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Review

Soil Health and Ecosystem Services in Mangrove Forests: A Global Overview

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Abstract: This study analyzed the role of soil health (SH) and ecosystem services (ESs) in global mangrove research articles from 1958 to 2024. The SH approach is vital for evaluating mangroves' ability to provide ES. However, most studies made no reference to these topics, an important gap that must be addressed. We performed a systematic literature review of the Scopus database using the following prompts: Level 1: "mangrove*" and "soil" or "sediment"; Level 2: "mangrove*" and "soil health" or "soil quality"; and Level 3: "mangrove*" and "soil health" or "soil quality" and "ecosystem service*" or "ecologic* service*". A total of 8289 scientific articles were published that explored mangrove soils or sediments, of which 321 included a discussion of SH, and 39 discussed SH and ES. There is a historical preference for the term "sediment" in marine sciences. Carbon is the most studied topic. Six of the fifteen most productive countries are also among the fifteen with the largest mangrove areas. There is a scientific gap regarding studies that link mangrove soil studies with SH and ES. We recommend the development of a soil health index fully adapted to mangroves, considering their physical and geochemical dynamics, climate conditions, and anthropic relevance.

Keywords: soil; sediment; mangroves; soil health; ecosystem services; bibliometric review

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1. Introduction

Mangrove forests are of major importance to coastal biodiversity and hydrological and climate processes and have critical roles in providing many ecosystem services (ESs) that are vital to coastal populations [1–3]. Mangrove forests concentrate organic particles and nutrients, which attract rich marine and freshwater fauna that use these ecosystems as feeding and reproductive areas [4]. As a result, these forests have a major role in the provision of food, coastal protection, and climate regulation, as well as fostering economic activities such as aquaculture, tourism, and agriculture [5]. According to [6], wetlands (including mangroves) represent 9% of the global landscape and provide 26% of ES value.

Mangroves are recognized as important hotspots of carbon sequestration through above and belowground plant biomass and, most importantly, soil [7,8]. The anaerobic conditions characteristic of mangrove soils cause decreases in carbon degradation levels and trigger biogeochemical processes that favor consistent long-term carbon sequestration, nutrient cycling, contaminant immobilization, and other soil functions [9,10]. Unlike terrestrial biomes, which allocate most of their carbon pool to biomass, mangrove forests may retain up to 90% of the carbon in their soils [10]. According to Donato et al. (2011) [7], mangrove soils store from ±193 to 283 tC ha^{-1} to 1 m depth, reaching up to 1023 tC ha^{-1} at 3 m depth in mangroves with high levels of organic content.

In recent decades, many have addressed the need for research and conservation practices for mangrove forests, considering their social, economic, and ecological significance [11–13]. Furthermore, the global commitment to achieving the United Nations' 17 Sustainable Development Goals (SDGs) by 2030 [14] has intensified efforts to protect and/or restore natural ecosystems, such as mangroves [15].

Most mangrove forests are no longer in their natural state due to human activities such as effluent discharges, deforestation for urban expansion, aquaculture, and agriculture, leading to degradation and reduced ES provision [16,17]. Therefore, mangroves represent an attention point for conservation practices, especially considering that once disturbed, these forests may release massive amounts of CO_2 into the atmosphere [18,19]. For instance, a recent study in Brazil revealed that changes in land use and land cover near or in mangrove areas on the Amazon coast would release three times more CO_2 per hectare into the atmosphere than the conversion of the upland Amazon or Atlantic rainforests [20].

Therefore, the conservation status of mangrove forests significantly influences their health and functionality, affecting vegetation, soil C sequestration, and the provision of other ES [9,19]. However, there have been limited attempts to evaluate and apply soil health (SH) or quality indexes in mangrove forests.

Soil quality is defined as the capacity of soil to function within the ecosystem and land use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health [21,22]. Over the last decade, the soil quality concept has been replaced by SH [23]. SH recognizes soil as a living ecosystem and is closely associated with soil functionality and its capacity to deliver multiple ES [24–26]. Therefore, conserving healthy soils is the foundation for the functionality of every ecosystem, including mangroves.

There have been a few studies focused on assessing the soil quality of mangrove forests, aiming to associate soil quality with the provision of ES [27,28]. Soil quality models have been applied to mangroves, adapting parameters typically used in agriculture (e.g., Soil Management Assessment Framework—SMAF) to standardize evaluation [28–30]. The SMAF uses integrative measurements related to ecosystem processes and functions, which are reflected in the index based on the chemical, physical, and biological parameters of soils [31–33]. It is a cost-effective framework that uses selected indicators and a reduced number of measurements (i.e., a minimum dataset) to reliably detect changes in soil quality [34]. However, the SH concept is not referred to in the majority of scientific articles about mangroves.

Integrating SH and ES in Mangrove Studies

Multidisciplinary research is required to provide solutions for climate change, food insecurity, and other threats expected to become more prevalent in the coming decades [35]. Integrating knowledge across diverse fields, despite being challenging, is key to advancing our understanding of environmental constraints [36].

Most mangrove studies are focused on the biogeochemical processes governing soil–plant–water interactions and the alterations promoted by anthropic activities [37]. The extensive literature has shaped the overall understanding of mangroves, highlighting the real effects of anthropic pressures, such as contamination [38], deforestation [39], land use alteration [40,41], and exploration of cultural and economic activities [42]. Moreover, it supported the development of effective restoration and conservation strategies implemented worldwide [43].

Although the literature about mangroves is extensive, further studies connecting scientific findings to mangroves' health and ES will provide a more realistic ecosystem analysis [6,44]. Mangrove soils perform multiple functions (e.g., nutrient cycling, contaminant immobilization, carbon sequestration) (Table 1). These functions are directly related to the provision of ES, which can be hampered when soil dynamics are altered [45]. Since mangrove degradation influences soil dynamics and functions, it is important to integrate these concepts and conduct multidisciplinary research. The challenge to integrate multiple concepts, methods, and approaches from different fields will allow an accurate assessment of how anthropic interventions impact the provision of ES.

Table 1. Connections between mangrove's soil functions, ecosystem services and their respective Sustainable Development Goal [14].

