 2022), Scotland (WARNER et al., 2021), Canada (HAMILTON, et al., 2022), Europe (KAUFMANN et al., 2021), among others. This practice has achieved positive results in restoring soil fertility (OLIVEIRA FILHO, 2019) and regulating the richness and diversity of microorganisms (PEREIRA et al., 2021) in drylands undergoing desertification in Brazil. However, the effects of grazing-exclusion on soil health (SH) remain poorly understood, mainly in tropical soil affected by desertification. Since soil desertification is a worldwide problem, knowing the effects of grazing-exclusion in recovery of soil functioning may fill an important scientific gap, which can contribute to the monitoring of soil degradation in dryland systems.

SH can be defined as the capacity of the soil to function to sustain animal productivity and maintain/improve the human quality of life (DORAN; PARKIN, 1994). The SH assessment occurs through the analysis of chemical, physical and biological indicators (ANDREWS; KARLEN; CAMBARDELLA, 2004; KARLEN et al, 2008; CHERUBIN et al, 2016a), which are directly linked to important ecological functions in the soil (CHERUBIN et al, 2021). Thus, SH can be used as an important tool in monitoring the recovery of degraded areas worldwide, one of the main objectives of the United Nations (UN) Decade of Ecosystem Restoration (2021 – 2030); and in Brazil through the National Plan for the Recovery of Native Vegetation (Planaveg) which has as its main objective the recovery of native vegetation of at least 12 million hectares by 2030 (Law no. 12.651, May 25, 2012).

However, few studies have used user-friendly tools to assess SH of Caatinga by integrating chemical, physical, and biological factors (SIMON et al., 2022). The Soil Management Assessment Framework – SMAF (ANDREWS; KARLEN; CAMBARDELLA, 2004) is a tool used to assess SH under different management/uses, as well as the capacity to support basic functions. Developed and widely used in the United States, SMAF was adapted for Brazilian soils in different production systems (pasture, sugarcane, agroforestry, mangrove) and biomes (Cerrado, Amazon, Atlantic Forest). However, this is the first study of SH using SMAF to evaluate long-term grazing-exclusion in drylands (Caatinga bioma). (CHERUBIN et al., 2016a; LUZ et al., 2019; CHERUBIN et al., 2021; CHAVARRO-BERMEO et al., 2022; JIMENEZ et al., 2022; MATOS et al., 2022). Thus, this is the first tentative to quantity SH indexes in a long-term grazing exclusion experiment, set up in 2000.

We hypothesized that i) the SMAF allows the evaluation of chemical, physical, and biological health indicators in soils from degraded Caatinga biome areas, and ii) the adoption of the grazing-exclusion technique restores SH in areas desertified by overgrazing. Here, this study aimed to characterize a highly degraded Caatinga biome soil (chemical, physical, and biologically), and apply SMAF to evaluate the impact of management practices (i.e., overgrazing, and grazing exclusion) on SH in a 21-years field experiment.

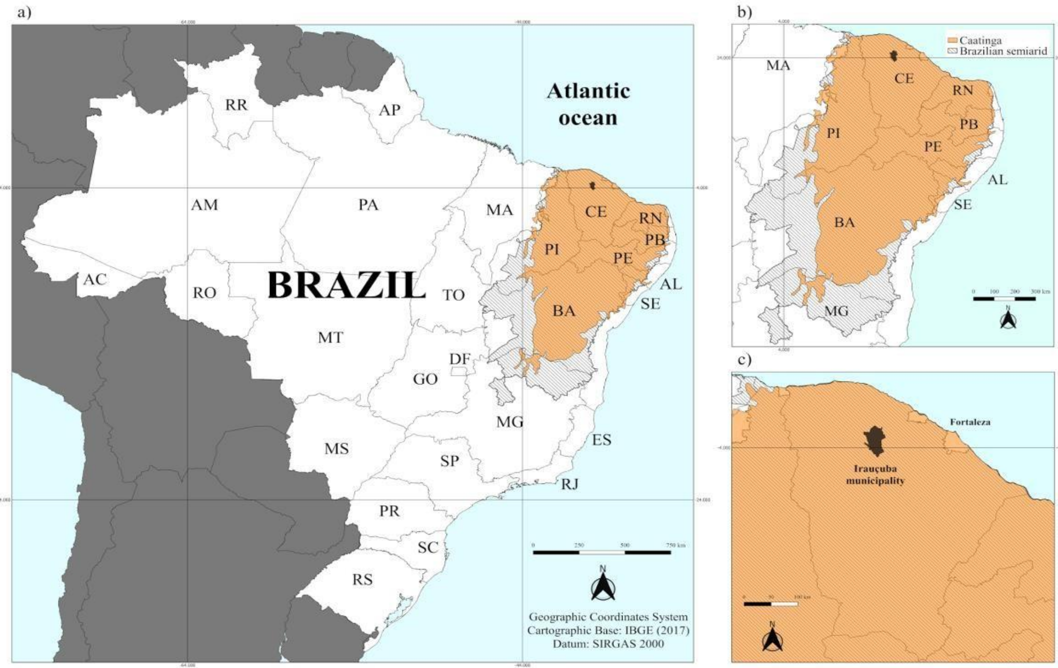
2. MATERIAL AND METHODS

2.1 Site description and soil sampling

The study was established in the Irauçuba municipality (Figure 1), Ceará State, Brazil (3°44′46 "S and 39°47'00 "W), in experimental research areas in the Irauçuba

