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REVIEW ARTICLE

A review of climate change mitigation and agriculture sustainability through soil carbon sequestration

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Abstract

As a result of human activities such as burning fossil fuels, organic materials, and engaging in unsustainable land practices, atmospheric carbon dioxide (CO_2) levels have been steadily rising, heightening worldwide concerns about climate change. It is expected concentrations to grow and changes in CO_2 sequestration in agricultural soils as a result of the industrial revolution's acceleration of CO_2 emissions. These emissions have been intensified by changes in land use, such as cutting down trees, burning biomass, altering farming operations, draining natural wetlands, and using the wrong methods for managing soil. The present study utilized the systematic literature review method to investigate soil carbon sequestration options as a possible means of reducing the impact of climate change and improving agriculture sustainability. As a result of soil degradation and poor management, soil organic carbon (SOC) levels have decreased, which in turn has increased atmospheric CO_2 levels. But cutting-edge land application and modern agricultural management methods have the ability to reduce CO_2 emissions. Several methods exist for replenishing depleted SOC, such as repurposing marginal lands for restoration purposes, advocating for reduced or zero-tillage methods in conjunction with cover as well as residue crops, and introducing nutrient cycling through composting, manure usage, and other environmentally friendly approaches to managing soil and water. One holistic approach to fighting climate change is long-term soil carbon sequestration. Soil carbon sequestration offers a comprehensive and efficient strategy for reducing the impact of climate change by recharging depleted soils, increasing biomass production, cleaning surface and underground water sources, and compensating for CO_2 emissions through fossil fuels. Soil carbon sequestration presents an exciting opportunity for management of the problems caused by contemporary changes in the environment, and the adoption of these novel approaches is essential for meeting these issues.

Keywords: Agriculture; Environment; Climate change: Mitigation; Carbon sequestration; Sustainability

Introduction

One of the most important ways to lower CO_2 levels in the air is through soil carbon sequestration, which is basically just putting carbon into the ground (Ali et al., 2022; Don et al., 2024). In order to reduce the overall rate of emissions into the atmosphere, this process incorporates elements from the ocean, petrology, biology, and geology.

Carbon sequestration can be aided by both natural and human-caused processes; the latter seeks to keep the world's carbon budget under check so that there are no net releases of carbon in the future (Saarikoski et al., 2023). Converting marginal areas to recover depleted soil carbon reserves is one promising method (Csikós & Tóth, 2023). Significant steps can be taken to reduce the impact of climate change by implementing conservation agriculture practices such as cover cropping, protecting crop residues, recycling nutrients, using compost, and efficiently managing water, energy, and nutrients used in agriculture (Francaviglia et al., 2023). These methods lessen the production of GHGs and encourage the growth of sustainable farming systems that can withstand the effects of climate change (Balasundram et al., 2023). Increased soil fertility, productivity, quality, biodiversity, and less compaction are just a few of the many advantages of soil carbon sequestration (Rodrigues et al., 2023). Soil management techniques that promote plant growth and microbial activity, such as cover cropping, crop rotation, no-tillage, and organic matter absorption, can increase soil carbon sequestration (Singh et al., 2024). The breakdown of stable carbon is the end result of these activities, which keep it out of the air. Several studies highlight the possibility of SOC sequestration to lessen the impact of contemporary agriculture on climate change by lowering GHG emissions (You et al., 2024). Offsetting about 10% of yearly GHG emissions, soil carbon sequestration might store large amounts of carbon for long periods (Paul et al., 2023). Climate, soil type, and management practices are just a few of the variables that affect how well the plan works, so it's important to choose methods that are specific to the area.

In the last hundred years, climate change—defined as the long-term shifts in Earth's average temperature, precipitation, as well as weather patterns—has received a lot of attention (Subramanian et al., 2023; Raihan & Bari, 2024). Most of the acceleration is due to human actions, such as burning fossil fuels, rapid industrialization, and deforestation (Nunes, 2023; Ahmad et al., 2024). Overproduction of greenhouse gases (GHGs), most notably CO_2, causes the planet's surface to warm because it traps more heat (Petrov et al., 2023; Ridwan et al., 2023). These changes are worsened by extreme weather events, which affect soil temperature and moisture, species distribution and composition in ecosystems, and, most significantly, soil vegetation (Furtak & Wolińska, 2023; Akter et al., 2023). Human health, ecosystems, food security, along with global poverty are all gravely threatened by the modern agricultural practices that have hastened the warming trend (Fenner & Cernev, 2021).

Deforestation, changes in land use, excessive fertilizer usage, and the burning of fossil fuels are some of the key anthropogenic actions that are causing climate change (Raihan & Tuspekova, 2022a; 2022b; 2023a). Consequently, one practical way to lessen the effect of contemporary farming on the environment is soil carbon sequestration (Tan & Kuebbing, 2023). Soil amendments, root exudation, biochar, and leaf litter all increase carbon inputs, which can be absorbed by plants and used as a buffer against soil carbon changes (Pandao et al., 2023). There is tremendous potential for soil to reduce carbon emissions because it contains around 2500 Pg of carbon worldwide and is 3.3 times larger than the pool of carbon in the atmosphere (Wang et al., 2024). It is possible to cut soil carbon emissions in half from 2010 levels by 2050 if the right mitigation strategies are put in place (Marvin et al., 2023). The objectives of this review study is to examine soil carbon sequestration's potential in light of current agricultural challenges; evaluate the ways in which modern agriculture has altered SOC sequestration and its broader implications; and determine how soil carbon sequestration contributes to the fight against climate change.

Methodology

This study delve into the relationship between soil carbon management and climate change challenges in agriculture sustainability. The current study utilized the systematic literature review process as recommended by Raihan and Bijoy (2023). The systematic literature review framework is widely regarded as a reliable and trustworthy approach (Raihan, 2023a; 2023b; 2023c; 2023d; 2023e; 2023f; 2023g; 2023h; 2023i; 2024a; 2024b). As can be seen in Figure 1, the review adhered to the tenets of the systematic review methodology. This helped to reveal how crucial soil carbon sequestration is to achieve environmental and agricultural sustainability beside reducing the negative consequences of global warming and climate change through mitigation activities. By deconstructing the research questions into their component concepts, the study developed a set of keywords that allowed to conduct a thorough and representative search of the literature on the topic of soil carbon and its relation to climate change mitigation and agriculture sustainability. Database classification terms have also been taken into account, along with synonyms, single and plural models, broader terms, alternative spellings, and more specific terms. The selected keywords used for searching documents for the review analysis are soil carbon, carbon sequestration, carbon emission, agricultural practices, tillage, cropping system, lobal warming, climate change, mitigation, modern agriculture, crop management, and sustainability.

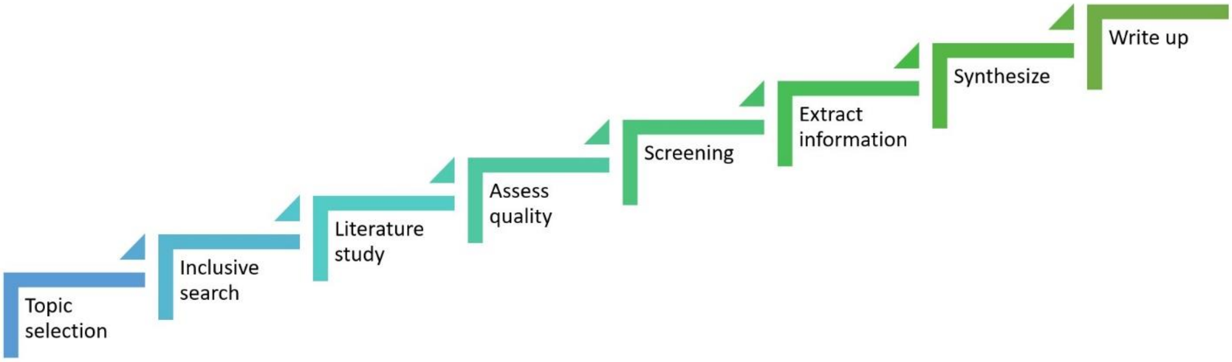

Figure 1. The procedure of systematic review conducted by the study.

