soil systems

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Review

Soil Carbon Sequestration in the Context of Climate Change Mitigation: A Review

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Abstract: This review article aims to acknowledge the multifaceted functions of soil, and given its status as the largest terrestrial carbon store, to reaffirm its previously established importance in carbon sequestration. The article outlines the key variables that affect soil's ability to trap carbon and highlights the significance of soil in halting climate change. A bibliometric study of seven sets of keywords relating to the significance of soil in carbon sequestration for climate change mitigation laid the foundation for this review. The literature review that followed, which was based on the bibliometric analysis, concentrated on carbon sequestration and the impact of the key factors that affect the amount of organic carbon in soil, including (1) climatic conditions; (2) topography; (3) parent material; (4) organisms; and (5) soil qualities. The goal of this review article is to recognize the diverse roles of soil, while reasserting its well-documented significance in carbon sequestration. This is particularly important considering soil's position as the largest terrestrial storehouse of carbon.

Keywords: carbon storage; carbon indicators; carbon mitigation; organic soil properties; soil functions

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1. Introduction

Climate change is one of the most significant challenges of our time. The increase in average temperature, now unequivocally proven, is occurring at an unprecedented rate. The growing concentration of carbon dioxide (CO_2), as well as other greenhouse gases, such as methane (CH_4) and nitrogen oxides (NO_X), which are the main drivers of the anthropogenic greenhouse gas (GHG) effect, are released through the burning of fossil fuels and biomass, notably through the decomposition of organic matter at the surface and at depth in the soil [1]. This leads to the need for reliable estimates of the amounts of organic carbon that can be sequestered by vegetation and soils.

The official GHG emissions data reported by the 27 European Union (EU) Member States confirm that the EU fully achieved its climate and energy targets for 2020. The EU-27 GHG emissions in 2020 were 32% below 1990 levels, far exceeding the 2020 target of a 20% reduction [2]. Estimates from preliminary data, reported by the most recent Member States, suggest that GHG emissions increased by 5% in 2021 compared to the 2020 levels. However, these estimated emissions remain 6% below the pre-COVID level of 2019 and over 8% below the 2020 target. At the level of GHG emission sources, the energy sector (26%) was the largest contributor in the EU in 2022, followed by domestic transport and industry sectors (22%). It is also important to note that the land use, land-use change, and forestry sectors show negative values (−7%), resulting from their positive contribution to carbon sequestration capacity [3].

In Portugal, similarly to trends observed in EU data, GHG emissions began decreasing in 2005 and continued since, with the exception of 2017. The most recent data, from 2020, indicate emissions of 52,939.2 kt CO_2eq [4], with the energy sector being the largest contributor to GHG emissions in Portugal. On the other hand, in general, over the 30 years of reference data, the forestry and land-use change sectors recorded negative emission values, representing the sector's ability to sequester carbon. However, it is worth noting that in 2017, the forestry and land-use change sectors were responsible for emitting 21,453.80 kt CO_2eq, which accounted for 23% of total emissions (92,404.1 kt CO_2eq) [4].

Increases in atmospheric CO_2 can lead to increases in terrestrial carbon storage, namely through photosynthesis, land-use changes, vegetation and soil responses to continuous warming, and changes in the water cycle [5]. On the timescale of decades and centuries, the main natural CO_2 sinks pertain to absorption by oceans, plants, and soils [5]. Given that more than two-thirds of terrestrial carbon reserves are found in soils [6,7], they play an important role in mitigating GHGs emissions [8]. The role of soils as sinks for atmospheric CO_2 is ambiguous [9], and various strategies to increase their carbon sequestration capacity are discussed in the literature, revealing an opportunity for soil to reduce carbon emissions or explore other sequestration opportunities [1,10]. Increasing carbon sequestration also supports several United Nations Sustainable Development Goals (SDGs), directly contributing to SDG 2 "End Hunger", SDG 13 "Combat Climate Change", and SDG 15 "Terrestrial Ecosystems and Biodiversity".

Under the United Nations Framework Convention on Climate Change, countries prepare inventories of all anthropogenic GHG emissions and removals, following methodological guidance prepared by the Intergovernmental Panel on Climate Change (IPCC). These GHG inventories include the "Land Use, Land-Use Change, and Forestry" (LULUCF) sector, covering emissions and sequestration, primarily through forests, but also from croplands, grasslands, wetlands, settlements, and other areas. Following this, in the EU, the net CO_2 absorption estimated in 2012 was 306 million tonnes of CO_2. This number results from the balance between net sequestration by forests (444 million tonnes of CO_2) and net emissions from other ecosystems (138 million tonnes of CO_2). EU ecosystems, and particularly forests, mitigate around 7% of all anthropogenic CO_2 emissions in the EU [11].

In the EU, there is great potential to increase soil carbon stocks over the next few decades through changes in agricultural practices [12]. In this context, the possibility of carbon sequestration should be considered as a potential means to mitigate increases in atmospheric CO_2 concentrations. However, it is important to note that recent studies recommend some precautions, highlighting that those efforts aimed at achieving carbon sequestration are often offset by other GHG emissions [9] and that soils generally have low potential to accumulate carbon [1]. Since carbon sequestration in soils is potentially finite, not permanent [6], and difficult to quantify and verify in the long term, it can be considered a risky strategy for minimizing climate effects compared to direct emission reduction. However, in the short term, it may be crucial for reducing atmospheric CO_2 concentrations [13]. The balance between carbon inputs and outputs in the soil is disturbed by land-use change until equilibrium is reached again. During this process, the soil can act as a source of carbon or as a sink of carbon depending on the relationship between carbon inputs and outputs [14].

Lal and Lal et al. [15,16] indicate that there are numerous benefits in terrestrial carbon sequestration, including compensating for anthropogenic emissions; reducing the net increase in atmospheric CO_2 concentration; increasing soil and water resource quality and their ecosystem functions and services; decreasing nutrient losses from ecosystems; reducing erosion risks; improving habitats; enhancing water retention; restoring degraded soils; and increasing land-use efficiency. Given the numerous co-benefits, there is great interest in defining concepts, experimental approaches, laboratory analysis procedures, and methods for determining carbon sequestration rates through plant units, plant residues, and other organic solids, which are stored and retained as part of the soil organic matter. In this sense, quantifying the global ecosystem carbon balance is necessary and fundamental, not only to assess the magnitude of global carbon reservoirs, but also to set new objectives for ecosystem management.