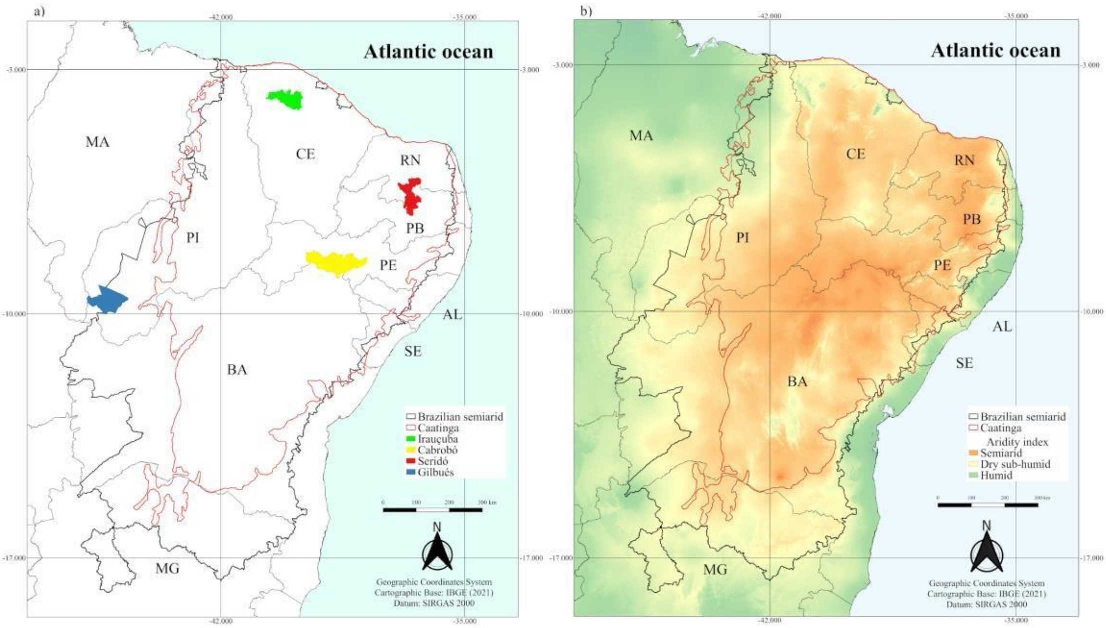
Desertification Nucleus (IDN). The Irauçuba municipality presents annual precipitation of 540 mm, mainly concentrated between January - April (PEREIRA et al., 2021). The climate is classified as tropical hot semiarid, with average temperatures ranging from 26 to 28°C and 152 m above sea level (IPECE, 2017). The main soils of the region belong to the orders Haplic Planosol and Natric Planosol (OLIVEIRA FILHO et al., 2019).

Figure 1. Geographic location of Irauçuba Municipality, Ceará State, Brazil. a) Map of Brazilian territory, b) Caatinga biome and Brazilian semiarid, c) Irauçuba municipality. The map was drawn with QGIS (v. 3.16.16).



The IDN, one of the 4 desertification nuclei in Brazil (Figure 2a), is characterized by intense livestock activity over the past 150 years, which promoted the uncontrolled removal of soil cover, not allowing the renewal of native vegetation. In addition, the high soil compaction caused by animal grazing and natural environmental conditions (e.g., high temperatures and water shortage) contributed to soil degradation (OLIVEIRA FILHO et al., 2019). The aridity index (AI) is defined as the ratio of annual precipitation to annual potential evapotranspiration. Drylands can be classified into hyper-arid ($AI < 0.05$), arid ($0.05 \leq AI < 0.2$), semiarid ($0.2 \leq AI < 0.5$), and dry sub-humid ($0.5 \leq AI < 0.65$) (HUANG et al., 2016). Irauçuba municipality presents an aridity index of 0.26 – one of the lowest in the Brazilian semiarid region (Figure 2b).

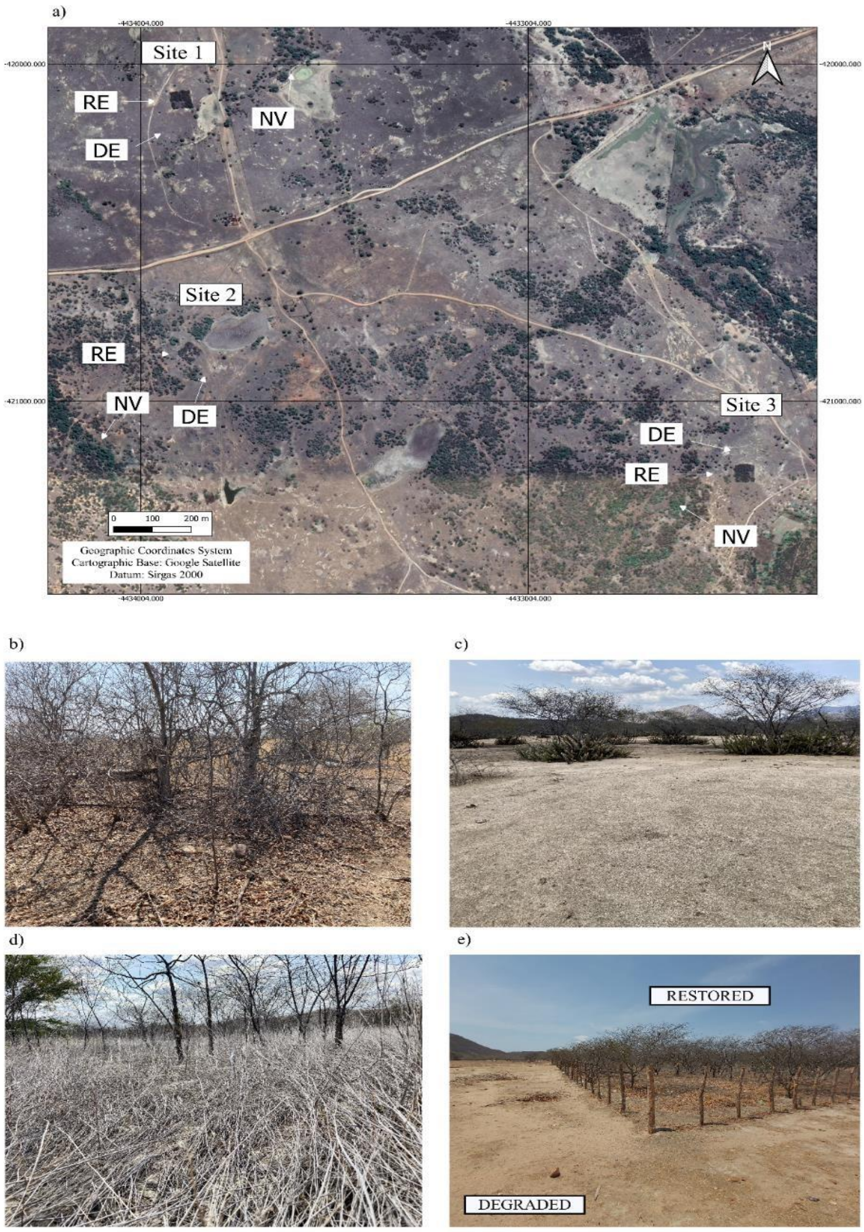
Figure 2. The geographic location of Brazilian Desertification Nuclei. a) Desertification Nuclei of Irauçuba (green), Gilbués (blue), Cabrobó (yellow), and Seridó (red), b) Aridity index of Brazilians drylands. The map was drawn with QGIS (v. 3.16.16).



In 2000, an experimental project was established to study the desertification effects in the IDN. Areas in an advanced desertification process due to overgrazing were mapped, fenced (to prevent animals access) and kept under fallow to study the effects of grazing-exclusion in experimental units with dimensions of 50 m x 50 m (2500 m^2). In these areas, the grazing-exclusion was used to stimulate the natural restoration of soil in IDN. Thus, since the installation of the experimental area, studies have been conducted in restored (isolated from animal entry for 21 years), degraded (receives a high animal stocking rate, especially during the rainy season), and native Caatinga areas in the IDN.