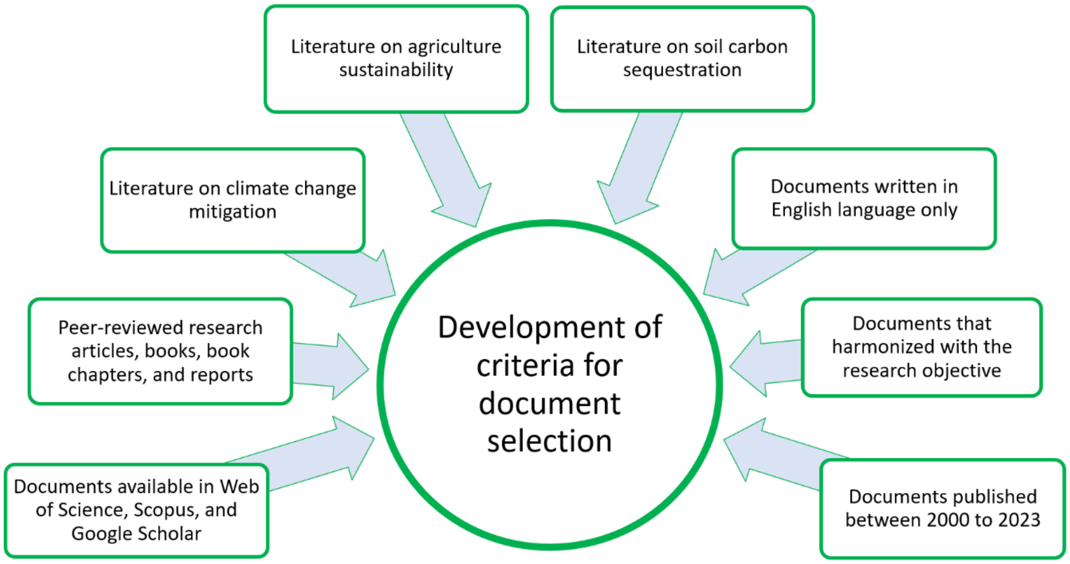

Figure 2. The development of criteria for document selection.

The initial search with the keywords led to 5398 documents. After scanning the documents based on the selection criteria and to remove possible duplication, 453 articles were selected for the next step of scanning.

After screening those article's title and abstract, the comprehensive literature review encompassed a total of 129 distinct scholarly articles published between 1990 and 2023 were chosen for further analysis. The papers came from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS).

Figure 2 depicts the evolution of review criteria used to choose appropriate documents for analysis. This investigation solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future agricultural research and management taking into account soil carbon sequestration, climate change mitigation, and environmental sustainability. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation.

Although a specific instrument for quality assessment was not used, the review ensured that the evidence extracted from the research papers (that met the inclusion criteria) was relevant and accurate by evaluating the research methodology and questions, sources of information, and the selection of the evaluation criteria. The quality of the studies was assessed based on several criteria, including the extent to which the research objectives were achieved through the study design, the accuracy of measuring the study variables, the appropriate use of statistics, the effectiveness of the intervention, the presence of generalizations, and any conflicts of interest among the authors. Nevertheless, it was crucial to consider the amount of time and effort invested in the search process in relation to the possible advantages of discovering all pertinent studies.

Contemporary Agriculture

Tillage and SOC

The ability of tillage management to significantly increase soil carbon absorption has garnered a lot of interest in agricultural practices (Bogale et al., 2023). Farmers commonly burn crop wastes, which contributes to air pollution. However, these residues can be managed to store carbon in the soil profile. Conservation of soil moisture through covering 30% of soil surface with crop stubble and leaf litter is one agricultural strategy that helps decrease wind and water erosion (Xiao et al., 2023). The nutrient composition of crop residues, the instruments used for tillage, and the specific tillage procedure all affect how much residue stays on the soil surface. To improve carbon sequestration, plant pulses and other leguminous crops as part of your crop rotation. Pulses absorb nitrogen and carbon and store them in the soil's deeper layers. Conventional tillage, residue burning, and over-input farming have all contributed to degraded soil health and lower crop yields in the past. Even with carefully chosen crop species and the necessary amounts of fertilizer and pesticide, crop failure can occur due to these antiquated practices, which impact the physical qualities of the soil and impede biodegradation (Khangura et al., 2023).

Conservation tillage, if widely used on croplands, has the potential to greatly enhance carbon sequestration (Thapa et al., 2023). SOC sequestration was found to be considerably affected by tillage systems in the surface layer (0-5 cm) of a Bhopal study by Hati et al. (2020). After three crop cycles, no-tillage and limited tillage had greater SOC levels than conventional tillage. Additional aid in preserving SOC came from combining residue retention with reduced tillage operations. While traditional tillage may boost output in the near term, it has the potential to deplete soil microorganisms, disrupt biogeochemical cycles, and exhaust mineral elements if used for too long.

Soils that have been farmed for a century or more have had their carbon levels lowered by 30–50% due to conventional agricultural cropping methods and intense tillage (Francaviglia et al., 2023). An essential component for long-term sustainability and productivity, soil organic matter (SOM) is intimately related to soil fertility. Hot zone soils can benefit from lower tillage methods and residue retention when it comes to SOC sequestration. These technologies can help reduce the impact of traditional soil agriculture on climate change and global warming by sequestering atmospheric CO_2 in the soil. Some have proposed reintroducing 500 Pg of carbon to Earth's ecosystem. The merits of SOC sequestration have been well-documented and generally acknowledged by scientists. Because reduced tillage approaches store more SOC than conventional tillage, they are incorporated into the first principle. Soil productivity can be reduced by using older tools, such as chisel plows and moldboard plows, which disturb the soil structure more than current tools (Mumah et al., 2023). How much carbon is sequestered by soil under various methods is proportional to the depth of tillage. As an example, SOC rose by 40% when no tillage was used for 20 years instead of reduced tillage (Waring et al., 2023).

In far too many research, the main reason soil carbon is being lost and moved from the higher slopes of farmed highland landscapes is due to tillage-induced soil erosion. Soil carbon stability is affected by the tillage system chosen; conventional tillage increases carbon storage, while decreased tillage increases it. Because reduced tillage is a reversible method of soil carbon sequestration, a transient shift in tillage practices would not lead to an obvious uptick in SOC accumulation right away. SOC sequestration and restoration are both negatively impacted by intensive tillage methods, which weaken the soil structure and release C pools into the atmosphere. Soil plowing, however, may have less of an exhausting impact on total SOC content if done once in a long-term cultivation utilizing shallow tillage procedures. In these situations, it is expected that a single shallow plowing will raise SOC because of increased inputs of carbon from crop residues, leading to an increase in crop production. Because undisturbed soils differ from tillage soils in terms of soil microbiology, fauna, and biochemical processes, changes in tillage methods can have an impact on carbon sequestration in both types of soils. Numerous international meta-analyses have shown that no-till farming increases carbon sequestration (Lockhart et al., 2023). To a given depth in the soil, the tillage system has a major impact on the dispersion of carbon. There is some evidence that tillage techniques have no detrimental effect on soil carbon in the upper 40 cm of the soil (Zhang et al., 2023).

Fertilizer impact on SOC

One known way to learn about the impacts of continual fertilizer and manure treatment on soil fertility along with ecological dynamics is to use fertilizers in soil for a long time. Applying the prescribed amount of fertilizer increased SOC concentrations from 7.9 to 10.5 g per kg, but using too much fertilizer can have detrimental effects (Yin et al., 2023). Incorporating fertilizer into soil can disrupt nutrient cycle, giving native microbial species a foothold to thrive even in stressful conditions and perhaps increasing SOC and microbial biomass. The saturation of organic carbon is increased by nitrogen fertilizer (Zuo et al., 2023). In addition, many soils have the potential to retain carbon as organic matter and become carbon-absorbing reservoirs after implementing conservation agriculture practices. Research in grasslands has shown that nitrogen enrichment does not affect soil carbon sequestration much, but in temperate, tropical, subtropical, and boreal forests, it actually accelerates sequestration (Ngaba et al., 2023). N enrichment also reduces litter decomposition in N-rich settings but has little effect in N-limited ones. Nitrogen addition typically has an effect on litter quality, speeds up the breakdown of labile C, and slows down the decomposition of resistant C in soil. Due to the diverse range of ecosystems and settings studied in N-enrichment research, it is not feasible to generalize the results of a single experiment to the entire world. Nitrogen deposition in the atmosphere has increased three- to fivefold throughout the last century due to the combustion of fossil fuels and the usage of inorganic chemical fertilizers (Raihan & Said, 2022; Pereira et al., 2023). An increasing amount of nitrogen is expected to be deposited on land, with a substantial fraction of this nitrogen being stored in ecosystems around the world. Plants can't develop without nitrogen, and while low amounts can reduce plant biomass, higher levels are thought to increase ecosystems' carbon pools

(Khan et al., 2023a). Additional research is needed to clarify the impact of nitrogen additions on soil carbon sequestration. As a natural reservoir for carbon and a source of CO_2 emissions, soils store approximately twice as much carbon as the atmosphere (Rodrigues et al., 2023). Soil carbon reactions to nitrogen additions may, therefore, have a significant impact on the trajectory of atmospheric CO_2 levels going forward (Jaafar et al., 2020; Begum et al., 2020; Jubair et al., 2023).