SDGs [1]	ES Class [2]	Ecosystem Services [2]	Soil Function [3]
1. No Poverty 2. Zero Hunger 14. Life below Water 15. Life on Land	Supporting	Nutrient cycling Nursery and breeding ground Biomass production Habitat (Terrestrial and marine fauna) Reducing Eutrophication	Nutrient cycling and availability Organisms' habitat and gene pool Food-biomass production Organisms' habitat and gene pool Acidity regulation
3. Good Health and Well-being	Provisioning	Food Products Fuel Wood Timber Products Charcoal Production Medicines Fresh Water Fishing and Aquaculture practices Water Transport Construction Materials	Food-biomass production Source of raw materials Source of raw materials - - Water storage and filtering Food-biomass production - -
13. Climate Action 6. Clean Water and Sanitation	Regulating	Climate Regulation and mitigation Coastal protection Sequester and store carbon Flood protection Storm protection Wastewater bioremediation Prevention of saltwater intrusion	Carbon storage Contain erosion and physical degradation Carbon storage Contain erosion and physical degradation - Contaminant immobilization Contain erosion and physical degradation
11. Sustainable Cities and Communities 16. Partnerships for the Goals 12. Responsible Consumption and Production	Cultural	Tourism or Eco-Tourism Nature-based Recreation Aesthetic value Cultural Amenities Education	Physical and cultural heritage Platform for man-made structures - Physical and cultural heritage -

Notes: [1] Sustainable Development Goals related to mangroves. [2] Ecosystem services and classes [1]. [3] Soil functions correspondent to each ecosystem service.

All ecosystem services provided by mangroves are supported by soil functions, to a greater or lesser extent [45,46]. These functions are key to understanding and achieving at least 10 of the 17 SDGs, which also represent the importance of mangroves for sustainability (Table 1). Mangrove soils provide 11 distinct functions, directly impacting 20 ES and 10 SDGs, emphasizing the need for further research to address these topics and meet global demands (Table 1).

Considering the limited application of the SH framework to mangroves and its potential as an integrative ecosystem function index, this work synthesizes the current knowledge in this area to find research opportunities for integrating mangrove soils and ES. Therefore, the objectives of this study are, i. to analyze the use of the terms "soil" and "sediment" to address mangrove substrates in different journal concentration areas and research fields, ii. analyze the time evolution, world distribution, concentration area, keywords, authors, and institutions related to scientific articles regarding mangroves, SH, and ecosystem services,

iii. investigate underexplored aspects of soil health and ES and explore future perspectives by assessing emerging approaches and multidisciplinary collaborations for SH and ecosystem services research for mangroves.

2. Materials and Methods

2.1. Bibliography Research Parameters

We selected the Scopus database to perform a systematic literature review since it has the major number of publications within the target subject. The literature review followed an approach of search with three levels. Level 1 included the terms "Mangrove*" AND "Soil" OR "Sediment". This step was essential in determining which concentration areas employed the terms "soil" or "sediment" to describe the mangrove substrate. Concentration areas refer to specific domains within a broader scientific discipline that focus on particular topics, such as Oceanography, Biology, Chemistry, and Hydrology.

In Level 2, the search terms were "Mangrove*" AND "Soil Health" OR "Soil Quality". We included soil quality or SH terms in the search since they have similar meanings in scientific research. In Level 3, two additional terms were added in the search, resulting in "Mangrove*" AND "Soil Health" OR "Soil Quality" AND "Ecosystem Service*" OR "Ecologic* Service*". This approach enabled the identification of SH articles that included a discussion of ES. Boolean Operators were employed to find the publications containing the terms of interest on the title, abstract or keywords of the research articles in the Scopus database.

The aim was to retrieve all articles that used these terms and analyze the source, country of origin, date of publication, concentration area, keywords, authorship, and institutional affiliation. Finally, only research articles were included, excluding the gray literature (i.e., books, book chapters, and conference papers). This comprehensive review aimed to provide a detailed review of the global intersection between mangrove ecosystems and soil health, identifying prevailing trends and the forefront of knowledge in this field.

2.2. Soil or Sediment (Level 1)

Three levels of search were established to quantify the articles focused on mangroves that include the perspective of SH or ES. Level 1 analysis retrieved articles that included the terms "Mangrove*" AND "Soil" OR "Sediment" in the title, abstract, and keywords. The mangrove substrate supporting mangrove vegetation is regarded as soil or sediment depending on the scientific area of the researcher [47–49]. The goal was to analyze the evolution of articles through the years, their distribution by country, and evaluate the frequency of articles by the concentration area of the scientific journal.

Furthermore, we analyzed the article's relationship with the drivers of global soil change established by FAO [50]. The search criteria allowed the retrieval of mangrove studies that analyzed the soil to a certain extent. The terms "Soil" OR "Sediment" helped exclude studies that focused only on mangrove vegetation or water dynamics from fluvial and marine sources.

2.2.1. Soil Quality or Soil Health (Level 2)

Soil quality and SH have similar meanings according to their definitions [22,26]. Thus, we employed the terms "Mangrove*" AND "Soil Health" OR "Soil Quality" to evaluate how many articles addressed soil quality or health topics.

2.2.2. Ecosystem Services or Ecological Services (Level 3)

Finally, the Level 3 search in the Scopus database included the terms "ecosystem services" or "ecological services" ("Mangrove*" AND "Soil Health" OR "Soil Quality" AND "Ecosystem Service*" OR "Ecologic* Service*"). The asterisk symbol was used to include any suffix after the word "Ecologic". We included the term "Ecologic*" to retrieve articles that referred to ES as ecologic or ecological services, which are common expressions used for similar purposes. The objective was to quantify the number of articles that addressed mangroves, soil, and ES subjects. The search criteria for Levels 2 and 3 were even more restrictive, focusing on specific articles that explored the concepts of SH and ES, respectively. These search prompts resulted in a comprehensive global overview of the application of SH and ES concepts in mangrove studies.

2.3. Bibliometric Analysis

The data retrieved in "Level 1" was subjected to analysis and displayed on a world map, indicating the number of papers produced by each country. The country of origin of each article was determined by using the address of the corresponding author, highlighting where the research was originally conducted. In this step, the packages rnaturalearth, maps, and ggspatial built in the R software 4.3.3 were used to generate the images [51–53].

The keywords of the articles in Levels 1, 2, and 3 were selected and displayed in a bar graphic for comparison. For additional analysis, each article in "Level 1" was assigned to the journal's concentration area. A Sankey diagram was used to illustrate the proportion of articles using soil or sediment and their respective concentration area.