The primary purpose of this review article is to furnish a comprehensive insight into the multiple roles that soil plays, with a special emphasis on its significant function in carbon sequestration and mitigating the effects of climate change. Soil, as the largest terrestrial carbon reservoir, plays a pivotal role in the global carbon cycle and is a crucial player in our battle against climate change. The article underscores this crucial role and brings into focus the key factors that impact its capacity to sequester carbon. These factors range from environmental conditions such as climate, geographical features including topography, the soil's original composition termed as the parent material, the variety of organisms that inhabit the soil, to inherent soil characteristics such as its texture, structure, and organic matter content. To provide a well-rounded understanding, the review was carried out using a two-pronged approach. Initially, a bibliometric analysis was conducted on seven distinct sets of keywords pertinent to the subject matter. This method of analysis allowed for an objective assessment of the current state of research in this field. Subsequently, a thorough literature review was performed to delve deeper into the selected studies, providing a nuanced understanding of the various aspects of soil's role in carbon sequestration and climate change mitigation.

2. Bibliometric Analysis

This study started with the definition of bibliometric analysis processes, using the Scopus database due to its extensive collection of relevant articles. We exported our findings from Scopus in BibTeX format to record detailed citation and bibliographic information. A thorough investigation of scientific articles was undertaken. This process involved using carefully selected keywords in various combinations, which were applied to the titles, abstracts, and keywords of database entries. To enhance the precision of the search, we employed additional filters. We confined the 'Study Area' to Environmental Science and Agricultural and Biological Sciences and the 'Document Type' to Review. The complete list of applied keywords can be found in Figure 1. Subsequently, the search results were further explored using the "Bioblimetrix" package [17], specifically with the "Biblioshiny" tool, available in RStudio software, version 5599.7.2.0, where publication data, such as authors, publication years, country of origin, number of citations, number of publications, and journal information, are compiled and organized to facilitate the extraction of more relevant data. To make data processing easier and to adapt the data for reading, the data were exported from this tool into Excel format.

The analysis of different keyword sets indicated distinctive trends in the scientific literature. 'Soil', 'Carbon', and 'Capture' resulted in 134 documents from 1995 to 2022, with a 100% increase from 2020 to 2021. A higher yield was seen with 'Soil', 'Carbon', and 'Sequestration', generating 995 documents from 1997 to 2023, and reaching over 100 publications in 2021. Despite a steady rate of one publication per year, 'Soil', 'Carbon', 'Sequestration', 'Soil', 'Carbon', 'Sequestration', 'Climate', and 'Change' showed significant growth, with 433 documents from 1997 to 2023 and more than 160 in the last three years. The sets 'Carbon', 'Sequestration', 'Soil', 'Types', and 'Carbon', 'Sequestration', 'Types', 'Land', and 'Use' yielded 154 and 98 documents, respectively, both showing an upward trend since 2019. 'Carbon', 'Sequestration', 'Soil', 'Organic', and 'Matter' generated 259 documents, peaking in the last two years. These topics, overall, show increasing attention over time. Journals frequently cited include "Science of The Total Environment", "Agronomy for Sustainable Development", and "Journal of Environmental Management", each associated with specific keyword groups. Considering author nationality, the U.S., China, and the U.K. are the most common, with China leading for 'Carbon', 'Sequestration', 'Soil', and 'Types', and Germany also featuring significantly for 'Carbon', 'Sequestration', 'Soil', 'Organic', and ‘Matter’. This bibliometric analysis, including the five most cited documents for each keyword set (presented in Table 1), serves as a foundation for the literature review.

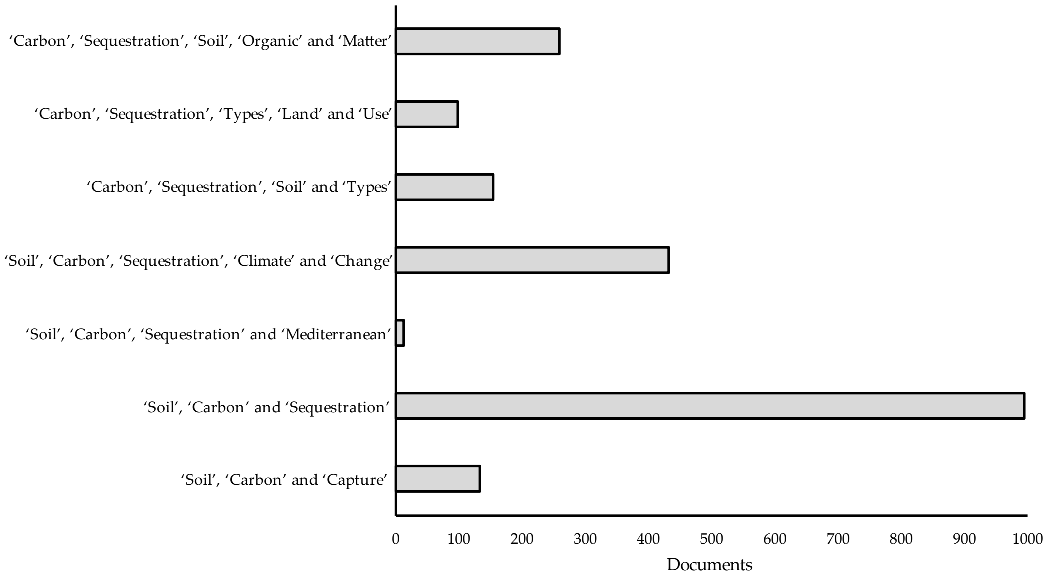

Figure 1. Sets of keywords used in the search, with the ‘Study Area’ confined to Environmental Science and Agricultural and Biological Sciences and the ‘Document Type’ to Review.

Table 1. Most cited documents worldwide for each set of keywords used in the search in the Web of Science database and processed in the Bibliometrix package (Biblioshiny tool) in RStudio: (a) ‘Soil’, ‘Carbon’, and ‘Capture’; (b) set of keywords ‘Soil’, ‘Carbon’, and ‘Sequestration’; (c) set of keywords ‘Soil’, ‘Carbon’, ‘Sequestration’, ‘Climate’, and ‘Change’; (d) set of keywords ‘Carbon’, ‘Sequestration’, ‘Soil’, and ‘Types’; (e) set of keywords ‘Carbon’, ‘Sequestration’, ‘Types’, ‘Land’, and ‘Use’; and (f) set of keywords ‘Carbon’, ‘Sequestration’, ‘Soil’, ‘Organic’, and ‘Matter’.