Mycorrhizal fungi, cover crops, mulching, farmyard manure, root exudates, plant litter, and roots are the main sources of soil C inputs. Concurrently, nutrient leaching, soil erosion, CO_2 emissions, and organic matter decomposition all contribute to soil C depletion (Francaviglia et al., 2023). Soil C sequestration can be enhanced by increased plant growth, litter formation, and N inputs caused by higher C inputs from human activities (Rodrigues et al., 2023). Soil pH can be decreased and lignin-modifying enzyme activity inhibited by nitrogen addition, which in turn slows the breakdown of organic materials (Neupane et al., 2023). The majority of N-enrichment studies fail to quantify the native SOM, which hinders their capacity to explain how soil carbon is sequestered mechanistically. It is important to understand how nitrogen addition affects soil carbon sequestration and how different carbon pools behave with the help of isotope labeling methods.

Irrigation and carbon storage

Despite a worldwide rise in crop irrigation over the past 60 years, little is known about how irrigation practices affect soil structure and carbon sequestration. More than 20% of the world's arable land is now irrigated, and this practice is responsible for 40% of the world's food supply (Zhao et al., 2023). Blanco-Canqui et al. (2010) looked at dryness's impact on SOC levels and aggregate stability in croplands during five to eight years. Soil macroaggregates were shown to grow as irrigation flows increased from 66 to 217 mm per year. The authors postulated that the elevated SOC content brought about by irrigation—linked to higher plant biomass input and soil microbial community carbon in the form of microbial biomass carbon—was responsible for the observed improvement in aggregate stabilization. There were no statistically significant changes in aggregate stabilization across the two irrigation treatments in the study of flood and drip irrigation's effects on soil structure in organic and conventionally managed citrus orchards conducted by Hondebrink et al. (2017). Some research indicated that irrigation contributed to larger organic carbon imports, while others shown higher SOC decomposition because of enhanced microbial activity; these findings were part of a literature review undertaken by Trost et al. (2013). Campos et al. (2020) performed a long-term experiment with three main conclusions: (i) irrigated sandy agricultural lands have restored SOC to a level comparable to native vegetation and continue to sequester carbon, (ii) rainfed agricultural lands with clayey soils also sequester carbon, even though these soil profiles don't represent the broader regional soil characteristics, and (iii) rainfed agricultural lands with sandy soils, the most common type of soil and management practice in Western Bahia, do not act as a CO_2 sink. Nevertheless, additional investigation into the effects of different irrigation schedules on SOC and improved carbon sequestration is necessary.

SOC Sequestration Types

Biocarbon sequestration

The conventional wisdom holds that agricultural inputs are crucial to crop production. However, with the rise of sustainable agriculture, there has been a movement toward more effective and eco-friendly methods (Gawande et al., 2023). Biological pest and disease management, soil regeneration, nutrient cycling, and nitrogen fixation are all components of sustainable agriculture (Khangura et al., 2023). The goal of these approaches is to maximize productivity while minimizing environmental impact (Isfat & Raihan, 2022). Sustainable land management relies on agricultural conservation, a relatively recent tactic for preserving agricultural practices (Francaviglia et al., 2023). Reducing soil disturbance, using crop rotations, and sustaining soil cover through agroforestry, cover crops, and crop residues are all part of this. Sustainable agriculture is based on these principles and seeks to keep soil healthy, make ecosystems more resilient, and encourage agriculture to be viable in the long run (Çakmakçı et al., 2023). The importance of these methods in soil carbon sequestration cannot be overstated. Sustainable agriculture is a way to increase output without compromising environmental quality or depleting natural resource stocks (Raihan &Tuspekova, 2022c; 2022d; 2022e; 2022f; 2022g; 2022h; 2022i).

Extremely variable and unpredictable rainfall, soils that are structurally unstable, and poor crop yield are major obstacles in semiarid and arid regions. Soil erosion and runoff can be exacerbated by tillage methods that do not leave agricultural waste on the soil surface (Fajeriana et al., 2024). This puts soil health at risk. The significance of soil cover in promoting conservation agriculture practices is emphasized by this. Thus, conservation farming methods that lessen soil disturbances—like less tillage—in conjunction with sufficient soil cover and varied cropping systems aid in decreasing runoff and erosion while enhancing soil aggregation, penetration, and lasting carbon sequestration.

Geological SOC

When it comes to soil depth, the top 40 cm of soil usually holds the most SOC, with the deepest levels found between 0 and 20 cm (Navarro-Rosales et al., 2023). The stratification structure of SOM is altered by tillage methods, which in turn affects the distribution of SOC. Since SOC is mostly added to the top layer of soil, tillage has less of an effect on carbon distribution further down the soil profile. In order to comprehend the total advantages of conservation tillage, it is crucial to assess changes in carbon sequestration in subterranean layers. Using data from 69 pooled studies, Wang et al. (2023) performed a meta-analysis that looked at the impacts of tillage deeper than 40 cm. According to the results, changes in the soil's carbon distribution significantly affected the outcome. For example, in most studies, the top layer of soil showed the effects of nitrogen additions within the first decade of the experiment. There was no accumulation of SOC in deeper soil layers over a 28-year long-term experiment that used the same traditional tilling strategy; nevertheless, tilled soils with lower native organic carbon levels had a greater mineralization proportion of SOC. This discovery emphasizes how soil management approaches in semiarid areas can improve soil quality. Soil carbon ratios are an important indicator of soil quality, but it would be a mistake to focus on them in isolation and ignore how the variable has changed over time (Reichenbach et al., 2023). Notwithstanding these constraints, organic matter addition can aid in soil quality restoration.

Technology-based SOC

Improved SOC distribution in soil fractions across the soil profile and stabilization of SOC inside stable micro and macro soil aggregates are two goals of recent technical developments that aim to raise SOC density and, by extension, SOC deposition. Soil carbon pool increases and decay constant values for carbon are decreased by this novel approach, which protects carbon from microbes and prolongs its persistence. One of the most important ways to increase the SOC pool and sequester carbon on land is to manage agroecosystems (Rattan, 2023). Uptake, fixation, emission, and transport among different carbon reservoirs are all aspects of carbon that humans have artificially manipulated in agricultural techniques (Raihan &Tuspekova, 2022j; 2022k; 2023b). SOC sequestration can be enhanced through the adoption of new agricultural techniques, irrigation schedules, erosion control measures, and mulch farming, among other RMPs.

Recovering degraded soils alongside ecosystems, repurposing marginal agricultural soils for restoration-promoting land uses like perennial vegetation replanting, and enacting RMPs on agricultural lands are all ways to increase SOM's ability to act as a CO_2 sink in the atmosphere. Although there are common RMPs like precision farming, integrated pest management, integrated nutrient management, mulch farming, and decreased tillage, site-specific adaptation is of utmost importance (Jayara et al., 2023). The key to making RMPs work better and last longer is tailoring them to each site's unique qualities and needs. Optimizing soil carbon sequestration and agricultural productivity requires consideration of factors such as soil type, local ecosystems, climate, and current agricultural methods (Rodrigues et al., 2023). In order to repair and maintain soil health, these ecological techniques take advantage of the interdependencies and connections within ecosystems. Sustainable soil management and long-term carbon sequestration can both be significantly improved by implementing these ideas into land management strategies.

Climate Change Mitigation through SOC Sequestration

More and more people are looking to SOC sequestration as a way to lessen the impact of climate change and cut down on emissions of GHGs (Paul et al., 2023). It is imperative that measures be taken to decrease atmospheric CO_2 concentrations, which have risen substantially (by 31% globally) due to the combustion of fossil fuels and shifts in land use patterns (Raihan, 2023j; 2023k; 2023l; 2023m; 2023n; 2023o; 2023p; 2023q; 2023r; 2024c; 2024d; 2024e; 2024f; 2024g). Global carbon emissions have been around 136 Pg from soil cultivation and 270 Pg from fossil fuel use since the industrial revolution (Chataut et al., 2023). The SOC pool has lost about 78 Pg of carbon due to human activities such as deforestation, agricultural conversion, biomass burning, wetland drainage, and soil cultivation (Bhattacharyya et al., 2023). Significant carbon losses have occurred as a result of SOC depletion; in fact, some agricultural soils have lost as much as two-thirds of their natural SOC pool (Don et al., 2024).

For agricultural sectors, sustainability, food security, water quality, and the rate of atmospheric enrichment of CO_2 to be reduced, restorative methods of land use and RMPs applied to agricultural soils are essential. SOC can be restored through techniques including conservation tillage, cover cropping, composting, mulching with crop leftovers, and manure application (Shah et al., 2023). When implemented properly, these solutions can capture 0.9 Pg of SOC per year, which is enough to counteract 25% to 30% of the projected 3.3 Pg per year rising atmospheric CO_2 levels (Subramanian et al., 2023). Soil carbon sequestration has the potential to naturally store 30-60 Pg C over a 25-50 year period (Rodrigues et al., 2023). Restoring damaged soils isn't the only benefit of using soil carbon sequestration tactics. These methods also boost biomass production, enhance groundwater quality, and reduce overall emissions to the environment, which helps to equalize CO_2 emissions from fossil fuels.