This study was conducted at three sites (site 1, site 2, and site 3) with three land use and management scenarios each: Caatinga's native vegetation (NV), advanced degradation stage (DE) with the plant species: *Aristida adscencionis* and *Urochloa plantaginea*, and grazing-exclusion (RE) with the plant species: *Mimosa tenuiflora*, *Caesalpinia bracteosa, Croton sonderianus, Urochloa plantaginea* and *Anthephora hermaphrodita*, (OLIVEIRA FILHO et al., 2019) (Figure 3). The Caatinga biome has deciduous vegetation, i.e., litter deposits (including leaves, bark, branches, and miscellaneous) are intensified in the dry season. In RE areas, the dimensions of 40 m x 40 m (1600 m^2) were used to avoid the border effects. Two soil samplings were conducted in February/2020 (S1), and in October/2021 (S2), where samples were collected at a depth of 0 – 10 cm. Thus, sampling resulted in 3 sites x 3 soil managements x 3 blocks and 2 seasons, totaling 54 soil samples. A sequential water balance was performed for the sampling period (01/11/2019 – 01/01/2022) to help understand the status of soil water content at the period of each soil sampling. (Supplementary Figure 1).

Figure 3. 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.



The deformed composite samples were sieved (2 mm) and stored at 4 ºC for biological analyses. Another portion was dried until obtaining the air-dried fine soil for chemical analyses. The undisturbed samples were stored for physical analyses.

2.2 Soil characterization

Briefly, soil pH was determined in $CaCl_2$ solution (0.01 mol L^{-1}), available phosphorus (P) and potassium (K^+) were extracted by ion exchange resin and sodium (Na^+) was extracted by Mehlich 1 solution (RAIJ et al., 2001). Bulk density (BD) was determined by the Beaker method (TEIXEIRA et al., 2017) in S1, and by the paraffin-embedded clod method (BLAKE; HARTGE, 1986; TEIXEIRA et al., 2017) in S2. Soil organic carbon (SOC) was extracted using potassium dichromate ($K_2Cr_2O_7$) and determined by colorimetry (NELSON; SOMMERS, 1996). Microbial biomass carbon (MBC) was quantified by the fumigation-extraction method (VANCE et al. 1987; POLLI; GUERRA, 1997). The activity of the enzyme β-glucosidase (BG) (EC 3.2.1.21) was determined using ρ-nitrophenyl βglucopyranoside as substrate under incubation (1 h, 37°C) in a modified buffer (pH 6.0). The ρ-nitrophenol was determined by spectrophotometry (410 nm) (TABATABAI, 1994).

2.3 Soil Management Assessment Framework tool

The Soil Management Assessment Framework (SMAF) is a tool used to assess the SH – soil functioning by integrating chemical, physical, and biological indicators into a single SH index and is based on three steps: i) selection of indicators, ii) interpretation of indicators, and iii) the integration of the indicators used in a soil health index (SHI) (ANDREWS; KARLEN; CAMBARDELLA, 2004). The current version of SMAF has available algorithms for 13 indicators, which are: (i) chemical: pH, electrical conductivity, sodium adsorption ratio (SAR), P and K^+; (ii) physical: BD, macroaggregate stability, available water capacity and pore space, and (iii) biological: SOC, MBC, potentially mineralizable nitrogen and BG activity (ANDREWS; KARLEN; CAMBARDELLA, 2004; WIENHOLD et al., 2009; STOTT et al., 2010). In addition, SMAF uses information on soil classification, crop productivity, nutrient cycling, environmental protection (KARLEN et al., 2013), average temperature, average annual precipitation, texture, mineralogy, and slope, among others (NUNES et al., 2020). The SHI is subdivided into chemical, physical and biological attributes, as well as their correlations, allowing the identification of the most important attributes and those that need more attention in SH management (CHERUBIN; TORMENA; KARLEN, 2017; LISBOA et al., 2019).

Here, eight soil health indicators were used: pH, SAR, P, K^+ (chemical indicators), BD (physical indicator), SOC, MBC, and BG (biological indicators). The parameters used are considered key to soil functioning (CHERUBIN et al., 2016a) and encompass at least one indicator from each chemical, physical, and biological component (KARLEN et al., 2008; CHERUBIN; TORMENA; KARLEN, 2017). These indicators also are among the most frequently used in SH health studies in Brazil (SIMON et al., 2022) and worldwide (BUNNEMAN et al., 2018).

Each SH indicator values were transformed into a value from 0 to 1 using non-linear scoring curves, that were based on site-specific algorithms. The factor for organic matter class (used to score SOC, MBC, and BG) was 4 (low organic matter content). The texture factor class (used to score BD, SOC, MBC, and BG) was 1 for treatments with clay content < 8%, and 2 for treatments with clay content > 8%. The climate factor (used to score SOC, MBC, and BG) was 2 (≥170°C and ≤550 mm average annual precipitation) for all treatments. The season factor (used to score MBC) was 2 (summer) for all treatments. Fe oxide content was 2 for all treatments. The mineralogy factor class (used for BD scoring) was 3 (other), and the slope and weathering class factors, used for P scoring, were 2 (2 – 5% slope) and 3 (little weathering), respectively, for all treatments. The method used to measure extractable P was resin (class 5). Phosphorus and pH thresholds were established according to the "Recomendações de Adubação e Calagem para o Estado do Ceará" (FERNANDES, 1993), whose optimum values for P and pH were 10 mg dm^{-3} and 5.5, respectively. The indicator scores were integrated into an overall SH index (SHI) using a weighted additive approach. The indicators were weighted based on chemical (pH, SAR, P and K^+), physical (BD) and biological (SOC. MBC and BG) components, with each group having an equal weight (33.33 %) in the final index (CHERUBIN et al., 2016a)

2.4 Statistical analyses

Homogeneity and normality of variance were examined by Levene and ShapiroWilks tests, respectively. The data were processed by a pooled analysis (Nested-ANOVA) and the significance of the means was tested by Tukey's test at 5% ($p < 0.05$). The analyses were performed in RStudio® software (Version 1.3.1093). Multivariate analysis was performed using the statistical computing package Canoco for Windows v. 4.5 (BRAAK; ŠMILAUER, 2002).

3. RESULTS

3.2 Impact of land-use change on soil health indicators

3.2.1 Chemical indicators

NV presented the highest soil pH values, independently of the sampling period (S1 and S2), while DE presented the lowest values. However, there was a significant reduction in the soil pH in RE from S1 to S2 ($p > 0.05$). The SAR presented the highest values in DE, while the RE and NV presented the lowest SAR values, independently of sampling period. Available P content was significantly higher in NV and lower in DE, especially in S1. However, P content of NV showed a significant decrease in S2 (67.82%). Interestingly, P values increased significantly in S2, mainly in DE and RE areas (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).