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(b)	Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176.	2803
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	Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **2004**, *123*, 1–22.	2137

Table 1. *Cont.*

	Reference	Citations
(c)	Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **2004**, *123*, 1–22.	2137
	Atkinson, C.J.; Fitzgerald, J.D.; Hipps, N.A. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant Soil* **2010**, *337*, 1–18.	1432
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(d)	Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char sequestration in terrestrial ecosystems—A review. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 403-427.	2138
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(e)	Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char sequestration in terrestrial ecosystems—A review. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 403–427.	2138
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(f)	Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176.	2803
	Githinji, L. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agron. Soil Sci.* **2014**, *60*, 457–470.	1894
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	Running, S.W.; Nemani, R.R.; Heinsch, F.A.; Zhao, M.; Reeves, M.; Hashimoto, H. A continuous satellite-derived measure of global terrestrial primary production. *Bioscience* **2004**, *54*, 547–560.	978

3. Literature Review

3.1. Framework

Soils represent an integral facet of the global carbon cycle, serving as the most sizable terrestrial carbon reservoir [18]. They harbor an estimated 1526 PgC of soil organic carbon (SOC) and approximately 940 PgC of soil inorganic carbon [19]. Moreover, a depth of one meter reveals that soil, accommodating 2500 PgC, and vegetation, hosting 620 PgC, jointly hold thrice the amount of carbon as compared to the atmospheric carbon levels, which stand at 880 PgC [19]. This amount of carbon held within soils and vegetation emphasizes the critical role that they play in modulating the global carbon cycle and maintaining the Earth's climatic balance [20]. A critical function of soil is its capacity to act as a carbon sink, storing carbon in the form of organic matter [21]. This organic matter derives from various sources, such as decaying plant and animal materials, microbes, and carbonates [22]. Over time, the organic matter undergoes biochemical transformations, leading to the formation of humus, a stable form of organic matter [23]. This capacity of soil to store carbon not only contributes to soil fertility and health but also significantly mitigates the atmospheric levels of carbon dioxide, a potent greenhouse gas [20]. Meanwhile, soil inorganic carbon primarily consists of carbonates, a significant fraction of the global carbon pool [24]. The formation of soil inorganic carbon, a process known as soil carbonation, involves the reaction of carbon dioxide with basic metal oxides and hydroxides in the soil [25]. This process further contributes to the sequestration of atmospheric carbon dioxide into soils. However, it is important to note that soil carbonation is a slow process and depends on various factors, such as the availability of basic cations, soil moisture, and temperature [26].

In the grand scheme of the global carbon cycle, vegetation also plays an equally pivotal role [27]. Plants, through the process of photosynthesis, absorb carbon dioxide from the atmosphere and convert it into organic compounds, thereby acting as carbon sinks [28]. The death and decomposition of plant materials contribute to the SOC pool [29]. Certain plant species, such as those in mangrove and peatland ecosystems, are known to sequester large amounts of carbon [30]. The total carbon stored within soil and vegetation is vast, dwarfing the quantity present in the atmosphere [31]. This significant difference highlights the potential of soils and vegetation as tools for climate change mitigation, particularly in terms of reducing atmospheric carbon dioxide levels. Implementing land management strategies that enhance carbon sequestration in soils and vegetation, such as reforestation, afforestation, and the promotion of sustainable agricultural practices, can prove instrumental in combating climate change [32].

The reserves of carbon in soil and vegetation underscore their importance in the global carbon cycle (Figure 2). These terrestrial ecosystems serve not only as contributors to global biodiversity and ecosystem functioning, but also as carbon sinks that can help counterbalance the increasing atmospheric carbon dioxide levels, primarily due to anthropogenic activities [32]. Recognizing and harnessing the potential of soils for carbon sequestration can, therefore, be an important strategy for climate change mitigation [33].

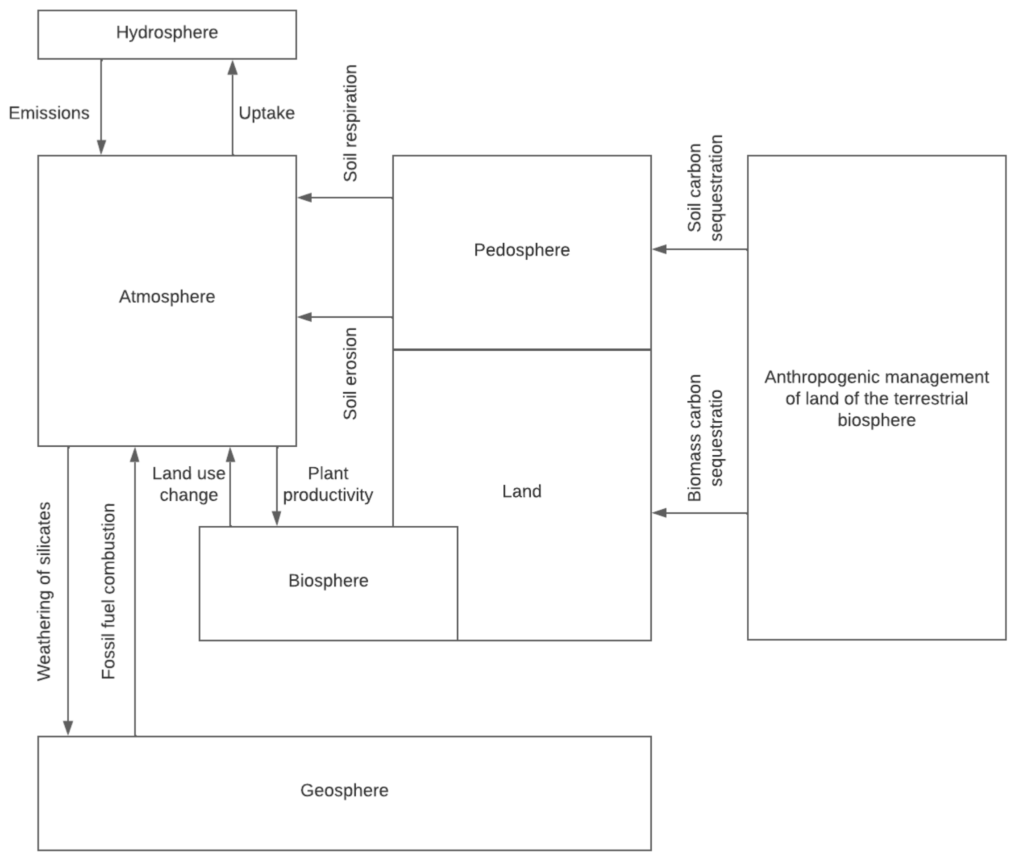

Figure 2. The role of soil and its management in moderating the global carbon cycle (adapted from [19]).