SOC Sequestration through Cropping Systems

SOC sequestration by crop rotation

Unlike continuous monoculture, crop rotation calls for a specific pattern of crops grown in the same area on a regular basis. This method changes nitrogen cycling, soil structure including aggregation, and SOC concentration, all of which have a major impact on soil quality (Hartmann & Six, 2023). Crop rotations benefit

SOM and carbon sequestration, decrease soil erosion, and influence soil phosphorus and carbon retention (Francaviglia et al., 2023). A key factor in SOC sequestration is the quantity of crop residues restored to the soil throughout crop rotation, the impact of which varies among crop rotations (Kroschewski et al., 2023). Hordeum vulgare monoculture resulted in far lower SOC concentrations than a rotation with Vicia sativa in the arid parts of Spain (Holder et al., 2019).

SOC sequestration with crop residue

To reduce erosion and improve SOC sequestration, it was helpful to combine tillage with fertilizer with crop residue additions (Ren et al., 2024). The retention of crop residue and other conservation agricultural measures, such as reduced or no-tillage methods, improve SOC sequestration (Francaviglia et al., 2023). Surprisingly, the top 0-5 cm of soil layer exhibits the maximum SOC sequestration irrespective of these techniques. Restoring SOC content is another way that organic manure and other residue management strategies can help with C sequestration (Thapa et al., 2023). According to Ghimire et al. (2008), conventional tillage removed 7.86 kilogram C m^{-3} from the top 0-50 cm of soil, while no-tillage methods kept 8.24 kg C m^{-3}. It is worth mentioning that compared to the other treatments, crop residue preservation in no-tilled soils absorbed a much higher amount of SOC in the upper 15 cm of soil. Based on these results, it seems that using zero- or minimum-tillage methods and keeping crop residues could improve SOC sequestration. Figure 3 illustrates conservation agriculture as a method for improving ecosystem services including carbon sequestration.

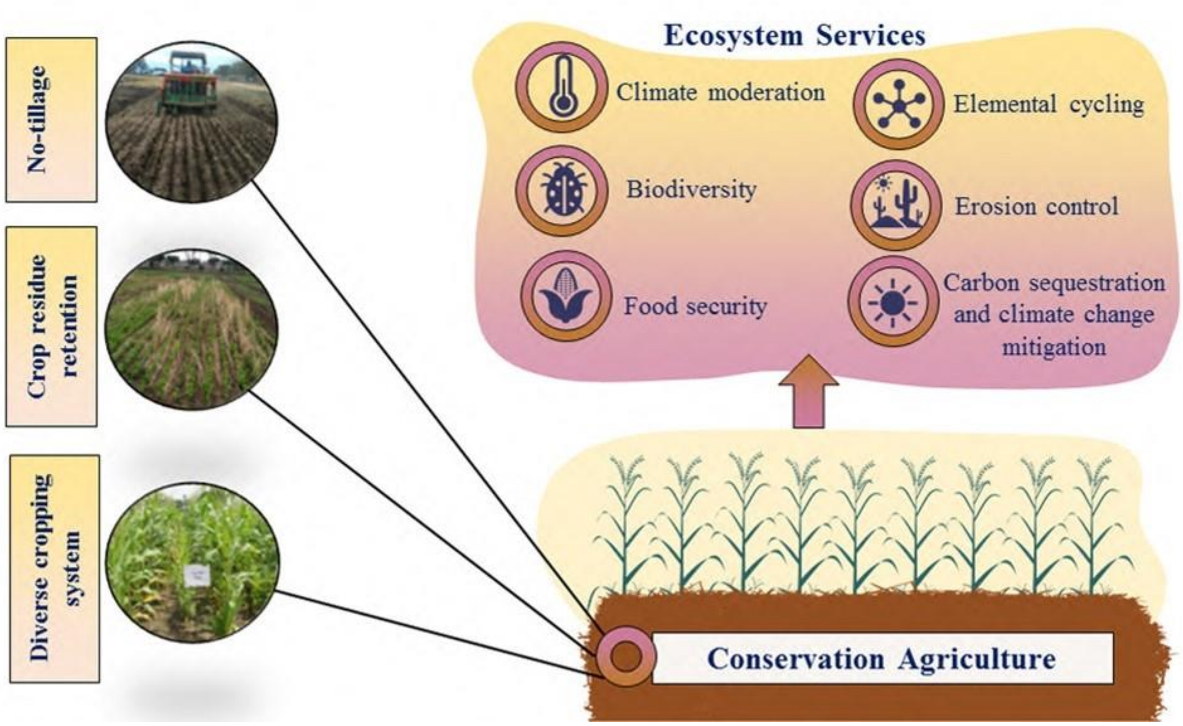

Figure 3. Conservation agriculture as a method for improving ecosystem services (Jayaraman et al., 2021).

SOC sequestration with cover crops

Soil carbon storage can be greatly improved by growing cover crops in between primary crops (Seitz et al., 2023). By boosting carbon inputs via photosynthesis and their own breakdown (root and leaves), cover crops help soils sequester carbon (Raihan et al., 2018; 2019; 2021a; 2021b; 2022a; 2023a). Reduced nitrogen losses through leaching, increased crop yields, and improved soil quality are just a few of the agroecosystem functions provided by cover crops (Arlauskienė & Šarūnaitė, 2023). A number of factors determine the precise effects and advantages of cover crops. These include the type of cover crop, the timing of planting and harvesting, the cropping system, the length of time the crop is allowed to develop, the amount and quality of cover crop residue, and the weather (Scavo et al., 2022). Assessing the efficacy of cover crops in various agricultural systems requires constant monitoring of the SOC pool in reaction to cover crop application. It needs long-term studies to find out how cover crops affect SOC sequestration in the long run. Cover crops have the potential to store almost 60 million tons of carbon, according to a review and analysis by Chahal and Van Eerd (2019) of data from 26 trials drawn from five sources of literature. Figure 4 presents the benefits of cover crops including carbon sequestration.

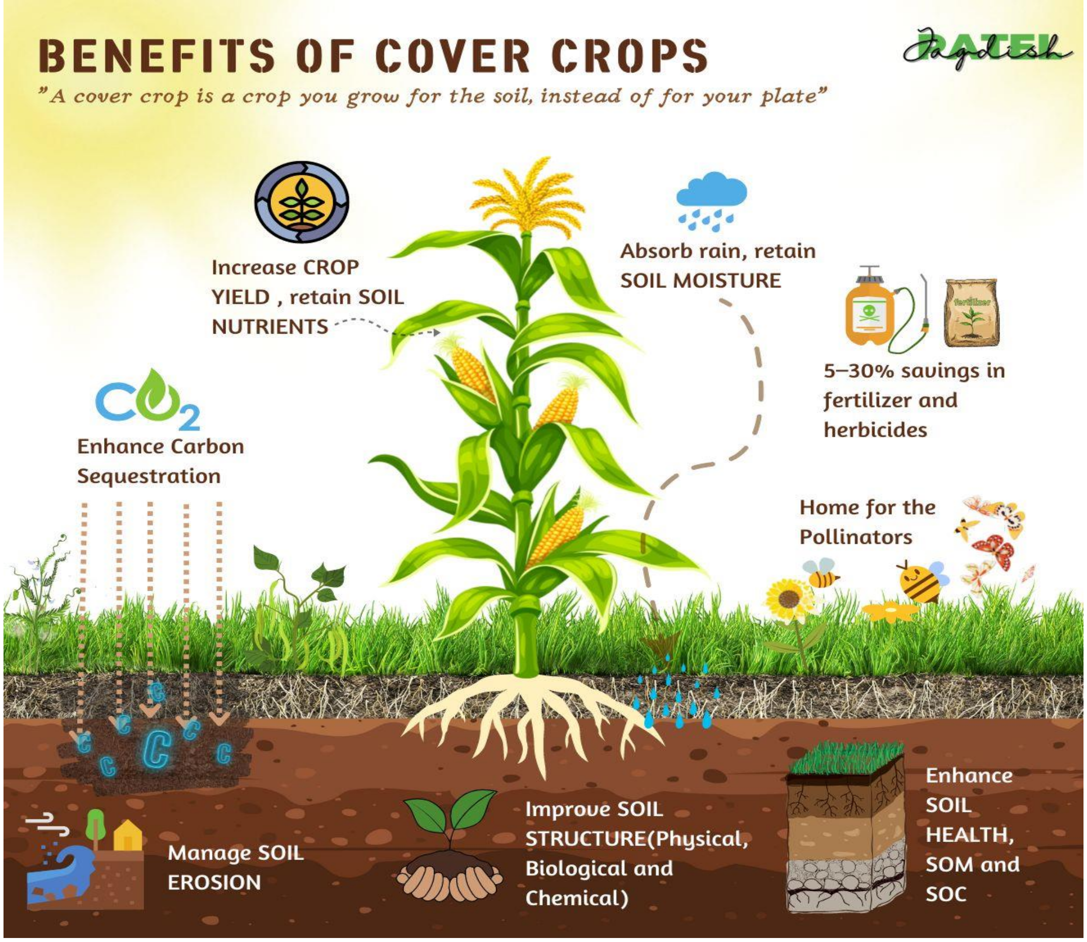

Figure 4. Benefits of cover crops including carbon sequestration (Patel, 2023).