The Sankey diagram was developed to map value flows in systems at local or global levels, especially to identify patterns and inefficiencies in industrial systems [54,55]. Additionally, the Sankey diagram was employed to compare the articles using soil or sediment terms with the drivers of global soil change established by FAO [50]. For Levels 2 and 3, the number of research articles published by country and by the concentration area of the journal were analyzed.

3. Results and Discussion

3.1. Level 1: Main Authors, Institutions, and International Collaboration

The literature search of papers that contained the words "mangrove" AND "soil" OR "sediment" in the title, abstract, or keywords identified a total of 8289 documents. Temporal analysis indicated a significant increase in the number of publications beginning in the 1980s, with 208 articles and reaching 744 by the 2000s. Subsequently, the number of publications grew exponentially, with over 1423 articles published between 2000 and 2010, nearly double the total from 1980 to 2000. This growth continued from 2011 and 2024 culminating in 6060 articles published in the period (Figure 1).

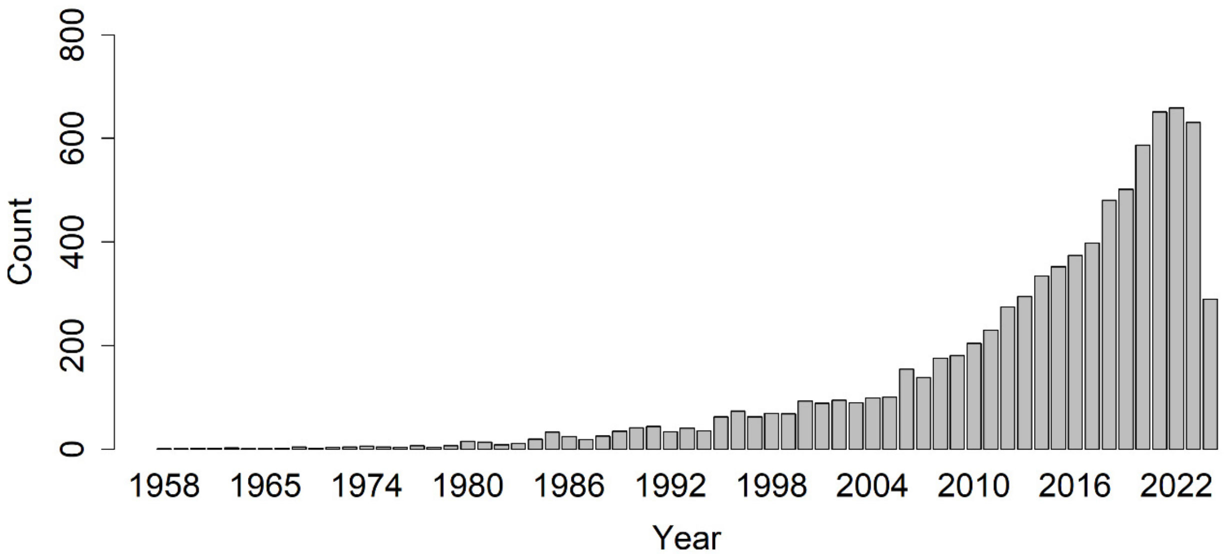

Figure 1. Evolution of scientific publications regarding the 8289 published articles analyzed in this study regarding "mangrove", "soil" and "sediment" between 1958 and May 2024.

The scientific production focusing on mangroves, soil or sediment continued to increase steadily during the last two decades, with 1218 articles published in the 2000s and 3447 in the 2010s. Between 2020 and 2024, a total of 2818 articles were published, demonstrating consistent growth.

The significant growth in scientific research related to mangroves, particularly in recent decades, can be attributed to the growing global emphasis on issues such as the degradation and restoration of natural ecosystems, climate change, ES, and biodiversity [56,57].

Multiple initiatives addressing environmental crises have been launched worldwide since the United Nations Conference on the Human Environment in Stockholm, Sweden in 1972 [58]. Followed by the conferences on Environment and Development in Rio de Janeiro, Brazil in 1992 and 2012, leading to actions such as the nature-based solutions by the European Union in 2013 [59] and the 17 Sustainable Development Goals by the United Nations in 2012 [14]. Moreover, the United Nations Decade on Ecosystem Restoration, launched in 2021, aims to restore ecosystems globally, including mangrove forests, to combat climate change, enhance biodiversity, and improve livelihoods [60,61].

To better understand the distribution of the scientific production we identified the country of the corresponding author for each article and plotted this information on a world map (Figure 2). The map revealed that 56% of all scientific production was concentrated in five countries: China, India, the United States of America, Brazil, and Australia. Despite this concentration, a total of 100 countries had published at least 1 article, with 16 countries producing over 100 articles between 1958 and 2024 (Figure 2).

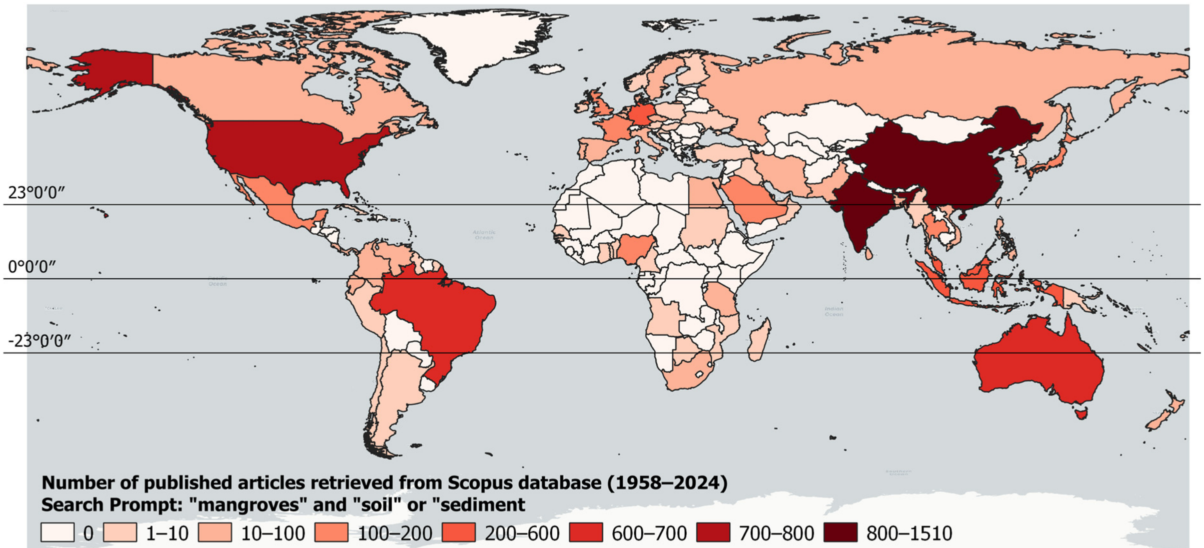

Figure 2. World map of published papers from 1968 to 2024 containing the words "mangrove" and "soil" or "sediment" on the articles' title, abstract, or keywords.