Different types of soils exhibit varying capacities for CO_2 sequestration, largely determined by their physical and chemical properties, as well as the influence of human activities and climate patterns [34]. Loamy soils, a balanced mix of sand, silt, and clay, hold a considerable potential for CO_2 sequestration [35]. Their capacity to store organic matter, owing to their well-structured nature that facilitates good aeration and moisture retention, is relatively high. Loamy soils tend to foster an environment conducive to biological activity, facilitating the decomposition of organic matter, which contributes significantly to carbon storage. Clay soils, due to their fine texture and high mineral content, can store vast amounts of CO_2 [36]. The high cation exchange capacity (CEC) of clay soils makes them effective in storing organic matter, thus promoting carbon sequestration. However, their poor aeration can hinder biological activity, which may limit the decomposition of organic matter, and by extension, the soil's capacity for CO_2 sequestration. Sandy soils typically have lower carbon sequestration potential compared to loamy and clay soils [37]. Their large particle size and low mineral content limit their ability to retain organic matter. The rapid drainage and lower water holding capacity of sandy soils can exacerbate these limitations. However, the incorporation of organic amendments can enhance their carbon storage capabilities. Peat soils, abundant in organic matter, are another vital player in the realm of carbon sequestration [38]. Under suitable conditions, they can act as significant carbon sinks, storing CO_2 for extended periods. However, their carbon sequestration potential can be compromised when they are drained or disturbed, leading to significant CO_2 emissions.

Soil management practices can considerably alter the CO_2 sequestration potential of each soil type [39]. Sustainable practices, such as organic farming, cover cropping, and minimal tillage, can enhance the ability of soils to sequester CO_2, while deleterious practices, such as overgrazing, excessive tillage, or land conversion, can diminish their carbon storage potential [40]. Climate is another determinant of CO_2 sequestration in soils. Warmer climates generally accelerate decomposition rates, reducing the soil's ability to store carbon, while cooler climates tend to slow down decomposition, potentially increasing carbon storage [41].

3.2. Soil Organic Carbon

Although atmospheric CO_2 can be dissolved in soil moisture, these amounts are relatively small, with photosynthesis being the main method of transferring carbon to the soil [42]. In this sense, the rate of carbon accumulation in an ecosystem is mainly due to the ecosystem's net primary productivity, which is equal to the difference between carbon input through photosynthesis and output through respiration [43–45]. The rate of carbon accumulation in an ecosystem diminishes over time owing to a gradual increase in respiration. Elevated concentrations of CO_2 stimulate the influx of carbon into ecosystems, leading to the sequestration of carbon and nitrogen in organic matter and enduring plant biomass [43].

The original levels of carbon in the soil are fundamentally determined by the balance between inputs of organic matter, mainly as plant residues, roots, and root exudates, and outputs (losses) of organic matter, caused by decomposition, respiration, erosion, acidification, leaching, nutrient depletion, changes in structure, and pollution/contamination [10,15,46–49], under the original conditions (i.e., productivity, moisture, and temperature regimes). However, since empirical evidence shows that carbon levels in intensively managed agricultural and pastoral ecosystems can exceed those recorded under original conditions [50], original levels do not necessarily represent an upper limit to carbon reserves. Despite the slow rates of SOC production compared to other fluxes in the carbon cycle, it is its relative stability against microbial decomposition that facilitates its accumulation [51]. However, the potential for carbon sequestration in soils may be much lower than expected, as the more carbon is stored in soils, the greater the decomposition due to biological activity [52]. Additionally, factors such as soil degradation and increased CO_2 emissions from soil respiration can decrease SOC reserves [10,51].

SOC can also decrease dramatically due to some human-induced changes in land, such as the conversion of natural ecosystems to agricultural ones, as this increases the maximum soil temperature and reduces soil moisture storage in the root zone, especially in drained agricultural soils [7,10], affecting the structure and increasing the rate of soil degradation. In this regard, land-use history has a strong impact on SOC reserves [14,53].

Lal [10] points out the main functions of SOC reservoirs, such as being a source and sink of major plant nutrients (e.g., N, P, S, Zn, and Mo), a source of charge density, being responsible for ion exchange, water retention in low moisture potential sites leading to increased available water capacity, being a promoter of soil aggregation, high water infiltration capacity and low losses from surface runoff, substrate for soil biota energy leading to increased soil biodiversity, source of soil aggregate resistance leading to reduced susceptibility to erosion, ensuring high nutrient and water use efficiency due to reduced losses from drainage, evaporation, and volatilization, being a buffer against abrupt fluctuations in soil reaction (pH) due to the application of agricultural amendments, and being a regulator of soil temperature through its effect on soil color and albedo. In addition, [10] also mentions that there are external functions of SOC reservoirs that have economic and environmental importance, namely, reducing sediment load in surface watercourses, filtering pollutants from agricultural chemicals, reactors for biodegradation of contaminants, and protecting greenhouse gas emissions from soil to the atmosphere.

Strategies with multiple benefits for water quality, biomass productivity, and CO_2 emission reduction involve restoring degraded soils and ecosystems [15], maintaining and enhancing soil carbon reserves, optimizing productivity, reducing decomposition rates, and adopting effective agricultural systems for soil erosion conservation and management [5,8,10], such as selecting appropriate varieties or species with greater root mass [42], adopting sustainable agricultural practices, such as intercropping, cover cropping, and crop rotation [49], adopting appropriate uses of soil amendments [54], and using improved pastures or agroforestry by redistributing the soil horizon or eliminating burning [12]. Since proper agricultural management often has a number of other environmental and economic benefits in addition to its potential climate mitigation, strategies to increase soil carbon storage are attractive as part of integrated sustainability policies [13].