Modern Agriculture's Climate Impact

Soil carbon fluctuations affect sequestration

Soil carbon sequestration, an important part of the global carbon cycle and climate change, can be greatly affected by changes in soil carbon (Rodrigues et al., 2023). In order to effectively manage soil carbon, it is crucial to understand the factors that impact soil carbon variations. These factors include changes in land use, climate change, alongside soil management methods (Rodrigues et al., 2023). Over time, SOC decreases due to inefficient land use management, leading to a soil carbon deficit compared to the quantities of carbon that were previously present (Gutierrez et al., 2023). A key approach to re-normalize the worldwide carbon balance is land management that avoids soil carbon loss and promotes storage. Another successful strategy to enhance soil carbon storage is to increase inputs of carbon via natural ecosystems (Wiltshire & Beckage, 2022). Some major tactics for carbon sequestration include making carbon inputs easier and preventing the rate of carbon decomposition from increasing (Mäkipää et al., 2023). To deepen our comprehension of soil carbon dynamics, future studies ought to center on wetlands and soil carbon budgets.

Mitigation by reducing SOC depletion

Efforts to slow down climate change include using land management techniques that make soil more effective at soaking up carbon (Sünnemann et al., 2023). Climate change, changes in land use, and soil management methods are three of the many factors that affect soil and, by extension, the soil carbon pool (Raihan, 2023s; 2023t; 2024h). A small number of factors or even individual ecosystems have frequently been the center of attention in earlier research. In order to better understand the worldwide soil carbon cycle and how to manage it, a thorough analysis is required that takes into account the combined impact of multiple factors on soil carbon sequestration.

The rapid decline of the SOC pool, mostly as a result of human activities, has led to an increase in atmospheric CO_2 concentrations, which has had devastating impacts on both the environment and the economy (Dong & Huang, 2023). In terms of soil quality, the SOC reservoir is vital because it does things like absorb moisture at low moisture levels to make more water available to plants and encourage the formation of soil aggregates, contribute to charge density, and play a role in ion exchange processes. It also acts as a sink for important plant nutrients like N, P, Zn, Mo, and S (Rodrigues et al., 2023).

Atmospheric accumulation of CO_2

An increase in the average surface temperature of the Earth is only one of several environmental problems brought about by the dramatic increase in atmospheric concentrations of GHGs such as CO_2, methane (CH_4), and nitrous oxide (N_2O) during the industrial revolution (Raihan et al., 2022b; 2022c; 2022d; 2022e; 2022f; 2022g; 2023b; 2023c; 2023d; 2023e; 2023f; 2023g; 2023h; 2024a; 2024b). Take atmospheric CO_2 levels as an example; they jumped from 280 to 367 parts per million in just one year. Temperatures are currently rising at a rate of 0.17 ◦C per decade, which is higher than the threshold of 0.1 ◦C per decade and is making it harder for ecosystems to adapt, while global warming has been going on throughout the late 19th century (Sultana ey al., 2023a; 2023b). Following the worldwide policies and trends specified by various regulatory bodies, the latest trends focus on CO_2 reduction (Voumik et al., 2022; 2023a; 2023b; 2023c).

Droughts are becoming more common as a result of global warming, with the northern hemisphere seeing an increase of 0.5-1% every decade and the subtropical land regions experiencing a decrease of 0.3% per decade.

Impacts on soil stability, organic carbon sequestration, runoff and erosion, water, nitrogen, carbon, phosphorus, and sulfur cycles, biomass production, biodiversity, and the environment as a whole are negative outcomes of these altered precipitation patterns.

Soil erosion

Deterioration in soil quality leads to changes in physical and chemical properties that make it less effective at retaining SOC on farms (Francaviglia et al., 2023). These changes include things like aggregation, crust formation, soil texture, compression as well, water infiltration capacity, and water/air ratio. Soil erosion also causes carbon losses, which makes the effect of contemporary agriculture on global warming even worse (Roy et al., 2023).

Low SOM

To lessen the impact of agriculture on global warming, more people need to know about SOM. There has been a marked decline in the global absorption of SOC due to the transformation of natural environments to agricultural land. The conversion of tropical forests along with savannas into farms perpetuates this troubling trend. There is an imbalance in soil carbon sequestration in agricultural systems compared to natural ecosystems like prairies and forests (Moradi & Shabanian, 2023). Soil carbon sequestration can drop by 1500 ppm during the changeover from natural to agricultural ecosystems, especially in the first few years after the land is converted. Even with RMPs in place, the yearly rate of SOC loss in farming can be higher. Therefore, in order to enhance soil health and boost carbon input, it is crucial to restore the SOM pool in agricultural lands. In addition, nitrogen inputs and other agrochemicals are a major source of GHG emissions, which makes carbon sequestration attempts more difficult.

Climate Smart Agriculture (CSA) and SOC

Climate-smart agriculture (CSA) is an approach that strategically controls the cultivation of crops, rearing of livestock, maintenance of forests, and management of fisheries in order to mitigate the adverse impacts of climate change on agricultural activities (Ariom et al., 2022). Implementing CSA methods can enhance soil fertility, boost crop yields, and mitigate GHG emissions by promoting soil carbon sequestration (Tadesse et al., 2021). This can assist small-scale farmers in adjusting to the vagaries of climate change (Raihan, 2023u; 2023v; 2023w; 2023x). CSA practices can partially counteract previous soil carbon losses and aid in mitigating climate change. Additionally, it has the potential to improve the resilience and adaptive ability of production. The adoption of CSA methods, such as no-tillage, cover cropping, organic soil fertilization, and crop-livestock and crop-livestock-forestry systems, has been widespread (Raihan et al., 2022h; 2022i; 2022j; 2023i; 2023j; 2023k; 2023l; 2024c). These practices aim to increase soil carbon accumulation and improve soil quality, all while maintaining agricultural yield (Anghinoni et al., 2021).

Several exclusive activities in CSA that can enhance soil carbon include the use of soil additives, analysis of soil data, cultivation of salinity-resistant and high-yielding crop types, and use of carbon farming techniques (Jat et al., 2020). Composting and using biochar have the potential to enhance soil composition and augment the amount of organic matter in the soil. Enhancing the soil's water retention and permeability can ameliorate the effects of droughts, heatwaves, and heavy precipitation events. Soil amendments can additionally enhance biological activity and supply nutrients, thereby fostering the growth of healthier plants that exhibit reduced vulnerability to pests and diseases (Akanmu et al., 2021). In addition, farmers have the ability to utilize instruments to assess and track soil characteristics in order to execute specific strategies aimed at enhancing soil health and its ability to capture and store carbon. Furthermore, the utilization of salinity-resistant and high-yielding crop types can assist farmers in mitigating the impact of climatic hazards on their crops (Haque et al., 2021). In addition, carbon farming practices encompass the application of soil additives, conservation tillage, agroforestry, whole orchard recycling, and the use of cover crops that optimize the presence of living roots (Quintarelli et al., 2022).

In contrast, non-CSA practices prioritize maximizing crop output by relying heavily on chemical fertilizers, pesticides, and weedicides. However, this approach can have detrimental effects on the ecosystem and soil quality. Monoculture methods that are not part of a CSA system might result in the spread of diseases and increased vulnerability to predation, necessitating the usage of pesticides. Moreover, the act of clearing forested areas for agricultural techniques that are not part of CSA might result in the depletion of wildlife populations. The use of non-CSA techniques results in soil erosion, a decline in water levels, reduced soil fertility, and a decrease in the soil carbon pool. Therefore, the adoption of non-CSA techniques increases agricultural emissions and contributes to the phenomenon of global warming and climate change.