Notably, among the five countries that published the most on mangroves, only two (Brazil and Australia) are included among those with the largest mangrove coverage in the world (i.e., Indonesia: 31,894 km^2, Brazil: 13,000 km^2, Australia: 9910 km^2, Mexico: 7701 km^2, and Nigeria: 7356 km^2) [62]. Furthermore, only 6 of the 15 most productive countries also rank among the 15 with the largest mangrove areas (e.g., India, Brazil, Australia, Malaysia, Indonesia, and Mexico), highlighting the need to expand research efforts on mangrove soils in mangrove-rich countries.

The map also indicated a smaller number of studies in the tropics, despite the presence of approximately 12 million ha of mangroves [63]. Notably, countries with the largest areas of mangroves such as Indonesia, Mexico, and Nigeria showed lower scientific contributions with 240, 185, and 101 studies, respectively (Figure 2).

We further analyzed the scientific distribution by counting the number of published articles by institution (Table 2). There is a predominance of Chinese institutions (5) among the 15 most productive in the subjects of interest, followed by the United States of America

(3), Australia (2), and Hong Kong, Malaysia, Singapore, Brazil, and India (1). The Chinese Academy of Sciences (465 articles) and the Xiamen University (454 articles) were the most productive institutions, underscoring China's leading role in research on mangrove soils and sediments.

Table 2. The top 15 most productive research institutions in Level 1.

Institution	Country	Publications
Chinese Academy of Sciences	China	465
Xiamen University	China	454
Southern Cross University	Australia	178
City University of Hong Kong	Hong Kong	162
University of Malaya	Malaysia	142
Florida International University	USA	138
Louisiana State University	USA	123
National University of Singapore	Singapore	121
University of São Paulo	Brazil	110
Southern Marine Science and Engineering Guangdong Laboratory	China	93
University of Chinese Academy of Sciences	China	90
East China Normal University	China	68
University of Sydney	Australia	56
Smithsonian Environmental Research Center	USA	54
Jawaharlal Nehru University	India	50

The ten most productive authors were distributed across seven countries, with Hong Kong, Australia, and China each represented by two authors, followed by France, Brazil, India, and Sweden with one author each (Table 3). For this analysis, we considered the number of times the scientist was listed as either the first author or a coauthor. Tam, Nora Fung Yee from the Hong Kong Metropolitan University was the most productive researcher with 122 published articles, followed by Lovelock, Catherine E. and Sanders, Christian J. from Australia with 90 and 84 published articles, respectively, regarding Level 1 (Table 3).

Table 3. Top 10 authors most productive authors in Level 1, their institution and country.

Author	n [1]	Soil	Sed [2]	Institution	Country
Tam, N.F.Y.	122	48	74	School of Science and Technology, Hong Kong Metropolitan University	Hong Kong
Lovelock, C.E.	90	70	20	School of the Environment, The University of Queensland	Australia
Sanders, C.J.	84	34	50	Faculty of Science and Engineering—Southern Cross University	Australia
Yan, Chonglin	73	49	24	State Key Laboratory of Marine Environmental Science, Xiamen University	China
Marchand, C.	59	30	29	Université de la Nouvelle—Calédonie	France
Lu, Haoliang	56	38	18	College of the Environment and Ecology, Xiamen University	China
Gu, Jidong	56	14	42	School of Biological Sciences, University of Hong Kong,	Hong Kong
Ferreira, T.O.	55	52	3	"Luiz de Queiroz" College of Agriculture—University of São Paulo	Brazil
Kathiresan, K.	47	31	16	Faculty of Marine Sciences, Annamalai University	India
Santos, I.R.	47	22	5	Department of Marine Sciences, University of Gothenburg	Sweden

Notes: [1] number of published articles. [2] number of articles using the term "sediment".

From the ten most productive authors, only three had a greater number of publications using the term "sediment" than "soil" (Table 3). The authors Ferreira, T.O. and Santos, I.R. had only three and five articles, respectively, using the term "sediment" (Table 3).

3.2. Main Concentration Areas and Research Topics

We classified the 8289 articles retrieved in Level 1 based on their primary concentration area according to the scope of the journal (e.g., oceanography, biology, paleontology, chemistry, hydrology, geotechnologies, forest, and multidisciplinary). The result was plotted in a Sankey diagram to visualize the distribution of the articles (Figure 3). There is a high difference in the number of articles using the terms "sediment" (5049) and "soil" (3240). Multidisciplinary and oceanography journals had the most publications in the period, both favoring the term "sediment" (Figure 3). Specifically, oceanography journals had 70% of articles using "sediment", while multidisciplinary journals had 60%, and biology journals had 55%. This pattern indicates a preference for the term "sediment" in marine sciences.