3.3. Indicators of Soil Organic Carbon

3.3.1. Climate

Climate conditions, namely annual average temperature and precipitation, influence the amount and vertical distribution of organic carbon in soil as well as its storage, both at global and (sub-) regional scales, affecting both the input of carbon into the soil and the decomposition of organic carbon in soil [48,54–59]. The concentration of organic carbon in soil varies in different regions, as low temperatures and waterlogging inhibit decomposition and mineralization, resulting in the accumulation of organic carbon [60]. Therefore, the concentration of organic carbon in soil is higher in cold and humid regions than in hot and dry regions [10,61]. Precipitation determines the plant primary productivity in many terrestrial environments, and therefore, the input of carbon into the soil [57]. Additionally, wet conditions favor the formation of mineral surfaces stabilizing organic carbon in soil by intensifying weathering of the parent rock [52,62], and often cause soil acidification, leading to reduced organic matter decomposition [59]. Changes in temperature and moisture levels affect microbial and biotic activity, leading to alterations in microbial decomposition of organic matter, as its complex molecular attributes are highly sensitive to temperature [5,44,54,63,64]. Although this relationship is subject to multiple constraints, numerous studies found that an increase in air temperature accelerates organic matter decomposition and tends to increase organic carbon losses [64–66], while lower temperatures limit organic matter decomposition, and consequently, increase organic carbon concentrations [67].

3.3.2. Topography

Topography is a frequently underestimated aspect of our environment that exerts significant influences on various ecological processes [54]. Its three main characteristics—geographic location, altitude, and slope—serve as defining parameters that influence vegetation growth and erosive processes, which in turn profoundly impact soil carbon storage [52,68]. Geographic location is a key determinant in the type and extent of vegetation that an area can support. Different regions are endowed with varying climatic conditions, which can influence the vegetation's composition and density [69]. For instance, lush tropical forests are a characteristic of regions near the equator, while sparse vegetation is the norm in arid areas near the tropics [70]. This vegetation cover, in turn, has an influence on soil carbon storage. Vegetation contributes organic matter to the soil, which, over time, becomes a significant part of the soil's carbon store. Altitude and slope, two other crucial topographical features, also play key roles in shaping vegetation patterns and controlling erosive processes [71]. Higher altitudes tend to have cooler temperatures, which can limit the growth of certain types of vegetation. Similarly, steeper slopes often experience more rapid runoff, leading to higher rates of soil erosion. This erosion not only physically removes soil, but preferentially targets light, low-density particles that are often rich in clay and carbon. Consequently, erosion can result in increased mineralization rates, leading to higher carbon emissions and lesser carbon storage capacity in the soil [72]. Topographical characteristics also control precipitation and water flow dynamics, which are crucial determinants of soil moisture content [73]. Soil moisture regulates not only plant productivity, but also microbial activity and organic carbon release [74]. When the soil's moisture content is either exceedingly high or low, it can limit substrate mobility and oxygen availability, thereby reducing microbial activity. As a result, these conditions favor the accumulation of organic carbon within the soil. It is worth noting the paradox of erosion's effect on carbon sequestration. Although erosion contributes to carbon loss at the site of disturbance, it can also lead to the burial and storage of carbon downstream, thus potentially offsetting emissions to some extent [75]. Topography's influence on vegetation and erosion, and by extension on soil carbon storage, underscores the need to integrate it into our understanding and management of carbon sequestration processes. The interplay between topography, vegetation, erosion, and soil moisture offers myriad pathways for carbon sequestration, each deserving further research to reveal their potential in mitigating the escalating threat of climate change [76].

3.3.3. Origin of the Material

The intricate relationship between parent material and its potential influence on soil attributes such as mineralogy, texture, and fertility is a topic of significant interest in the realm of soil science. Parent material is undeniably linked to the inherent properties of soil, which have a pivotal role in shaping plant productivity and the stabilization of organic matter [45,58,77]. Therefore, understanding this association is critical in our quest to foster sustainable agricultural practices and mitigate climate change. Parent material is responsible for defining the mineralogical composition of the soil [78]. Different minerals have varying abilities to adsorb and retain nutrients, which consequently affect the nutrient availability for plants. For instance, soils rich in clay minerals, often derived from basaltic parent materials, tend to have high nutrient retention capacities [79]. This directly influences the productivity of the ecosystem, with nutrient-rich soils generally fostering higher plant production levels. Parent material significantly contributes to the soil's texture—a critical determinant of water holding capacity, aeration, root penetration, and the soil's propensity to erosion [80]. Sandy soils, usually originating from granitic or sandstone parent materials, tend to drain quickly and hold less water, potentially limiting plant productivity [81]. Conversely, clayey soils, derived from parent materials such as shale or basalt, retain water effectively but may pose challenges to root penetration due to their compact nature [82]. The fertility of soil, an aggregate measure of its capacity to support plant growth, is greatly influenced by the parent material [83]. Fertility typically encompasses aspects such as the soil's nutrient content, pH, and organic matter—parameters that are all intrinsically tied to the type of parent material [84]. As an example, limestone-derived soils often exhibit near-neutral pH values, which tend to favor nutrient availability and microbial activities, promoting overall soil fertility [85,86]. Despite these correlations, the connection between parent material and SOC storage is more complex and less direct. SOC storage is a key component in the global carbon cycle and is instrumental in carbon sequestration and mitigating greenhouse gas emissions [87]. Soil type, which is closely tied to parent material, is known to associate with SOC storage [88]. For instance, peat soils, usually developed from organic parent materials, can store considerable amounts of carbon. However, the extent of SOC storage is also influenced by factors such as climate, land use, vegetation type, and management practices, which can override the influence of the parent material. Despite a soil's inherent capacity to store carbon due to its parent material, poor land management or inappropriate use can lead to significant carbon losses [89].

3.3.4. Organisms

Natural Vegetation

The intricacy of SOC stocks and their dynamics is an increasingly recognized aspect of environmental studies. Encompassing a multitude of variables, these stocks are found to be heavily influenced by factors such as vegetation, land use, and climatic conditions, particularly on a sub-regional scale where the climate is more uniform [14]. Unveiling the critical relationship between these elements and SOC stocks allows us to better understand their role in carbon sequestration and climate change mitigation. Across the globe, in various climate zones, it is notable that SOC stocks display distinct characteristics. These are found at diverse depths and among different plant functional types, such as shrubs, grasslands, or forests, among others [58,64,68]. This diversity is attributed to the differing carbon allocation patterns that these types of vegetation present. For instance, the more profound the soil profile, the more likely it is that the stored SOC is older [90]. This observation aligns with findings from multiple studies revealing higher carbon stocks situated nearer the soil surface, which then decrease with depth [16,68,91,92]. The type of tree species present also significantly influences ecosystem carbon storage. Shallow-rooted conifer species, for example, tend to accumulate less organic matter in forest soil compared to deciduous trees, but they also have a lower rate of litter transformation [48]. This highlights the different contributions each species can make to the carbon cycle, affecting both the accumulation and decomposition of organic matter. In further delving into the effect of vegetation on SOC stocks, it becomes apparent that it not only affects carbon input, but also impacts decomposition rates [57]. As an intricate network of life, the rhizosphere hosts an abundance of micro and macro-organisms. This biodiversity creates a dynamic environment where organic matter is both contributed to and broken down, directly impacting the levels of SOC. The rhizosphere's vitality, therefore, cements its importance as a significant factor in SOC sequestration [54].