CSA in developing countries

Agriculture serves as the primary economic driver for numerous emerging nations. The phenomenon of climate change poses multifaceted challenges to agricultural production and food security in developing nations. Therefore, it is imperative to prioritize the enhancement of agricultural production efficiency, the assurance of food security, and the promotion of economic growth when establishing goals for the development of CSA in these developing countries. Simultaneously, the mitigation of GHG emissions within agricultural systems should be incrementally achieved by allocating supplementary financial resources (Leng et al., 2023). In accordance with the concept of CSA, emerging nations have devised appropriate solutions tailored to the specific circumstances of various locations. The state of Maharashtra in India is considered to be a region of considerable climatic vulnerability. One of the primary challenges encountered in agricultural production within the state of Maharashtra is the insufficiency of irrigation water during periods of drought. Hence, the mitigation of drought conditions can be achieved by using irrigation water management technologies, including techniques such as well excavation, pipe wells, rainwater harvesting, drip irrigation, and various types of groundwater extraction. The integration of nutrient management techniques, such as the application of farmyard manure, earthworm compost, and straw residue incorporation, along with the implementation of sprinkler irrigation and other micro irrigation technologies, has the potential to enhance the efficiency of water and fertilizer utilization, as well as agricultural productivity. Additionally, this approach can contribute to the reduction of overall agricultural water and fertilizer usage, as well as greenhouse gas emissions (Khatri-Chhetri et al., 2019).

The implementation of high-quality rice cultivars, strategic adjustments to sowing and harvesting schedules, decreased reliance on chemical fertilizers, and modifications to irrigation strategies in the Mekong Delta region of Vietnam have collectively contributed to the enhancement of crop productivity, reduction in production expenses, and the establishment of food security for farmers (Ho & Shimada, 2019). In Nepal, agricultural practitioners employ many management strategies, including but not limited to no tillage, crop rotation, and straw incorporation into the soil, with the aim of enhancing soil biological activity, water utilization efficiency, and soil physical characteristics (Gairhe et al., 2021). Enhanced soil quality has the potential to augment the tiller count, plant stature, and grain productivity of wheat, while concurrently mitigating erosion. In the context of Pakistan, it has been observed that indigenous cotton producers have embraced the concept of CSA by employing bed seeders and laser technology to achieve field leveling. According to Imran et al. (2018), the implementation of strategies such as reduced tillage and fallow practices, as well as the cultivation of enhanced cotton varieties that are resistant to drought and waterlogging, have led to enhancements in the local cotton quality and a subsequent indirect reduction in greenhouse gas emissions.

In the African context, addressing the intertwined challenges of food security and climate change necessitates the implementation of substantial agricultural reforms (Khan et al., 2023b). In the context of Zambia in Southcentral Africa, agricultural practices aimed at protection are implemented. These practices include the use of organic mulch on surface crops in farms, the rotation of legumes and cereals, and the utilization of enhanced crop varieties (Kaczan et al., 2013). The implementation of these measures in Zambia has the capacity to enhance soil fertility and carbon sequestration capabilities, leading to a significant increase in average grain yields and effectively ensuring local food security. Furthermore, it should be noted that Malawi, a country located in Africa, has used a strategy known as continuous agroforestry intercropping, which involves the cultivation of two primary fertilizer species. Additionally, they have also employed the practice of orderly agroforestry fallow, which entails the deliberate planting of fast-growing leguminous trees or shrubs. Another approach utilized in Malawi is the agroforestry complex system, as discussed by Harawa et al. (2006). The implementation of these techniques in Malawi has been found to enhance soil nitrogen fixation, enhance soil nutrient levels, and effectively mitigate the release of greenhouse gases, including CO_2 and N_2O (Kaczan et al., 2013). Farmers in Namibia have effectively augmented their income by implementing several strategies, including the collection of nutrient-rich earthworm compost leachate, engaging in hydroponic agriculture, and cultivating mushrooms in the coastal regions of the Namib Desert. To conserve irrigation water, the researchers additionally collected fog water for the purpose of agricultural irrigation in coastal desert regions. Alternatively, they combined seawater with fog water to implement precision drip irrigation at the crop root level (Mupambwa et al., 2019). By implementing these supplementary measures, Namibia has successfully mitigated the issue of food scarcity and bolstered its capacity to cope with the impacts of climate change.

CSA in developed countries

Developed countries have advanced agricultural systems characterized by efficient production, high-quality agricultural products, abundant per capita land resources, and well-established mechanization and intensification techniques. Consequently, the development objectives of the CSA in these industrialized nations generally revolve around the reduction of GHG emissions and the enhancement of agricultural ability to effectively cope with the impacts of climate change. Simultaneously, it is imperative to include advanced and innovative technologies, prioritize the development and execution of regulations, bolster the adaptability of the agricultural system, and mitigate greenhouse gas emissions while concurrently enhancing production efficiency (Long et al., 2016). California, situated in the United States, is widely recognized as a highly productive and resource-abundant agricultural area on a global scale. The state places significant importance on the sustainable administration of water resources and the mitigation of GHG emissions as part of its efforts to attain CSA objectives (Lewis & Rudnick, 2019). The California government has successfully achieved the objective of lowering GHG emissions through the implementation of a range of laws, regulations, and relevant agricultural technological measures facilitated by the public research system. As an illustration, the most recent legislation pertaining to methane mandates a 40% reduction in methane emissions from the dairy sector by the year 2030, as outlined in the study conducted by Vechi et al. (2023). The California government considers enhancing agricultural water usage efficiency as a viable approach to address the water resources challenge within the context of water resources management. The local government provides assistance to farmers in addressing the challenges of high investment costs, GHG emissions reduction, and water restrictions. This assistance involves the upgrading of underground water pumps and the installation of drip irrigation or micro sprinkler irrigation systems, which aim to enhance water storage and recovery capacity (Ayars et al., 2015).

In the European context, there is a heightened focus on the effects of climate change on agricultural development, as evidenced by the research conducted by Lehtonen et al. (2021). As a result, European countries primarily leverage the service activities provided by agricultural ecosystems. The utilization of satellite data inside agricultural models, wherein remote sensing techniques are merged with agricultural models to facilitate the advancement of precision agriculture, was implemented in France. The utilization of technological advancements to enhance our ability to adapt to climate change has the potential to yield several benefits, including improved decision-making in the face of variable weather conditions, enhanced time management, increased savings on expenditures, and perhaps reduced greenhouse gas emissions (Zilberman et al., 2018). Switzerland implements a waste recycling system wherein the farm's waste is directed to the biogas plant at no cost. This initiative serves to mitigate GHG emissions by facilitating the generation of renewable energy. Additionally, the biogas plant enhances the quality of fertilizers and feed additives provided to the farm (Loboguerrero et al., 2019). The implementation of LED horticulture technology in the Netherlands has enhanced the sustainability of horticultural practices, hence reducing its susceptibility to the impacts of climate change. In contrast to conventional lighting methods, the utilization of LED technology yields a reduction in both heat generation and energy consumption. Furthermore, it enhances the dispersion of light and exerts a favorable influence on the cultivation of plants (Engler & Krarti, 2021). According to Adamides (2020), Cyprus employs agricultural robots for the purpose of applying pesticides to crops. This practice serves to enhance crop protection and productivity, while concurrently diminishing the reliance on pesticides and advancing the sustainability of agricultural ecosystems.

The nations described above have implemented a range of methods focused on the development goals of the CSA in response to different regional circumstances. Additionally, they have separately assessed the implementation of the CSA to different extents. The aforementioned findings demonstrate that the implementation of CSA has been effectively carried out in multiple nations. Certain countries have effectively achieved their goals through reducing greenhouse gas emissions, increasing economic growth and productivity, enhancing resilience to climate change, and implementing improved agricultural methods.

Socioeconomic Advantages

Sustainable growth and alleviating poverty evaluate the socioeconomic benefits along with trade-offs of SOC sequestration. This is especially true in low-income societies, where farms frequently encounter social and financial issues. To stop land degradation and keep carbon in the air, ecosystem restoration is essential (Roy et al., 2023). Land that is no longer used for farming has the potential to act as a large-scale carbon sink, reducing atmospheric CO_2 levels (Ruehr et al., 2023). Nevertheless, there is a spectrum of land restoration solutions available, from active restoration methods that are more costly to less expensive minimal management approaches. Planting seeds on land that has been farmed in the past is one example of active restoration, which aims to speed up carbon recovery and return different ecological functions (Jakovac et al., 2024). A new worldwide study, however, reveals that tropical forests may see a quicker return to primary produce via natural regeneration—that is, by letting abandoned crops recover naturally—than through intensive restoration (Elliott et al., 2023). The results show that aggressive restoration, which requires substantial investment, does not necessarily result in more carbon sequestration than inexpensive spontaneous regeneration.