	Chemical				Physical		Biological
Land use	**[1]pH**	**[2]SAR**	**[3]P**	**[4]K**	**[5]BD**	**[6]SOC**	**[7]MBC**	**[8]BG**
			mg dm^{-3}	mmol dm^{-3}	g cm^{-3}	g dm^{-3}	mg kg^{-1}	mg p-nitrophenol kg^{-1} solo^{-1}
				S1				
NV	5.59^{a}	0.20^{b}	37.61^{a*}	106.26^{a}	1.51^{b*}	13.41^{a}	77.71^{b}	114.11^{a}
DE	5.02^{b}	0.89^{a}	7.73^{b}	115.12^{b}	1.62^{a}	6.69^{b}	48.08^{c}	37.12^{b}
RE	5.48^{a*}	0.39^{b}	13.41^{b}	69.86^{a}	1.52^{b}	16.17^{a}	92.63^{a}	102.72^{a}
				S2				
NV	6.08^{a}	0.17^{b}	12.10^{b}	114.23^{a}	1.41^{b}	21.02^{a*}	130.36^{b*}	175.62^{a}
DE	5.14^{b}	0.63^{a}	10.06^{b*}	84.69^{b}	1.85^{a*}	8.61^{b}	84.01^{b*}	83.09^{b*}
RE	5.04^{b}	0.31^{b}	19.21^{a*}	132.75^{a*}	1.41^{b}	26.77^{a*}	285.21^{a*}	197.43^{a*}

[1]Hydrogenionic potential, [2]Sodium Adsorption Ratio, 3Avaliable Phosphorus, [4]Potassium, [5]Bulk density, [6]Soil Organic Carbon, [7]Microbial Biomass Carbon, and [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%), *n* = 9.

SMAF scores for pH showed no differences between management in S1, while S2 presented higher values in NV (0.91) and RE (0.89). SAR presented low scores regardless of management and sampling. Also, RE showed the highest scores for P, while DE showed the lowest scores for K^+, in both periods (Table 2).

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

	Chemical				Physical	Biological		
Land use	**[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, 3Avaliable Phosphorus, [4]Potassium, [5]Bulk density, [6]Soil Organic Carbon, [7]Microbial Biomass Carbon, and [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%), $n = 9$.

3.2.2 Physical indicators

DE presented the highest values of BD (1.62 g cm^{-3} in S1 and 1.85 g cm^{-3} in S2), while NV and RE showed lowest values, regardless of the period (Table 1). Thus, BD presented the higher scores in NV (0.75 in S1, and 0.89 in S2), but with an increase in S2 (Table 2). Interestingly, BD score decreased in the DE in S2 (~ 60 % reduction).

3.2.3 Biological indicators

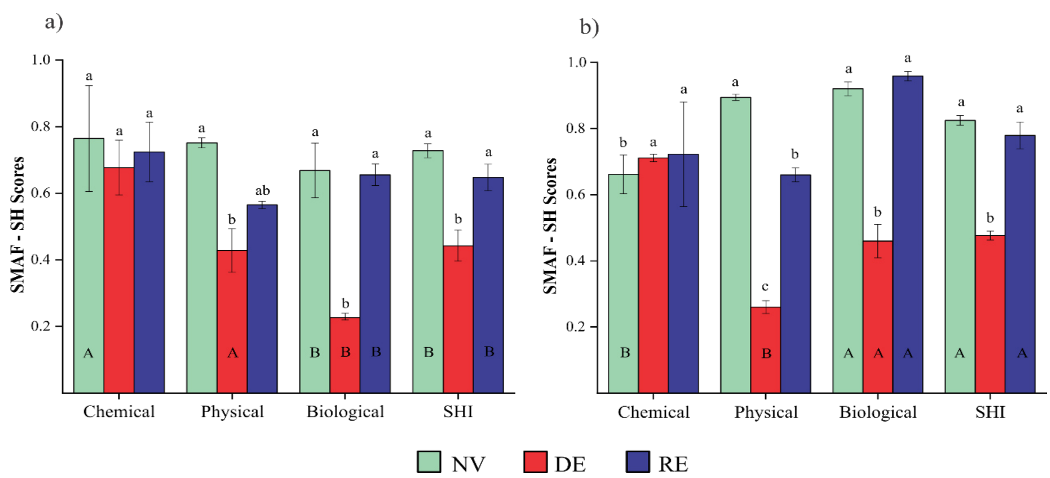
NV and RE presented the highest SOC contents in both sampling periods, but with a significant increase in S2. However, DE showed the lowest values in both S1 and S2 (6.69 g dm^{-3} in S1 and 8.61 g dm^{-3} in S2). MBC contents were higher in S2 in all management but RE showed the highest content (285.21 mg kg^{-1}). On the other hand, MBC contents in DE were lower in both periods (6.69 mg kg^{-1} in S1 and 8.61 mg kg^{-1} in S2). The potential activity of the β-glucosidase was higher in RE and NV than DE in both S1 and S2 (Table 1).

SOC showed high SMAF scores in NV and RE, regardless of the period, but DE showed lower results (0.42 in S1 and 0.62 in S2). The scores of MBC and BG showed similar behavior between the treatments in both periods. However, DE showed the lowest scores in both periods (Table 2).