Land Use and Management

The rapid changes in land use across the globe play a crucial role in alterations to SOC levels, thus becoming a significant determinant of SOC storage potential [60]. As land-use patterns shift, there are consequential fluctuations in the concentrations of organic carbon stored within soil strata, with significant implications for the environment and agricultural productivity. A major factor contributing to the depletion of SOC (SOC) stocks is the intensification of soil cultivation. Numerous studies pointed out that cultivated soils often experience losses in SOC for a variety of reasons, with key factors being erosion, reduced carbon inputs into the soil, and breakdown of organic matter stabilization. Erosion, driven by the aggressive tilling and plowing practices common in intensive farming, results in the loss of topsoil rich in organic carbon. This phenomenon accelerates the depletion of SOC stocks, disrupts the carbon cycle, and negatively impacts soil fertility. Additionally, reduced carbon inputs in croplands, primarily due to a decrease in the return of crop residues and organic manure, can also lead to a decline in SOC levels. When carbon inputs are low, the rate at which organic carbon is replaced in the soil fails to compensate for the carbon losses through erosion, respiration, and leaching. Another contributing factor is the breakdown of organic matter stabilization. As tillage operations disaggregate soil particles, the physical protection of organic matter decreases, making it more susceptible to decomposition. This destabilization process is further exacerbated by increased temperatures and soil aeration often seen in cultivated lands [93,94]. These conditions promote mineralization, a biochemical process that converts organic carbon into inorganic forms, thereby leading to a net loss of SOC from the soil profile. However, it is important to note that not all changes in land use result in the diminution of SOC. Land-use extensification, namely the transformation of croplands into grasslands or forests, often leads to an increase in SOC levels [14,54,93,95]. This transition facilitates greater accumulation and stabilization of organic carbon in the soil. Grasslands and forests typically contribute more substantial organic matter, which is attributed to their high biomass production and slower decomposition rates of organic material. These ecosystems also provide protection against erosion and enhance soil structure stability, thus further promoting SOC storage. Consequently, through these mechanisms, the intensification of land use can significantly contribute to the enrichment of SOC in the soil and augment its storage potential.

Soil Biota

Soil microorganisms, particularly heterotrophs, play an integral role in the cycling and transformation of organic matter within the soil ecosystem. This function is critical for the preservation of soil health and fertility, as it contributes to the nutrient cycling processes that ensure the viability of plant and animal life. Heterotrophic soil microorganisms, including bacteria, fungi, and protozoa, engage in the decomposition of organic matter to fulfill their nutritional and energy needs. They actively metabolize organic substrates, producing by-products that are integral to the formation of soil organic matter. Specifically, microbial residues and exudates, which can make up to 80% of the carbon in the stable parts of soil organic matter, significantly contribute to this process. This aspect highlights the dual functionality of soil microbial biomass in the turnover of organic matter. The microbial role delicately balances two crucial processes: the mineralization and stabilization of organic matter [57]. During mineralization, microbes transform organic matter into inorganic nutrients, a process that releases nutrients such as nitrogen and phosphorus into the soil. Concurrently, the stabilization of organic matter involves the transformation of decomposed organic materials into humus, a stable, long-lasting form of organic matter that serves as a reservoir for nutrients and water. Soil microorganisms do not exist in isolation but form a complex network of interactions with other soil components, including the soil fauna. These interactions can significantly influence various soil properties and processes, such as aeration, porosity, infiltration, and aggregate stability. They also contribute to the stabilization of nitrogen and carbon, carbon turnover, reduction in carbonate, nitrogen mineralization, nutrient availability, and metal mobility. The influence of these microbial processes extends beyond nutrient cycling. By improving soil structure and fertility, they enhance the soil's capacity to sequester carbon, thereby mitigating the effects of greenhouse gas emissions. Moreover, these microbial activities are essential to maintaining soil biodiversity, a crucial aspect of ecosystem resilience. In this complex and intricate ecosystem, organic matter can follow two paths. It can be assimilated into the soil profile, becoming readily available to soil microorganisms for decomposition. Alternatively, it can be protected from mineralization by forming associations with soil particles to create humic-clay complexes [44,57]. These complexes are a major component of stable soil organic matter, contributing to soil fertility and carbon storage capacity.

3.3.5. Soil Properties

Soil Types

The process of carbon stabilization diverges from that of accumulation. Factors such as excessive soil moisture or lower temperatures, which restrict soil respiration, predominantly drive accumulation. To enhance the reserves of stable soil carbon, pinpointing locations with soil characteristics favorable for carbon sequestration is imperative [48]. There is a consensus regarding the relationship between soil type and SOC storage at multiple scales and under different climatic conditions. During pedogenesis, weathering chemical reactions leads to changes in soil mineralogy composition that strongly influence mineral surface area reactivity and carbon storage [96–98], and the resulting characteristics are categorically described by soil types. In contrast to climate, vegetation, and parent material, which can serve as indicators for SOC storage at larger scales, carbon stocks can be stratified according to soil type even at smaller scales (local to sub-regional) [57]. Many studies reveal a predominant influence of soil type on SOC reservoirs, both at the surface and in the subsoil [52,68,91,92,99]. However, soil type is not an independent controlling factor, but integrates a set of factors such as climate, parent material, and topography related to properties that directly affect soil potential for carbon storage, particularly soil moisture regime and texture. If soil property information such as texture and moisture is not available, soil type can be an adequate indicator for SOC storage, integrating a wide range of decisive factors [57].