Return on investment optimization for ecosystem restoration remains a highly unknown subject. It has been difficult to distinguish the effect of restoration techniques with changing environmental circumstances since studies evaluating active restoration with natural regeneration have frequently looked at different treatments performed at different locations. This has led to a lack of confidence in the results of these studies and an absence of agreement on how to best use scarce management resources to increase soil carbon sequestration. The Chinese government's 'Grain for Green' initiative is a massive ecological restoration effort on a global scale (Li et al., 2023). Converting farmland back into a semi-natural habitat like a woodland, shrubland, or grassland is the ultimate goal of the project. So that it may compare the two restoration methods side by side, this study includes several locations that use both active restoration and natural regeneration. In order to determine what parameters, such as recovery period, climate, ecological type, SOC, and soil depth, impact carbon recovery following fallow cropland, researchers conducted a large-scale pairwise comparison utilizing the distinctive dataset from the Grain for Green project (617 observations). This research was useful in determining when and how active restoration and natural regeneration are most effective for SOC sequestration.

SOC Sequestration Factors

There are a number of elements that affect soil carbon sequestration, and they include soil characteristics, management elements, and environmental considerations (Elkhlifi et al., 2023). For carbon sequestration, soil texture is key. Soils with a coarser texture tend to mineralize nitrogen and carbon at a faster pace than those with a finer texture (Vaidya et al., 2023). This is probably because finer textures are better able to protect organic carbon from microbes. Under different land uses, such as forests, shrublands, and croplands, the soil's texture affects the carbon equilibrium in the deeper soil layers. Soil bacteria in clay-dominated soils have a harder time getting to organic carbon than in sandy soils because clay minerals adsorb carbon chemically and microaggregates physically occlude it (Stoner et al., 2023). SOC aids in mineral binding and aggregate formation, which in turn protects carbon from degradation, and both processes are intrinsic to soil structure (Kunmala et al., 2023). In contrast to fine-textured soils, natural ecosystems, or soils produced by minimal tillage, the carbon preservation capacity of soil aggregates with low consistency is lower in soils with coarse textures and soils that have been intensively tilled (Francaviglia et al., 2023). Soil carbon sequestration or accumulation is a function of land management methods. Soil carbon stores can be achieved through practices which boost carbon inputs while decreasing heterotrophic respiration (Kudeyarov, 2023). For example, shifting from traditional tillage methods to no-tillage ones might lengthen the time that SOC stays in the soil. Causes of SOC stock loss due to tillage include enhanced water or wind erosion, leaching of dissolved carbon, and mineralization of exposed carbon after aggregate breakdown (Francaviglia et al., 2023).

The net SOC balance, which is the difference between inputs and outputs, is influenced by environmental factors like temperature, humidity, and aeration (Longo et al., 2023). Even at ideal soil moisture levels, SOC breakdown is accelerated by higher temperatures. To facilitate microbial growth, which in turn affects respiration rates and carbon turnover, sufficient soil aeration is critical for carbon sequestration (Rodrigues et al., 2023). Figure 5 presents the factors influencing SOC.

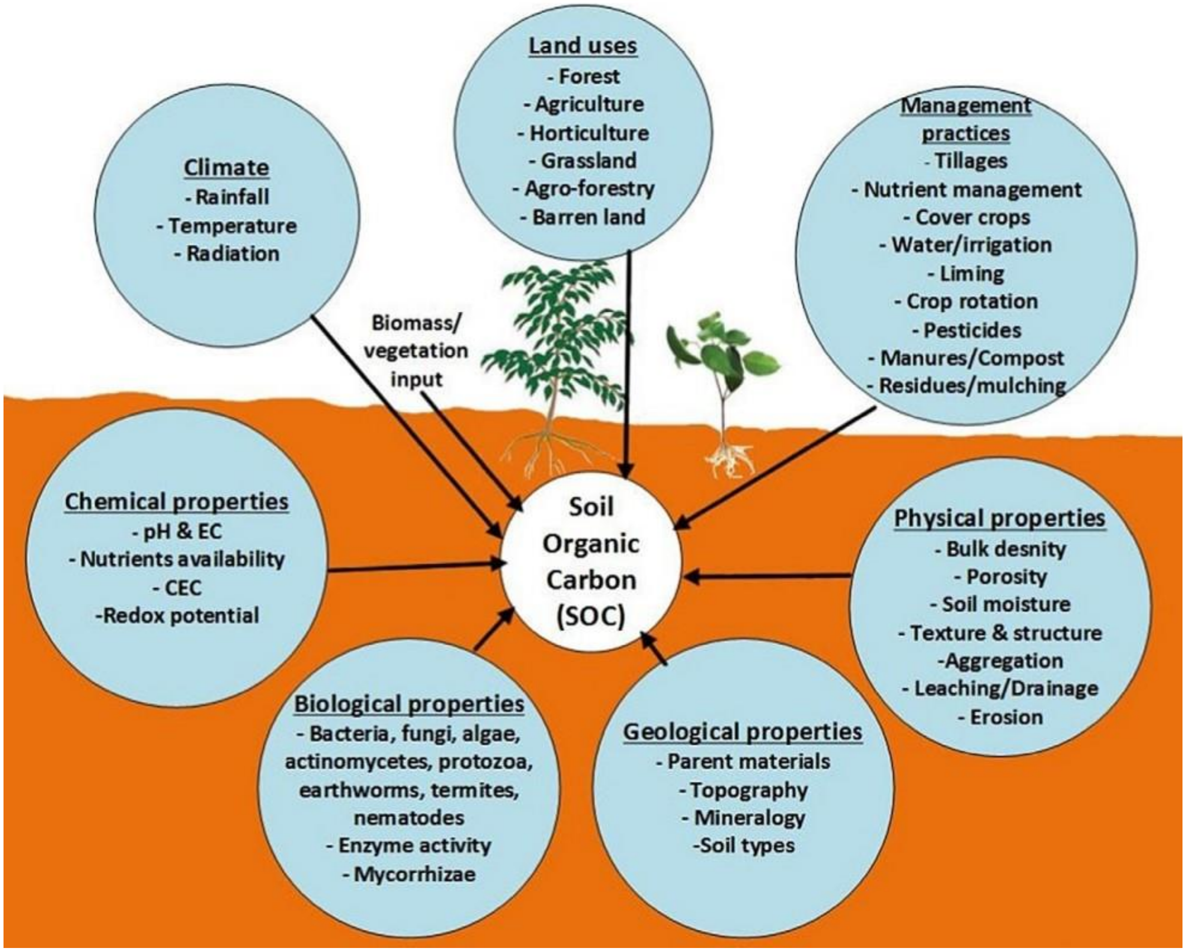

Figure 5. Factors influencing SOC (Ramesh et al., 2019).

Crop Management to Sequester SOC

Soil carbon sequestration and soil quality are greatly improved by many crop management strategies. These include crop rotations, agroforestry, cover cropping, nitrogen fertilizer, precision farming, tillage, applications of manure and biosolids, irrigation, and more (Mohanty et al., 2024). Soil fertility, productivity, and carbon sequestration are three factors that farmers can control in their fight against climate change. By implementing these techniques, farmers can also secure food supplies for the future (Balasundram et al., 2023).

Ecosystem management to restore carbon

All organic matter in the soil, including decomposing plant and animal matter, chemicals produced by microbes and other living organisms, and the biomass of soil microbes and other fauna, as well as their metabolic products, are collectively known as SOM (Wani et al., 2023). Plants cover, temperature, species, management techniques, and human activities are some of the variables that affect an ecosystem's capacity to sequester carbon in soil and plants, whether it's an aquatic or terrestrial ecosystem (Rodrigues et al., 2023). Enhancing soil carbon sequestration and mitigating excess atmospheric CO_2 are two key components of ecosystem management for carbon restoration (Rodrigues et al., 2023; Ghosh et al., 2023). Soil carbon sequestration effects may be compared on a broad scale since numerous restored sites have used both active restoration and spontaneous regeneration at the same time (Jakovac et al., 2024). The soil, history, climate, and amount of disturbance in these locations are very comparable. For croplands, naturally restored locations, and actively restored sites, data on soil carbon has been provided, including mean values, sample sizes, and recovery timeframes for up to 60 years (Tian et al., 2023).

SOC concentration and bulk density are the main variables that impact soil carbon stock (Ameer et al., 2023). Almost 40% of the studies included bulk density data, while a small number of them solely reported SOC concentrations (Gholamahmadi et al., 2023). SOC concentration fluctuations can provide light on changes in soil carbon stock when bulk density is taken into account when evaluating the consequences of active restoration with natural regeneration on the same site (Cheng et al., 2023). One way to increase the residence time of SOC is to return crop residues along with other biosolids at a rate that is higher than their rate of decomposition. Another way is to reduce the degradation of the natural vegetative structure and the groundwater table, both of which have an impact on the carbon dynamics of the ecosystem. Loss of biodiversity is another consequence of converting forests to plantations or grasslands (Prangel et al., 2023). By developing deep root systems and engaging in bioturbation, SOC is integrated into the subsoil, reducing the impact of plowing and other human activities on the soil (Sierra et al., 2024). Providing the necessary nutrients (nitrogen, phosphorus, and sulfur) while also influencing soil properties (such as clay content and landscape orientation) to preserve the soil's intrinsic C sink capacity. The systemic implications of ecosystem management for carbon restoration are shown in Figure 6.