3.3 Soil health index and seasonal effects

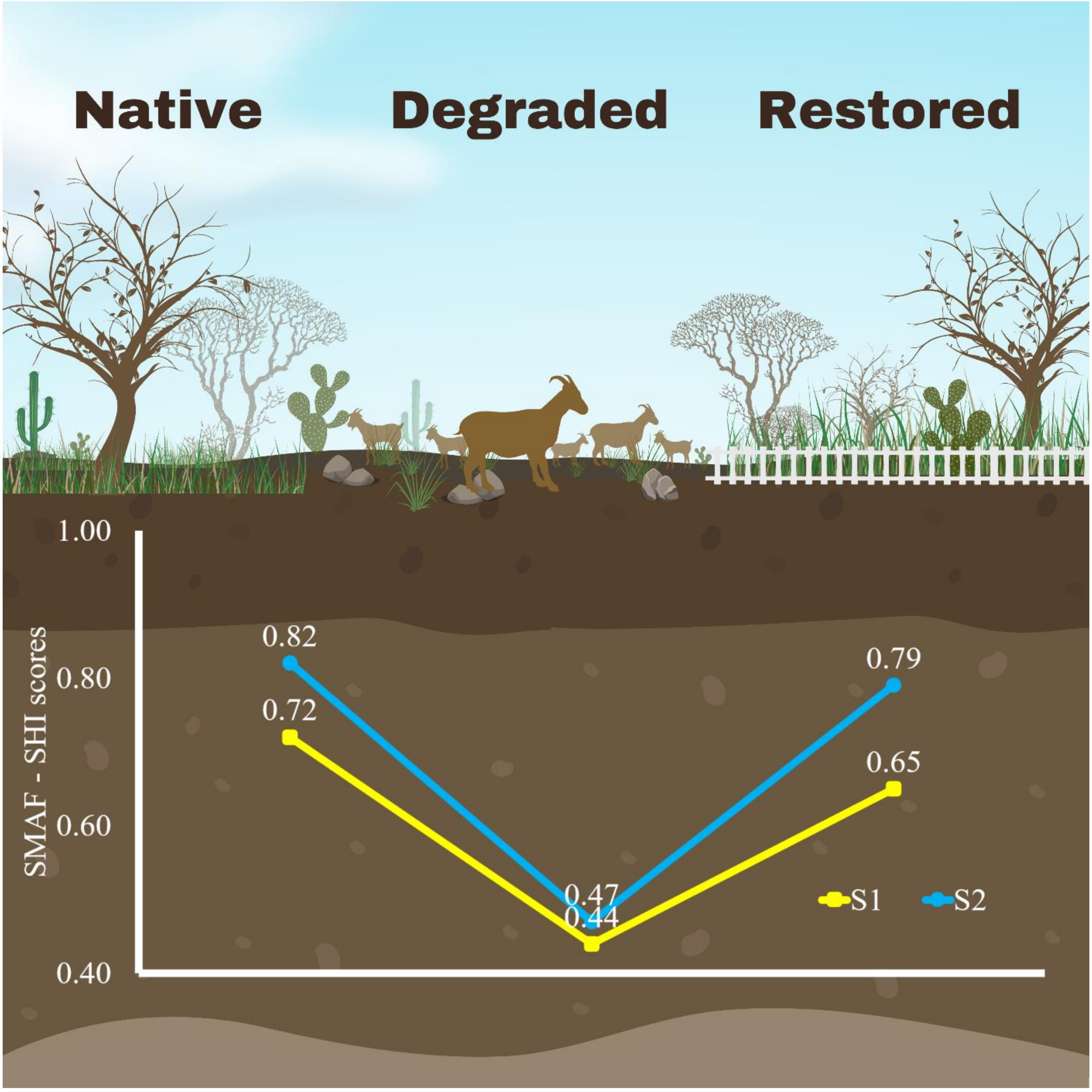
SHI was higher in NV (0.73 in S1 and 0.82 in S2) and RE (0.65 in S1 and 0.79 in S2), independently of sampling period. However, the SHI was lower in DE (0.44 in S1 and 0.47 in S2) (Figure 4). To analyze the overall SHI score in each period, the seasonal effect on the Chemical, Physical and Biological components were evaluated, as well as the response of each of these in the SHI composition (Supplementary Figure 3). The SHI of S2 (0.69) was higher than that of S1 (0.60). There was no seasonal influence among the Chemical and Physical components, unlike what was observed in the biological component, which showed a positive seasonal effect in S2.

Figure 4. 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%. 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.



Soil Chemical score reduced in S2, mainly in NV (from 0.76 to 0.66) (Figure 4). The Physical component showed a reduction in S2 in the DE (from 0.42 to 0.26), while the biological component showed improvement in all evaluated managements in S2. The SHI showed an overall increase in scores in NV and RE in S1 and S2, while there was no significant variation in DE (Figure 5).

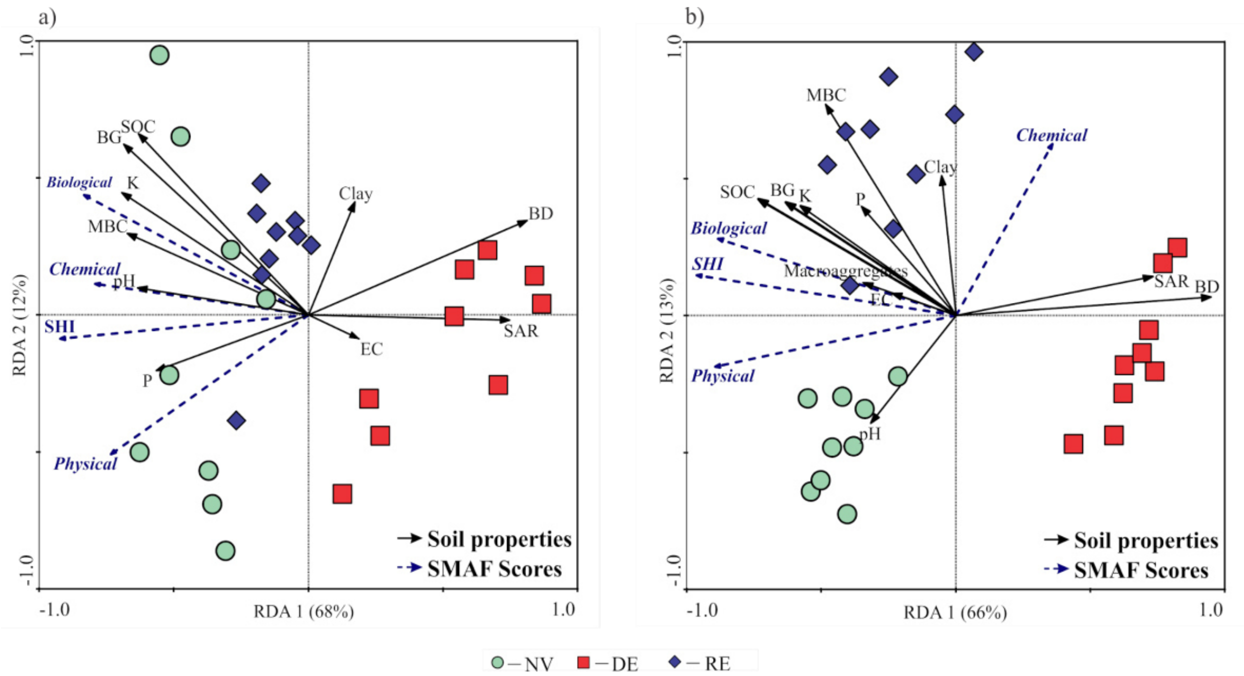
Figure 5. SMAF - SHI in Caatinga's native (NV), degraded (DE), and restored (RE) vegetation in Brazilian desertification hotspot. (S1) sampling 1 and (S2) sampling 2.