Soil Aggregation

Regarding aggregation agents, particularly the carbon source, whether organic or inorganic, significantly influences their composition and the concentration of soil aggregates. This, in turn, affects the efficiency of the soil's cation exchange capacity and the aggregation of its particles. The composition of SOC mirrors the rate of cation decomposition and release, and also reflects the capability of the soil's cation complexes. It is directly associated with soil heterogeneity and the enhancement of soil aggregation. Conversely, inorganic carbon in the soil consists of primary and secondary minerals. Primary, or lithogenic, carbonates originate from the parent rock, while secondary carbonates form from primary ones when they dissolve and are transported by water (H_2O), along with organic acids and/or CO_2, from the soil and the atmosphere [54]. Pertaining to the makeup of SOC, it is important to recognize that its chemical properties govern its ability to hold and complex various substances and shape the decomposition rates that directly impact soil aggregation [100]. Processes that affect soil aggregation also affect carbon sequestration capacity [48]. For example, cultivation causes a release of carbon by breaking down aggregated structures, thus increasing the availability of carbon [50].

Clay Content

Clay minerals influence properties that affect aggregation, such as specific surface area (SSA), charge density, dispersibility, and expansibility, which in turn affect rates of SOC decomposition [100,101]. The interaction of clay, SOC, and aggregates is affected by soil pH, cation exchange capacity, and ions (Na^+, Ca^{2+}, and Mg^{2+}), all of which are related to the amount and type of clay present in the soil [77,98,101]. Among the main mechanisms of organic matter stabilization, the interaction of organic matter with mineral surfaces is considered quantitatively more important in a wide range of soils [44,54], indicated by a strong correlation of SOC stocks with clay contents observed in numerous studies at different spatial scales [77,101–103]. Fine-textured soils have higher SOC concentrations than coarse-textured soils when other characteristics are similar [101]. In this sense, soil texture is likely one of the most promising factors to be used as an indicator of SOC storage.

Specific Surface Area

Soil plays an indispensable role in our planetary ecosystem, as one of its often-overlooked aspects is its ability to sequester organic carbon. This process is crucial to the global carbon cycle, and by extension, climate change mitigation. The relationship between soil properties, particularly the SSA, and the capacity to retain organic carbon is an intriguing area requiring detailed study. SSA, the total exterior and interior surface area of soil particles per unit mass or volume, is critical to the soil's ability to adsorb humic substances. Soils with high SSA are typically composed of fine particles such as clay and silt, providing extensive surfaces for organic matter adherence, thereby effectively capturing and storing organic carbon. Consequently, it is reasonable to conclude that soils with a high SSA, due to their superior adsorptive properties, will secure more humic substances compared to those with lower SSAs [77]. Consequently, the soil's capacity to retain organic carbon is likely limited by the available surface area for adsorption. Put simply, the greater the surface area available, the larger the soil's ability to sequester carbon. This has profound implications not only for understanding the mechanisms governing soil carbon storage, but also for guiding land use practices and soil management techniques aimed at enhancing carbon sequestration. However, while a high SSA is beneficial for carbon storage, it is not the sole factor influencing the soil's ability to retain organic carbon. Soil texture, structure, mineral composition, as well as climatic and biological factors, also play roles in carbon storage. A comprehensive understanding of these varied elements is therefore critical for advancing our knowledge of soil carbon dynamics. The impact of human activities on these natural carbon sinks is substantial. Deforestation, intensive agriculture, and land misuse are just a few examples of actions that can degrade soils, decrease their SSA, and thereby reduce their capacity to sequester carbon [57]. Conversely, sustainable land management practices, such as cover cropping, conservation tillage, and reforestation, can help increase soil SSA and enhance its carbon storage potential.

3.4. Organic Matter

The soil organic matter is the key component for any terrestrial ecosystem, and any variation in its concentration and composition has important effects on many of the processes occurring within the system [104]. Plants primarily fix atmospheric CO_2 to form organic compounds through photosynthesis. The degradation of soil organic matter returns carbon to the atmosphere in the form of CO_2 or CH_4, resulting from the metabolism of aerobic and anaerobic microorganisms. The stability of soil organic matter is not only influenced by the physical and chemical environment (mainly soil moisture, temperature, pH, and aeration), but also by the chemical composition of soil organic matter itself and its susceptibility to decomposition, as well as its accessibility to microbial attack and exoenzymes [105]. More than two-thirds of the stored organic carbon in terrestrial ecosystems are contained in soil organic matter [44,46,49,90], and therefore, can have a significant influence on the global carbon balance [55]. Soil organic matter has important chemical, physical, and biological functions in the soil [101], and is composed of a mixture of materials that includes organic particles and charcoal, along with live microbial biomass and fine plant roots [90,106], existing in a state of dynamic equilibrium between inputs and outputs of carbon [107]. The soil organic matter content depends on the balance of rates of input and decomposition of soil organic matter [56], with decomposition being directly influenced by the soil's physical and chemical properties, as well as climatic and management factors [65]. The amount, quality, and timing of organic matter input into the soil significantly vary, and are largely contingent on the type of soil. For instance, sandy soils may contain less than 5% organic matter, while in contrast, wetland soils can contain nearly 100% organic matter [15]. These previously referred interactions can be complex and vary over time [90]. During soil organic matter decomposition, these variations may influence analytical processes, making studies on soil organic matter composition and its implications for the global biogeochemical carbon cycle very challenging [7]. Soil organic matter plays a fundamental role in influencing many of the soil characteristics and processes that are important for its functioning [53], namely, in building and maintaining soil fertility, affecting the physical, chemical, and biological properties of the soil [106]. The increase in soil organic matter in the soil leads to increased water availability [51]. The natural renewal of soil organic matter depends on the chemical quality of carbon compounds, climatic and topographic conditions, organisms, and soil properties (such as clay, moisture, pH, and nutrients) [48,101].

3.5. Methods for Assessing CO_2 Sequestration in Soil

The assessment of CO_2 sequestration in soil is fundamental to our understanding of the planet's carbon cycle and the potential strategies to mitigate climate change. Various methods were developed to assess this important phenomenon, each with its unique prospects and inherent challenges. Two primary methods for assessing soil CO_2 sequestration include direct measurement and modelling [108,109]. Direct measurement techniques involve soil sampling and laboratory analysis, while modelling uses mathematical equations to predict carbon levels based on various parameters [110,111].

Direct measurement offers the most tangible evidence of CO_2 sequestration in soil. This method often involves sampling soil from different depths, then quantifying the carbon content in a laboratory setting. The standard approach, known as dry combustion, involves oxidizing the soil in a furnace and measuring the CO_2 produced [112–114]. While this method provides accurate results, it is labor-intensive, costly, and does not provide continuous data, instead presenting a snapshot of a dynamic process. Spatial variability is a significant challenge, as samples taken from two different parts of the same field may yield different results [115]. An alternative to direct measurement is the use of stable isotopes, particularly carbon-13 [116]. These techniques can provide more detailed information about the sources and turnover rates of SOC. However, isotopic methods can be complex and require specialized equipment and expertise.