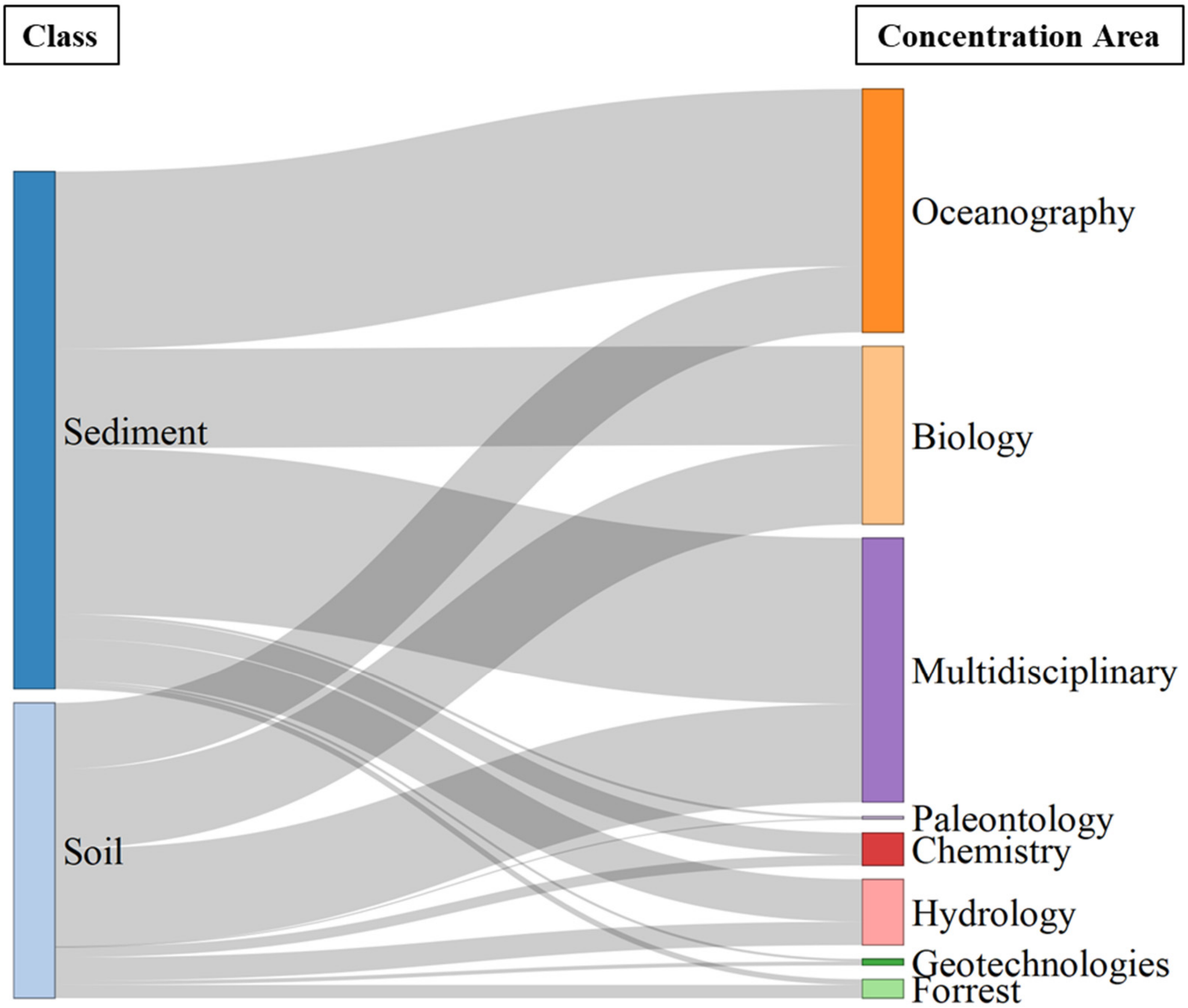

Figure 3. Sankey diagram representing the focus of the 8289 published articles analyzed in Level 1. The left bar represents articles that use the terms "sediment" or "soil". The right bar shows the different concentration areas of the scientific journals.

The other concentration areas had a smaller representation, accounting for 16% of all articles retrieved in Level 1 (Figure 3). However, the term "soil" is used more broadly in journals related to different concentration areas, such as biology, multidisciplinary studies, chemistry, hydrology, geotechnologies, and forestry (Figure 3). These research areas are typically more aligned with soil science studies, which often use the term "soil" even when soil processes are not directly addressed. The articles in these research areas usually focus on topics such as plant growth, nutrient cycling, microorganisms, coastal protection, climate regulation, environmental pressures, and related subjects, thereby addressing soil functions associated with ES [64–66].

Studies that address mangrove substrates as "sediment" are mainly concentrated on the physical aspects of deposition, erosion, and sediment transport, which are vital for understanding coastal dynamics and habitat stability [67,68]. Conversely, Ferreira et al. (2007) [47] argued that mangrove substrate should be considered "soil", as it is formed by pedological processes similar to terrestrial soils. This perspective clarifies the functions that the soil can perform, highlighting biogeochemical processes that are essential for carbon sequestration and ecosystem health [45,69,70].

To further evaluate the contribution of articles in Level 1, we compared them with the drivers of global soil change established by [50] and adapted these concepts to mangrove soils. We analyzed articles addressing the drivers of soil change (i.e., food security, climate change, degraded ecosystem, and water contamination) and the threats to soil change (i.e., carbon loss, soil erosion, contamination, nutrient imbalance, biodiversity loss, land use/cover change, and acidification) (Figure 4).

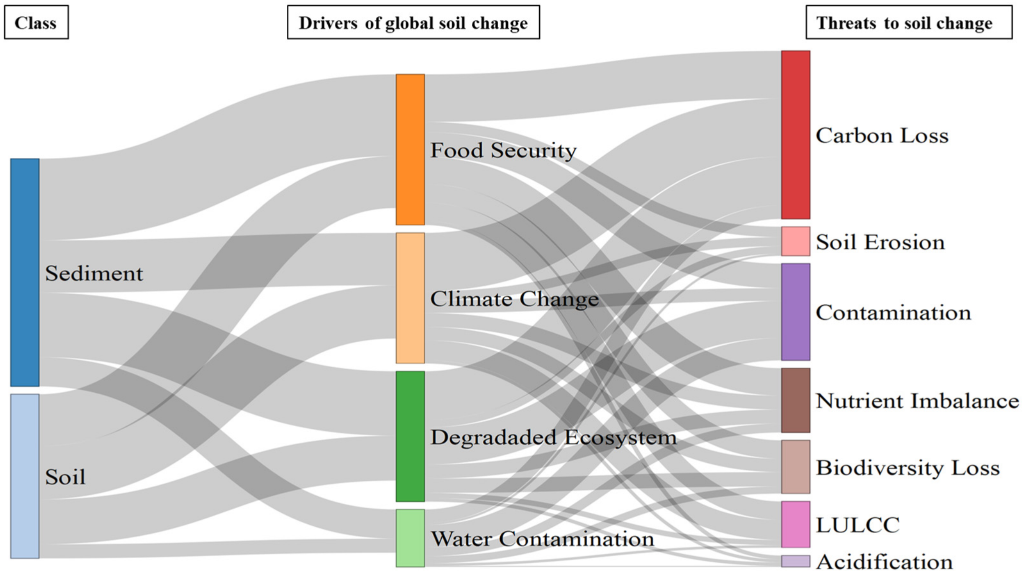

Figure 4. Sankey diagram representing the focus of the 8289 published articles analyzed in Level 1. The left bar represents articles that used the terms sediment or soil. The middle bar represents the drivers of global soil change. The right bar represents the threats to soil change, impacts and responses. This classification follows the framework established by FAO [50].