3.4 Redundancy analysis

Redundancy analysis (RDA) was performed to correlate SH indicators with the SMAF scores (Chemical, Physical, Biological, and the SHI). Briefly, axis 1 and 2 explained 80% of data variance in S1. RDA showed a higher positive correlation of MBC, BG, and SOC with the Biological component of SH, as well as its interaction with NV and RE. RDA showed that BD and SAR were negatively correlated with Physical component and SHI, being an important drive to cluster DE area in a separated group (Figure 6a).

Figure 6. 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.



Axis 1 and 2 explained 79% of data variance in S2. RDA showed a positive correlation between MBC, P, K^+, BG, and SOC, mainly in RE. pH shows a close relationship with NV. BD and SAR showed a strong relationship with DE and contrary to the Physical component of SH and SHI. (Figure 6b). There was a clear separation of areas with NV and DE at the extremes, and RE between the two, but closer to NV.

4. DISCUSSION

Soil health assessment is a key component for monitoring the effects of desertification in dryland ecosystems. Here, we attempt, for the first time, to analyze soil chemical, physical and biological scores of Brazilian drylands through SMAF – Soil Management Assessment Framework and understand how soil desertification and long-term restoration practices (e.g., grazing-exclusion) can change SH scores in tropical conditions.

The rainfall distribution influences the vegetation dynamics, since it is directly related to soil water storage and, consequently, with the vegetation development. In Caatinga, the response of vegetation to rainfall varies from 1 – 3 months (BARBOSA et al., 2019), indicating that in the S1 there were no positive effects of vegetation on soil attributes. This helps partially explain the lower SH indices in S1, even with results showing better results than in S2, where higher indices were observed.

"Recovery" effect in S1 highlights the difficulty that vegetation has to recover from long periods of drought (CUNHA et al., 2015) since the dry season can extend for 8 – 9 months in Caatinga. Thus, it partially explains the fact that Biological component of SH presented lower scores in S1 when compared to S2. It is believed that the first rains that preceded S1 were not enough to bring improvement in SHI, precisely because of the difficulty of vegetation recovery, directly influencing the biological component of SH, with low scores of BG and MBC. S1, carried out in 2020, succeeded in the most severe drought period (2012 – 2018) of the last 50 years (MARENGO et al., 2022), reinforcing the results found in this research. Prolonged periods of drought reduce resilience, making vegetation more susceptible to recurrent disturbances (CUNHA et al., 2015), which are attenuated by anthropogenic activities, characteristic of the IDN, even if there is greater biomass production during the rainy season (ANDRADE et al., 2021).

Grazing-exclusion in degraded drylands in the IDN brought positive changes in SH indicators. In both periods (S1 and S2), RE showed SHI higher than DE and similar to NV, indicating that the restoration of degraded drylands in the Caatinga biome raises the SHI to values similar to the native Caatinga vegetation. These changes were largely driven by SOC, BG, and MBC. Pereira et al. (2021) observed that grazing-exclusion increases bacterial diversity in these areas, which was closely related to soil C. Possibly, the increase in SH may be being driven by the increased biological balance that comes about through increased biological indicators. This was observed by Silva et al. (2022), where there was a significant increase in C content, enzyme activity, and diversity of arbuscular mycorrhizal fungi in areas of grazing-exclusion, reinforcing the importance of this management as a strategy to improve SH in drylands.

Bulk density was higher in DE, mainly due to the long-term effect of overgrazing. Matos et al. (2022) showed that degraded pastures present higher BD, bringing problems mainly for the development of the plant root system due to increased soil compaction. In IDN, soil compaction occurs through reduced pore space and soil water storage (OLIVEIRA FILHO et al., 2019). In addition, increased soil resistance to root penetration and reduced gas exchange as effects of overgrazing. BD influences important soil functions, e.g., filtering and buffering, physical stability, and water relations (ANDREWS; KARLEN; CAMBARDELLA, 2004), being a crucial indicator in the assessment of SH. Negative effects of increased BD were observed by Cherubin et al. (2016a) and Luz (2019) when the conversion of forests into pasture brought increased BD, causing soil degradation and reduction of soil functionality. However, the vegetation recovery and preservation of soil structural quality (CHERUBIN et al., 2016b; LUZ et al., 2022) helps maintain soil functionality, corroborating to the improvement and maintenance of the Physical component of SH.

Beta-glucosidase and MBC were determinant indicators for the improvement of the biological SH component, mainly in dry season. Matos et al. (2022) and Silva et al. (2022), showed that the contents of BG and the MBC were higher in the dry season due to the greater decomposition of plant material accelerated by high temperatures, resulting in increased enzyme activity and stress on microorganisms. Enzyme activity during the dry season also acts as an important driver in the transformation and decomposition of soil organic matter. Importantly, DE showed the lowest scores for BG and the MBC, much in function of the sensitivity that biological attributes have in areas that suffer from ecological disturbances, such as degraded areas in the IDN, reducing the levels of these indicators in the soil (VEUM et al., 2014), since BG and MBC area greatly influenced by SOC contents. In addition, NV and RE present high scores due to the presence of native Caatinga vegetation in NV and the stimulation of vegetation recovery in RE. Thus, it is evident that grazing-exclusion increases SOC contents in degraded areas, and this technique can be used to increase soil C pools in drylands and consequently, helps to mitigate climate changes. Increasing SOC is an important strategy for improving SH, playing a crucial role in soil fertility, water partitioning, and structural stability (HOFFLAND et al., 2020).

Ecological resilience (HOLLING, 1973) is another factor that influence SHI since dryland ecosystems are adapted to resist disturbances caused by drought (KUSH; DAVY; SEDDON, 2022). Thus, there is a natural variation in SH throughout the year. In this research, variations in the Chemical and Physical component of SH were minimal. Even in different treatments, the scores remained similar. This can be explained by the low water availability in the IDN, because of one of the largest droughts in history (MARENGO et al., 2022), influencing the non-variation of the chemical scores of SH.

The Caatinga biome presents mechanisms that help its resilience, but these are not sufficient to deal with the effects of overgrazing. DE presents SH scores that do not vary throughout the year, maintaining soil function < 50%. The period in which the DE remains without the presence of animals is not sufficient for significant improvement in SH in the pasture management. Grazing-exclusion in RE was able to raise SHI in areas degraded by overgrazing. NV and RE scores are in closer ranges, fluctuating between 65 % and 82 %, above DE. Thus, grazing-exclusion recovered the health of degraded soils in the Caatinga biome to levels similar to those of native vegetation.

The Caatinga biome is known for its resilience. This study shows that 21 years were enough to recover the ecological functionality of highly degraded areas. However, the exclusion of grazing cannot be the only recovery practice used, since agriculture and livestock are sources of subsistence and income, and the stoppage of these activities could bring socioeconomic problems to the local population. Alternative managements emerge as possibilities for agricultural activities to be sustainable, not causing increased soil degradation, and collaborating to improve the ecological quality of the Caatinga, such as rotational grazing in the Caatinga (allowing animals to enter one year and then excluding them for 5-10 years), and the implementation of integrated systems where part of the Caatinga is preserved and part is intensified for pasture production. Public policies such as incentive programs for agricultural production in larger volume in the rainy season and stockpiling for the dry season (mainly for animal feed), besides training programs and technology transfer for the population that inhabits these more vulnerable areas.