The advent of new technologies, such as remote sensing and spectroscopic techniques, offer promising opportunities for assessing CO_2 sequestration in soil [117]. These methods provide the ability to continuously monitor large areas with high resolution, presenting a big leap from the traditional soil sampling techniques. However, they also come with their own challenges. The interpretation of remote sensing data can be complex, requiring advanced computational models [118]. These methods can be expensive, and data can be influenced by factors such as soil moisture and surface roughness. Modelling methods, on the other hand, use mathematical equations to estimate soil CO_2 sequestration based on parameters such as soil type, climate, and land use. Models can provide continuous data and predict future trends, but they also have limitations. The accuracy of the models is highly dependent on the quality of the input data, and models may not capture the full complexity of soil processes [119]. The models need to be validated with direct measurements, and this fact again brings the issue of sample representativeness.

4. Carbon Sequestration and Climate Change

Climate change caused by greenhouse gas emissions is the greatest threat to humankind and is altering life on Earth [120]. Approximately 8.7 Gt of carbon is emitted into the atmosphere every year globally by anthropogenic sources [15,90]. However, the atmospheric increase is around 3.8 Gt of carbon per year, highlighting the important regulatory capacity of carbon reservoirs [90]. Within this scope, the scientific literature extensively debates the capacity of SOC to act as a sink for atmospheric CO_2. This is given the increasing apprehension about the potential impacts of climate change on soil processes. This concern is coupled with an aspiration to devise strategies that enhance carbon sequestration, encourage empirical research, and formulate theoretical models [10,14,15,95,121]. In this sense, soils have enormous potential to mitigate climate changes through the sequestration of SOC [122], with soil carbon reserves at depths greater than 1 m (~1600 Gt) estimated to be twice that of atmospheric carbon (~800 Gt) [19,104,123].

At the ecosystem level, soil influences vegetation through water availability, biogeochemical cycles, and soil temperature regimes [124]. Changes in soil moisture and temperature regimes can affect species in the ecosystem, and these changes affect SOC reserves and physical properties, which are caused by changes in biomass [10]. Rising soil temperatures are likely to accelerate mineralization rates, which could deplete SOC reserves. This decrease in SOC can negatively affect soil structure, potentially increasing its erodibility and susceptibility to issues such as crust formation, compaction, surface runoff, and erosion [10].

Small increases in SOC, which involve the removal of atmospheric CO_2 by plants and the storage of fixed carbon as soil organic matter [10], could minimize the annual increase in CO_2 in the atmosphere and mitigate the greenhouse effect and climate changes [125,126]. Moreover, maintaining and increasing SOC reserves is not only essential for reducing GHGs emissions, but also for ensuring soil health, fertility, and agricultural production [125]. However, climate change factors such as temperature, precipitation, atmospheric CO_2 levels, and drought periods strongly influence all biotic and abiotic processes involved in soil carbon transformations, which can destabilize SOC reserves [10,19,122].

Assuming that we can boost the soil's carbon sequestration ability through sustainable soil and crop management, soil carbon reserves become a viable strategy to both adapt to and mitigate climate change [19]. This can be achieved by increasing the SOC content, enhancing the depth distribution of SOC, and stabilizing SOC. The latter can be achieved by encapsulating the carbon in stable clay-humic complexes to shield it from microbial processes, or by converting it into recalcitrant carbon with a lengthy renewal period [10]. The resulting improvement in soil quality and functionality in agroecosystems can contribute to the United Nations' Agenda 2030 and several interrelated sustainable development goals [127]. In this context, managing agroecosystems and land-use changes are an important strategy for terrestrial organic carbon sequestration [95].

Soil carbon sequestration can be achieved by enhancing the net transfer of carbon from the atmosphere to the terrestrial biosphere. This can be achieved by increasing global carbon contributions to soils through heightened levels of primary productivity, retaining a larger percentage of carbon at these productivity levels, or reducing soil carbon losses by slowing the decomposition process [128]. Soil carbon sequestration strategies depend on the development of new technologies and soil quality improvement, which also have positive effects on soil physical properties and therefore improve soil resilience to climate stress, contributing to adaptation to climate changes and ecosystem services [16,129]. However, there are limitations to soil's capacity to sequester carbon; specifically, the ability to accumulate organic carbon is finite, so when carbon reaches its equilibrium value, soil no longer can increase the amount of carbon [129]. Increases in SOC are not permanent, and the benefits related to climate change hinge on the indefinite continuation of newly implemented sustainable management practices [130]. To provide long-term climate changes mitigation, the additional SOC must be in recalcitrant forms [129]. The largest amounts of SOC sequestration are achieved through the conversion of productive agricultural lands back to their original state (pastures or forests) [128], but this change in land-use conflicts with food needs and is also challenging due to soil variability and slow conversion rates [129]. The growing impacts of climate change highlight the pressing need for efficient mitigation strategies. Regions marked by their distinct biodiversity and weather patterns are becoming increasingly susceptible to the effects of climate change, such as heatwaves and droughts. Soil, which serves as an important repository for carbon, plays a vital role in climate change mitigation in these areas. By implementing practices that increase SOC, soil can concurrently strengthen these regions' resilience and decrease greenhouse gas emissions.

5. Conclusions

The role of soil as a pivotal agent in mitigating climate change cannot be emphasized enough. Representing the largest terrestrial carbon reservoir, SOC is a significant factor. Enhancing soil carbon reserves could have multifaceted benefits, including the reduction in greenhouse gas emissions, improvement in soil health and fertility, and the betterment of agricultural production. To increase SOC content, strategies such as the incorporation of organic matter, crop rotation, and the use of cover crops could be employed. However, it is important to note that the soil's capacity to sequester carbon is not infinite, and the benefits of mitigating climate change depend on the consistent application of sustainable management practices. The potential impacts of climate changes on soil processes, coupled with the need for innovative technologies and improvements in soil quality, are critical elements in achieving effective soil carbon sequestration. Changes in land use, along with the application of sustainable management practices, form the cornerstone strategies for terrestrial organic carbon sequestration. Consequently, the commitment to developing novel and differentiated approaches, strengthening collaborations, and pioneering new technologies should be unwavering in our pursuit to augment carbon reserves in the soil. This is essential to fulfill the United Nations' Agenda 2030 and several interconnected sustainable development goals.

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