The drivers of soil change are related to activities resulting in major socio-economic and environmental transformations [71]. The increasing need to enhance food production is primarily driven by economic and demographic growth, which impacts climate change and land use dynamics [50,72]. In this context, most articles in Level 1 presented a connection with the drivers of soil change, since mangroves face significant threats from climate change, including more frequent severe weather events, sea-level rise, and shifts in their distribution, as well as human activities such as deforestation, land-use change (e.g., aquaculture), and urban expansion. Moreover, global mangrove forests are projected to be severely affected in the next 50 years [73].

The articles in Level 1 predominantly focused on food security, climate change, and degraded ecosystems, which are major factors affecting mangroves (Figure 4). Water contamination had the fewest articles and the most uneven distribution between those using the terms "sediment" (313) or "soil" (150). The other topics showed more equal distribution, with climate change having more articles using "soil" (570) than "sediment" (560) (Figure 4).

Carbon loss and contamination are the two most relevant threats addressed by the articles in Level 1, reflecting the growing need to understand how mangrove forests will adapt to climate change and contamination [74]. According to Alongi (2015) [75], climate change will continue to negatively impact mangroves globally due to temperature rise, increased aridity, and deforestation. These effects have already been observed in Brazilian mangroves, where intense El Niño conditions increased estuarine salinity, which, when combined with atypical storms, caused mass mangrove mortality [73]. These impacts resulted not only in significant carbon loss in plants and soils but also in a decline in mangrove forest productivity, with consequences to the provision of nutrients and food by these ecosystems [76].

3.3. Analysis of Keywords

The number of papers and keywords decreased from Levels 1 to 3, reflecting a shift from a broader to a more specific scope. Level 1 retrieved 223,261 keywords from the 8289 articles, Level 2 included 9434 keywords from 321 articles, and Level 3 contained 959 keywords from the 39 articles (Figure 5).

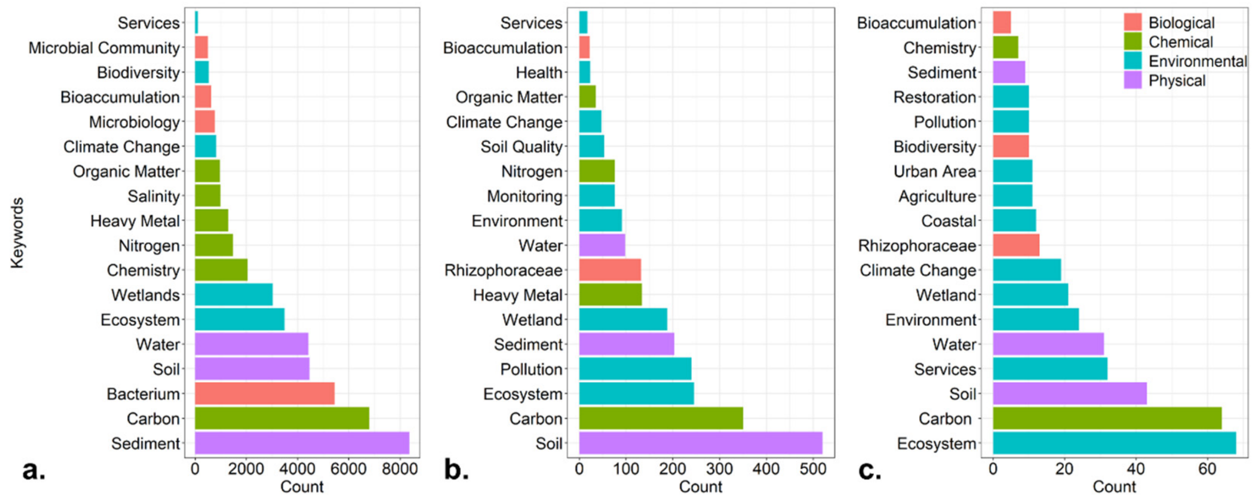

Figure 5. Graph showing the most expressive keywords used in the research articles. (**a**) Level 1 ("Mangrove*" AND "Soil" OR "Sediment") with 8289 articles and 223,261 keywords, (**b**) Level 2 ("Mangrove*" AND "Soil Quality" OR "Soil Health") with 321 articles and 9434 keywords, (**c**) Level 3 ("Mangrove*" AND "Soil Quality" OR "Soil Health" AND "Ecosystem Service*" OR Ecologic* Service*") with 39 articles and 959 keywords. The keywords are classified according to their emphasis, such as biological (coral), chemical (green), environmental (blue), and physical (purple).

The keywords were classified into four categories: physical, chemical, biological, and environmental, with the environmental category including broader subjects (e.g., pollution, urban area, wetland, climate change, restoration, and others) (Figure 5). In Level 1, the chemical and environmental categories were the most represented, with six keywords each, followed by biological (4), and physical (3) (Figure 5a). Level 1 included articles that used the terms "soil" or "sediment", encompassing studies from multiple research areas.

In Level 2, the environmental keywords occurred 10 times, followed by chemical (4), physical (3), and biological (2) categories (Figure 5b). The articles in this section were more aligned with soil science, resulting in 520 "soil" keywords, the most found in this search (Figure 5b). Conversely, "sediment" appeared 203 times, showing an opposite trend compared to Level 1. Level 3 had a similar pattern, with 11 environmental keywords, followed by physical and biological (3), and chemical (2) (Figure 5c). The terms "ecosystem" and "services" had 68 and 32 occurrences, respectively.

Carbon was a relevant keyword across all three levels, ranking as the second most frequently used keyword in Level 1 (6796), Level 2 (350), and Level 3 (64) (Figure 5). This pattern highlights the importance of carbon studies in understanding the role of mangroves in global initiatives against global warming [20,77]. The increase in scientific articles on mangroves in recent decades suggests progress in understanding mangrove dynamics and their capacity for carbon sequestration and storage. However, the limited number of articles published in Levels 2 and 3 indicates a gap in studies addressing SH and ES for mangroves.