5. CONCLUSIONS

The SMAF was able to detect differences in the impacts of management on SH, indicating that the restoration of drylands in the Caatinga biome provides SH improvement at levels similar to those of areas of native vegetation in the biome. SMAF presents itself as an important tool to be used in monitoring soil degradation and restoration and the effects of climate change, which tend to grow increasingly in one of the poorest and most drought-prone areas in Brazil.

Recovery of SH in areas with grazing-exclusion is predominantly due to increased C input via biomass in the soil and restoration of biological activity, as well as the exclusion of animal trampling, the main agent of soil compaction in the region. SOC, BG, and MBC positively contributed to improving SH, especially during the driest season of the year. This reinforces the importance of biological indicators in the assessment of SH. BD and SAR were the main limiting factors for SH, being strongly related to degraded areas, reducing the potential for plant development. The seasonality of rainfall promoted the development of adaptive mechanisms of the Caatinga vegetation to the effects of severe water shortage during the dry season, which contributes to the high resilience characteristic of the biome.

Our results demonstrated that the adoption of conservationist techniques, such as the grazing-exclusion, can restore degraded areas in the Brazilian semiarid. However, investments in research are necessary to find solutions for more sustainable uses of the Caatinga, which allow the preservation to be reconciled with the subsistence of the vulnerable population that lives in this region. This study can serve as a model for the SH assessment, as well as in the monitoring of degraded areas and areas in a high desertification process in the Caatinga biome. We believe that this study can guide new research on SH in the Brazilian semiarid, beyond making feasible the use of SMAF for the edaphoclimatic and vegetative conditions of the Caatinga biome.

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6 FINAL CONSIDERATIONS

Metrics evaluated in our bibliometric review show that the research on SH in the Caatinga biome is fragmented and incipient, has weak connectivity among authors and research institutions, with a theme restricted to the study of soil attributes or processes, lacks research on the general evaluation of SH.

The evaluation of Physical, Chemical, and Biological parameters showed that BD and SAR are limiting to SH in degraded areas, while SOC, MBC and BG contributed positively to the improvement of SH during the dry period. The seasonal effect of rainfall promotes the development of adaptive mechanisms of vegetation to the effects of scarcity, increasing resilience and justifying the improvement of SH in the dry season.

SMAF was sensitive when evaluating the effects of overgrazing and grazing-exclusion on SH in areas affected by desertification processes in the desertification nucleus of Irauçuba, Ceará State. This accredits the use of SMAF in soil evaluation under edaphoclimatic and vegetative conditions in the Brazilian drylands.

Investments are necessary so that farming and cattle raising activities is not an agent that increases soil degradation in the Caatinga, but rather so that there is awareness about the correct use and management of the soil.