3.4. Mangroves, Soil Health, and Ecosystem Services

We analyzed the scientific production by country and concentration area of the journals for Levels 2 and 3. China, India, and the United States were the three most productive countries in both levels, followed by a strong contribution from Brazil, Indonesia, Australia, and others (Figure 6). Level 2 retrieved only 321 articles, demonstrating a large reduction compared to the 8289 articles retrieved in Level 1.

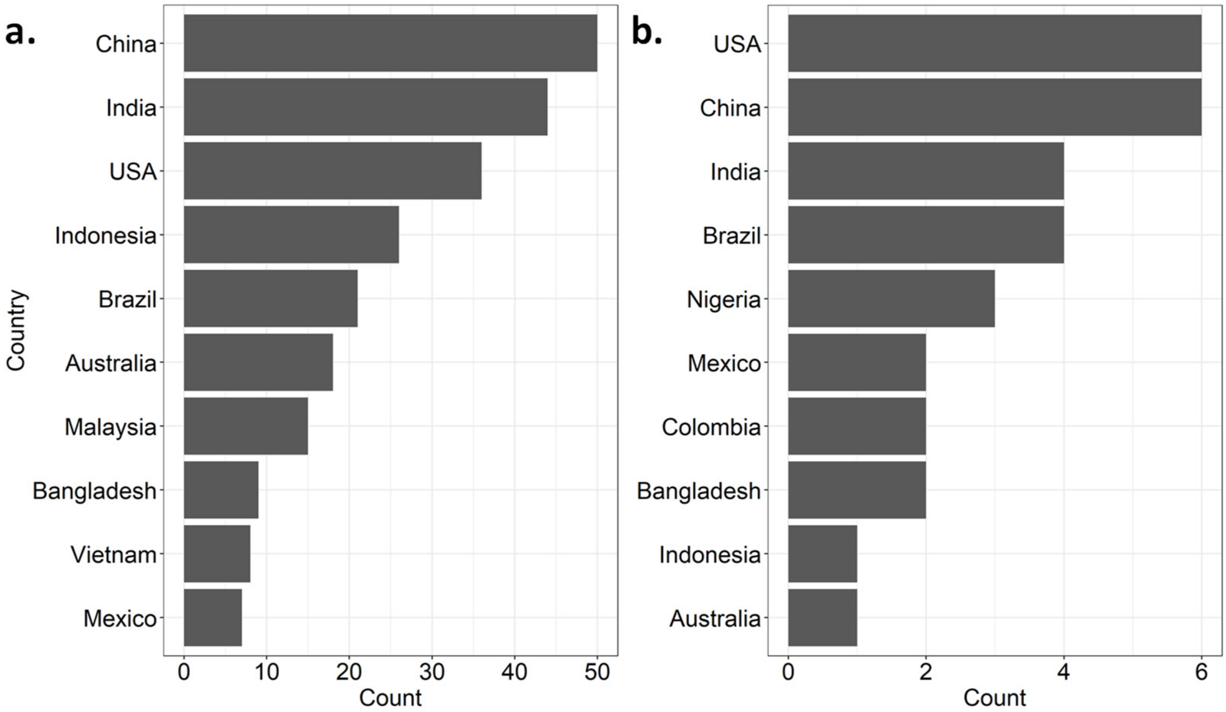

Figure 6. Published articles in the 10 most productive countries for Level 2 and 3 search in the Scopus database. (**a**) Level 2: "mangrove" and "soil health" or "soil quality" on the article's title, abstract, or keywords. (**b**) Level 3: "mangrove" and "soil health" or "soil quality" and "ecosystem services" or "ecological services" on the article's title, abstract, or keywords.

This difference suggests a gap in SH studies for mangroves, which limits the overall understanding of how mangroves provide ES [30,78]. Ferreira et al. (2024) [45] linked specific soil processes and attributes in mangroves to their ability to provide ES, such as contaminants immobilization and climate regulation (e.g., through organic carbon sequestration, high Fe levels, and slightly acidic to neutral pH levels) [79,80]. However, the results from Levels 1, 2, and 3 indicated that most studies focus on soil processes and external threats to mangroves without adequately linking these factors to their direct impacts on ES performance.

It is also important to note that although mangrove forest conservation is critical to ecosystem health, the services provided by mangroves directly impact coastal and traditional communities living in these areas [3]. Therefore, there is an urgent need to integrate community-based local ecological knowledge into assessments of mangrove ES.

Furthermore, the majority of journals retrieved in Levels 2 and 3 are from multidisciplinary areas including *Science of the Total Environment*, *Environmental Pollution*, *Nature Communications*, *Scientific Reports*, *Marine Pollution Bulletin*, *Environmental Research*, *Plos One*, and others (Figure 7), most of which are multidisciplinary journals able to publish studies about soil science.

Specific soil science journals accounted for 11 publications in Level 2 (3.7%) and none in Level 3 (Figure 7). Although soil science has a significant role in mangrove research [66,81,82], there is a need for more studies focusing on SH and ES, especially considering the continuous pressures on this ecosystem [28].

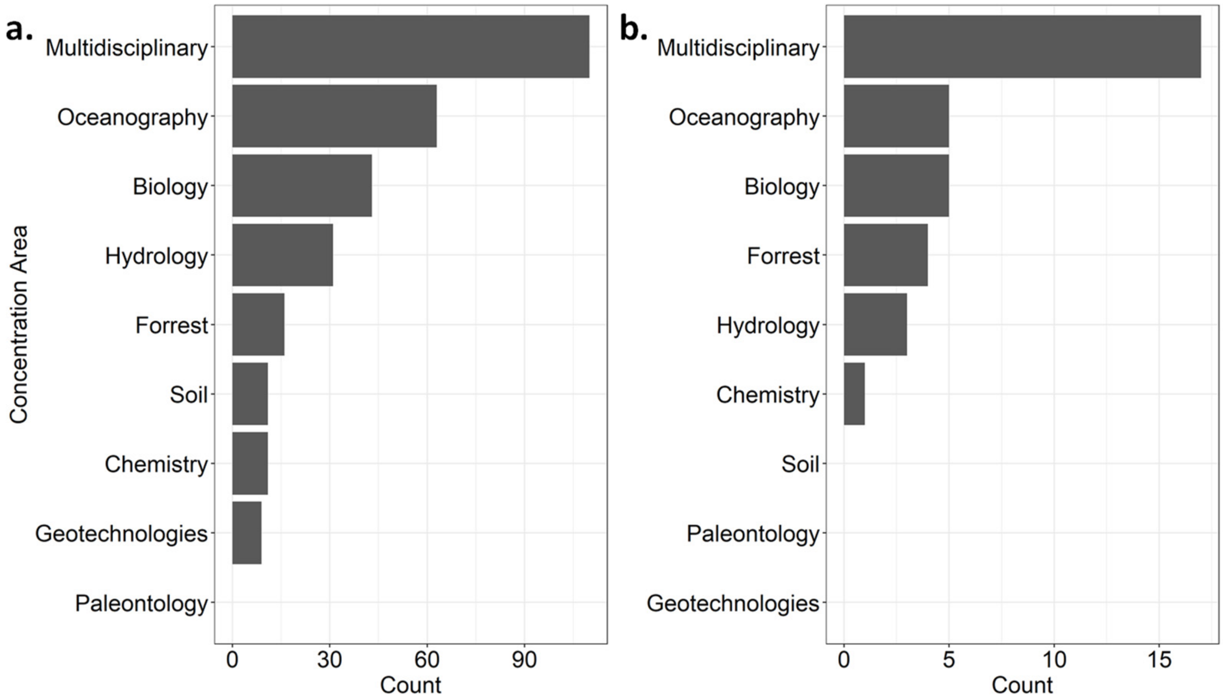

Figure 7. Published articles by concentration areas for Level 2 and 3 search in the Scopus database. (**a**) Level 2: "mangrove" and "soil health" or "soil quality" on the article's title, abstract, or keywords. (**b**) Level 3: "mangrove" and "soil health" or "soil quality" and "ecosystem services" or "ecological services" on the article's title, abstract, or keywords.

4. Future Perspectives and Opportunities

The growing number of published articles in recent years indicates a continuous increase in research, particularly in light of their importance in addressing global climate change initiatives [75,83]. For instance, there were only 867 articles published in Southeast Asia in a span of ±65 years (Level 1), which alone contains 33.5% of all mangroves in the world [62]. In contrast, Brazil alone produced 678 articles (Level 1) in the same period, despite having only 6% of the world's mangroves.

Research on SH is more established in agricultural systems, with a focus on evaluating impacts on soil physical, chemical, and biological attributes [25,84]. For mangroves, land use change, contamination, and sea level rise are considered the greatest threats to their stability [75,85]. However, there is much to be studied on how these pressures impact soil functions in mangroves and, consequently, their capacity to provide ES.

A functioning ecosystem is beneficial for society by providing multiple social and economic goods (Table 1). However, the malfunctioning of ecosystems and the compromised delivery of ES directly impact human welfare and economic stability [44]. Degraded ecosystems are more susceptible to long-term sustainability loss, reduced flood control, and diminished water purification, increasing risks for communities' health and security [17,37].

These pressures also require large public investment for natural disaster recovery and reforestation programs, in order to reestablish ES functioning [86,87]. The different estimates for the direct and indirect economic value of ES ranged over the tens of trillions (USD) per year, while the loss of ES by land use change is approximately USD 4.3–20.2 trillion/year [6,44,88]. Therefore, further scientific research about mangroves must combine knowledge from different concentration areas and their impacts on ES.

Coastal communities around mangroves are more vulnerable to the consequences of climate change, including sea level rise, intense storms, coastal erosion, loss of biodiversity and loss of economic activities like tourism, fishing, and other ocean-based activities [89,90]. Moreover, most mangroves are located in tropical areas within developing countries, which often have limited climate regulation and monitoring [42], worsening conditions for economic and environmental security [91]. The evaluation of SH in more scientific works is a first step to subsidize decision making and policies to protect and restore coastal ecosystems such as mangroves, saltmarshes, hypersaline tidal flats, seagrass meadows, and coastal lagoons.

Finally, future studies must address critical gaps to enhance the understanding of SH. For instance, to perform tests to define an adequate minimum dataset required to measure SH in mangroves, to evaluate different soil parameters at multiple depths and to check their sensibility to SH. Moreover, it is important to apply the gathered knowledge to an SH index methodology, testing different approaches (e.g., total dataset, principal component analysis, expert knowledge, and others), in order to establish an efficient and clear way to classify mangroves under different climatic, geomorphic, and conservation scenarios. The index must account for physical, chemical, and biological indicators, in order to provide a strong representation of the soil. Moreover, it is recommended that soil indicators be related to soil functions (e.g., carbon sequestration, and contaminant immobilization). Finally, the index will indicate how much a given soil is able to provide one specific function.

Advancing the knowledge on how to evaluate soil health in mangroves will improve the ability to determine which mangroves are able to provide their ES on a large scale, assuring the conservation of these ecosystems.

5. Conclusions

There has been a growing number of articles related to mangrove soils in recent years. However, our study revealed that 56% of all the scientific production regarding mangrove soils originates from China, India, the United States, Brazil and Australia, while only 867 articles were published in Southeast Asia in a span of $\pm$65 years, which alone contains 33.5% of all mangroves in the world. Countries with large mangrove areas (e.g., Indonesia, Mexico, and Nigeria) had fewer articles published in the period, confirming the need to support scientific development in mangrove-rich countries. Scientific advancements in mangrove SH and its links to the provision of ES are key to implementing actions to combat major global crises such as food insecurity, climate change, and biodiversity loss, as well as achieving the goals of the Decade of Restoration and the SDGs.

Research in this area is particularly published in multidisciplinary journals. Therefore, we emphasize the need for soil scientists to direct their articles to specialized soil science journals and for these journals to be receptive to contributions in this field. This would strengthen the soil science community in wetlands. In addition, we encourage more soil science scientists to engage in studies of mangroves and wetlands, as this will enhance the understanding of mangrove soils and their ability to perform ES.

Our study revealed that carbon is one of the most studied topics, reaffirming the relevance of mangrove soils as a major compartment for carbon storage and combating climate change. Despite that, it is expected that the number of studies focusing on carbon will continue to increase in the coming years to elucidate mechanisms of carbon stabilization, impacts of land use change, the carbon market, and other related topics.

Finally, we strongly recommend the development of a soil health index fully adapted to mangroves, considering their physical and geochemical dynamics—an index that considers relevant physical, chemical, and biological attributes, their optimal value in different soil profile depths, and that reflects the impacts caused by anthropic or natural pressures. The development of the index must result in a reproducible methodology effective to evaluate mangroves globally and to support decision making and public policies aiming to restore and preserve this ecosystem.

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