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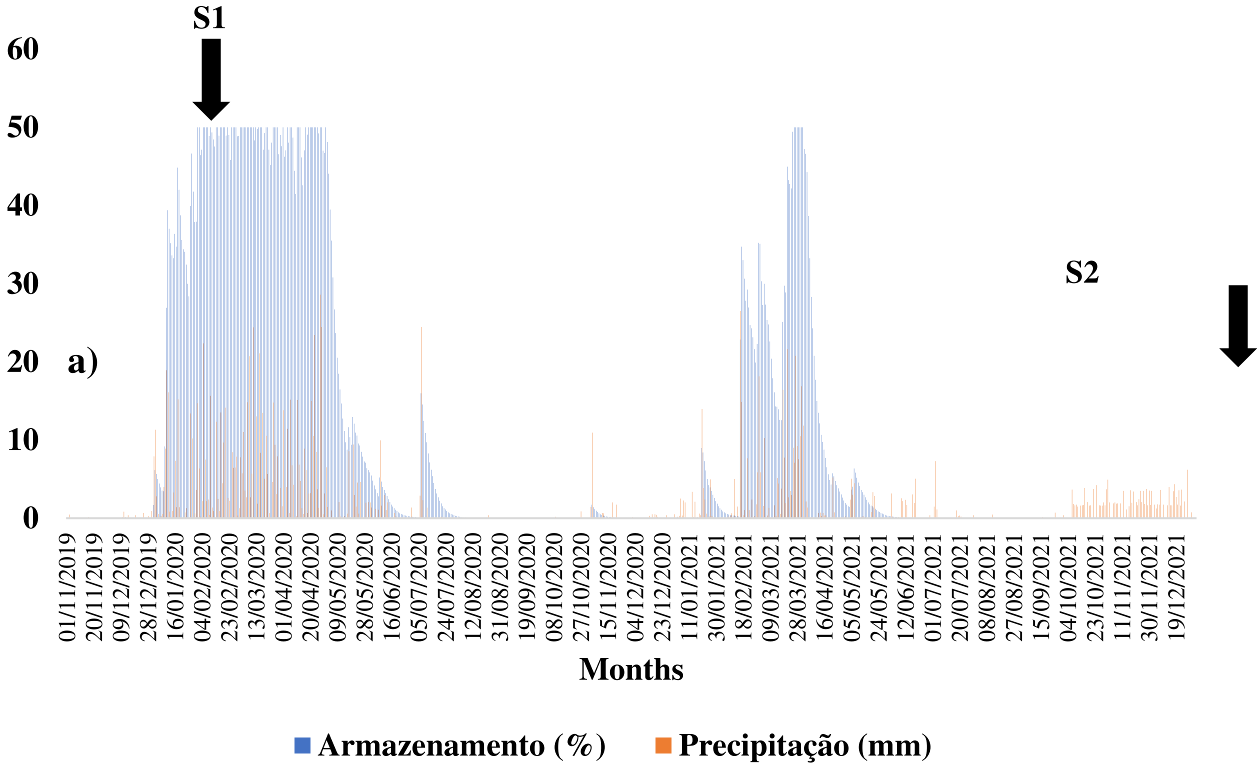
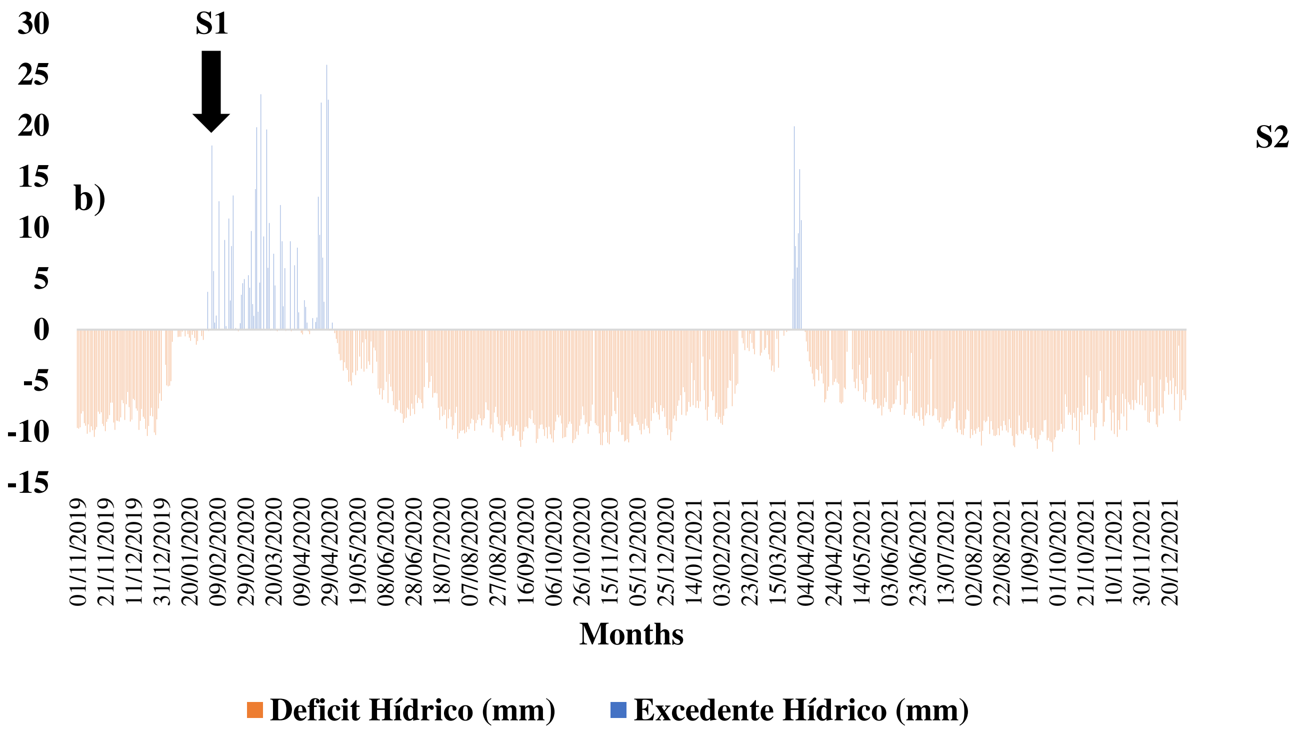
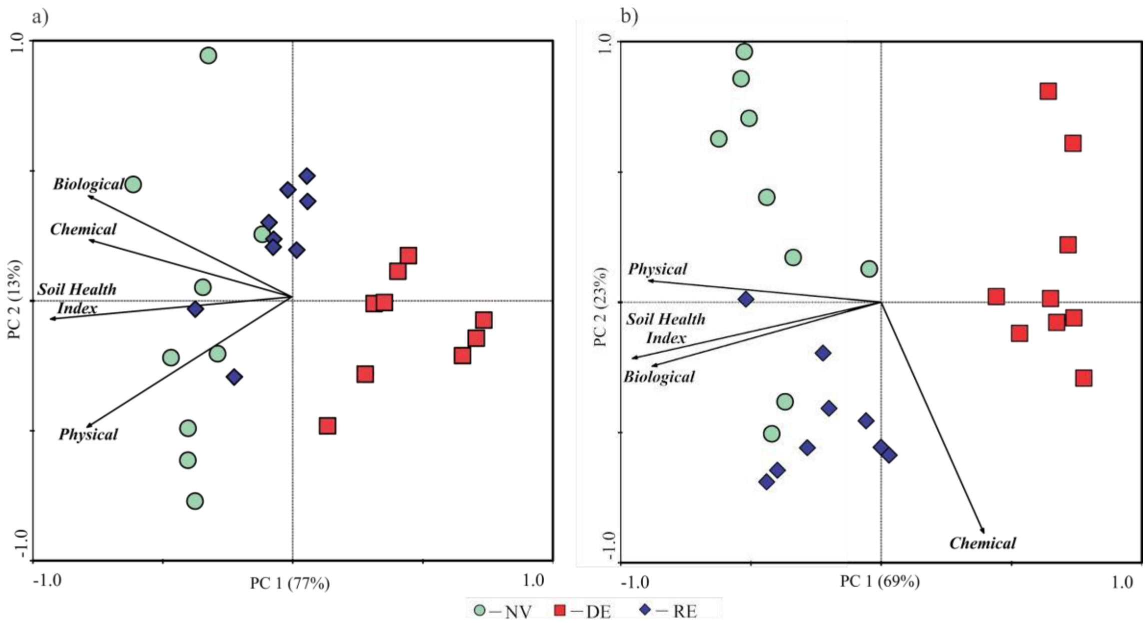
APPENDIX A - SEQUENTIAL WATER BALANCE FOR THE IRAUÇUBA MUNICIPALITY (METEOROLOGICAL STATION "W40S04 (E) – CE", IN THE PERIOD 01/11/2019 – 01/01/2022 (SANDY SOIL, CAD = 50). SOURCE: INMET AND SISDAGRO (https://sisdagro.inmet.gov.br/sisdagro). IN a) STORAGE (%) AND PRECIPITATION (mm) MONTHLY AND b) SOIL DEFICIT AND WATER SURPLUS (MM) DURING THE TWO SAMPLINGS PERFORMED (S1 AND S2)





APPENDIX B – PRINCIPAL COMPONENT ANALYSIS WITH THE RELATIONSHIP BETWEEN SOIL HEALTH SCORES (SH AND COMPONENTS) AND NV = NATURAL VEGETATION OF CAATINGA BIOME, DE = DEGRADED DRYLAND, AND RE = RESTORED DRYLANDS TREATMENTS OF SAMPLING 1 AND SAMPLING 2. a) SAMPLING 1 AND b) SAMPLING 2.



APPENDIX C – SMAF – SHI PERIODS SCORES. MEANS FOLLOWED BY THE SAME LETTER DO NOT DIFFER BY TUKEY'S TEST AT A SIGNIFICANCE LEVEL OF 5 %. LOWER-CASE LETTERS COMPARED CHEMICAL, PHYSICAL AND BIOLOGICAL COMPONENTS WITHIN EACH PERIOD, AND UPPER-CASE LETTERS COMPARED PERIODS. SAMPLING 1 IN FEBRUARY/2020 AND SAMPLING 2 IN OCTOBER/2021.