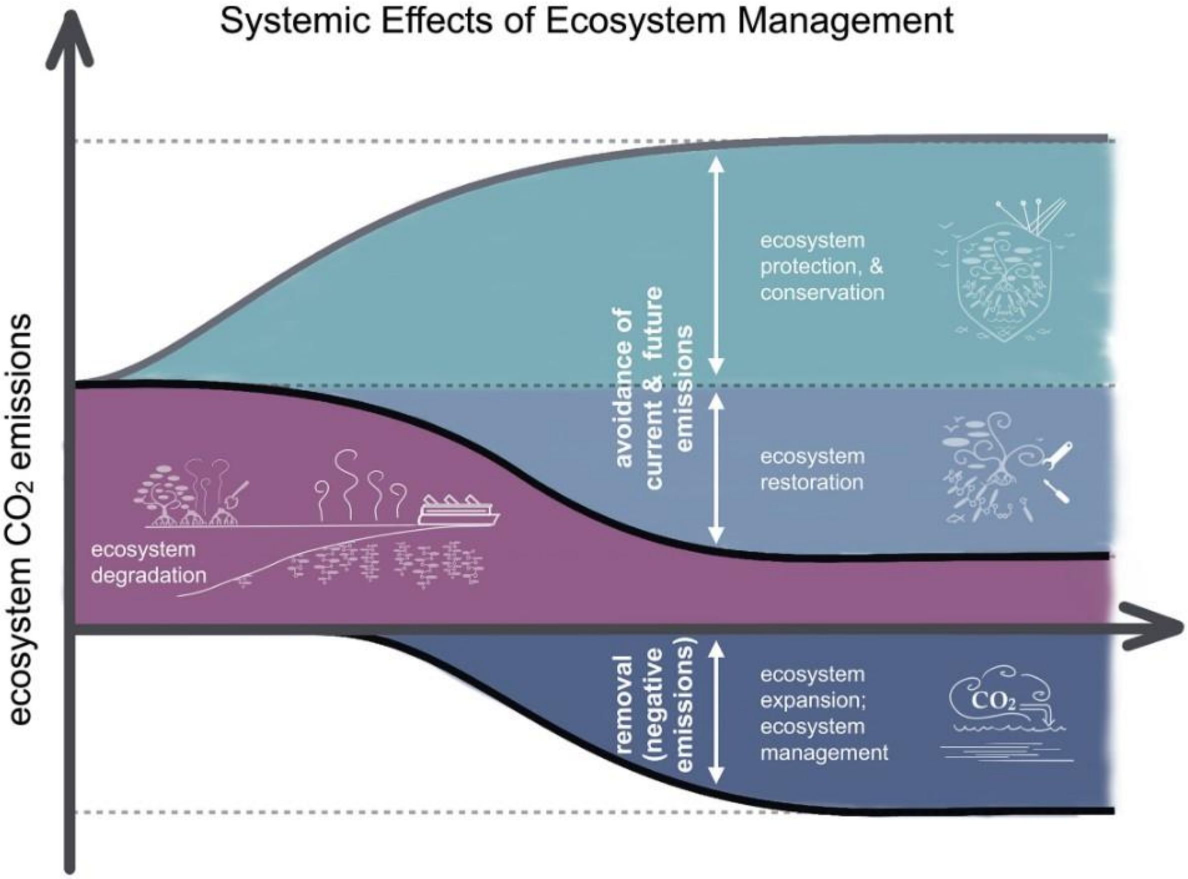

Figure 6. The systemic implications of ecosystem management for carbon restoration (Mengis et al., 2023).

Optimizing SOC sequestration in grasslands

Soil processes, especially biogeochemical cycling, have been significantly transformed as a result of human-induced modifications in around 60% of the grassland ecosystem worldwide (Meng et al., 2024). Depending on the level of grassland management, different factors like stocking concentrations, mineral fertilizer usage, possible irrigation methods, and animal species are taken into account (Puech & Stark, 2023). In remote areas, farmers use intensive land management techniques like applying fertilizers, reseeding annual and preferred perennial plant species, and using a variety of stocking strategies, including changing the timing of the grazing season, among other things.

Soil carbon sequestration is already a major function of grasslands and managing them can make this function even more efficient (Norderhaug et al., 2023). Soil carbon sequestration and plant growth can both be enhanced by establishing long-term plant shields and efficiently adding subsurface biomass. A number of management strategies and environmental factors affect the relative contributions of carbon sequestration and respiration of soil, which in turn determines the extent to which grassland soils sequester carbon (Rodrigues et al., 2023). Ranches often utilize grasslands for cattle grazing and hay production. SOC sequestration and soil microbial populations are both influenced by these methods. Soil carbon sequestration can be improved through grassland management practices, leading to more efficient release of CO_2 and other GHGs. The SOC stock (surface layer of 24 + 6 cm) was estimated to be 31.1 Mg C ha^{-1}, grasslands at 47.4 Mg C ha^{-1}, and forestland at 49.9 Mg C ha^{-1} based on an analysis of wide land use classifications throughout 28 studies in the southeastern United States, which is a warm-humid area with comparatively weathered as well as coarse-textured soils (Franzluebbers and Poore, 2023).

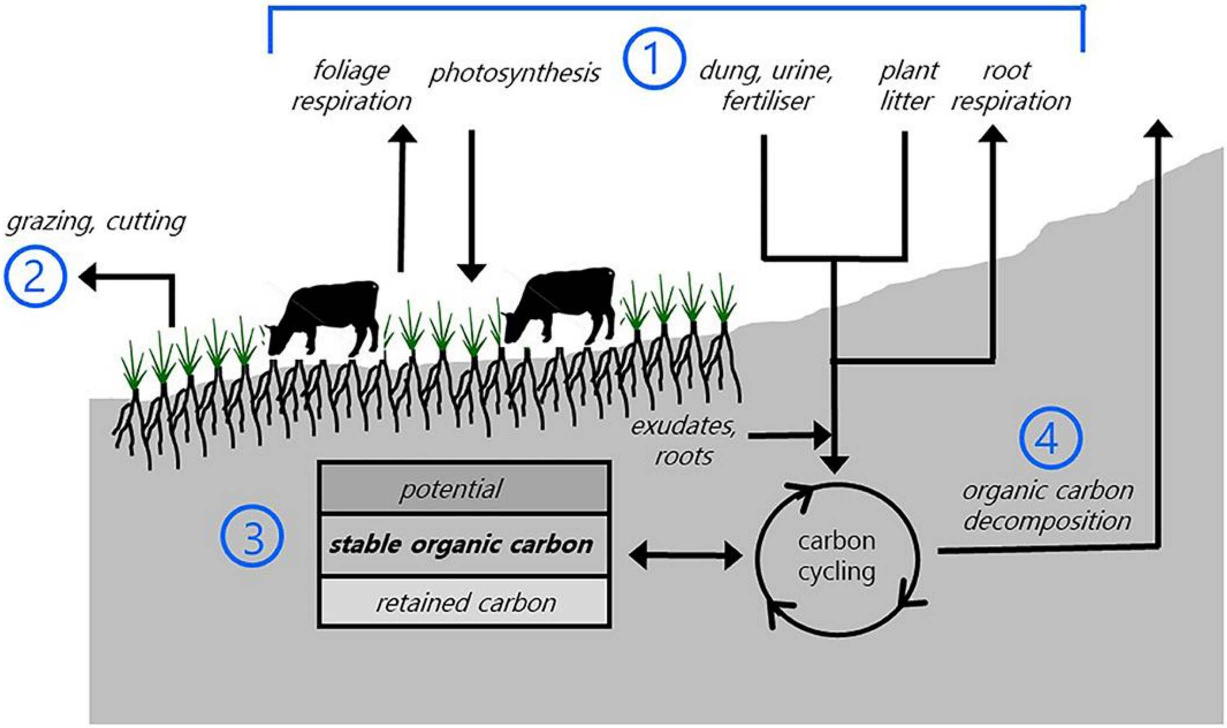

Figure 7. The management of grasslands to maximize soil carbon sequestration (Whitehead, 2020).

Loss of gaseous emissions, such as CO_2, CH_4, and N_2O, into the atmosphere can cause a dramatic rise in the buildup of GHGs (Liu et al., 2023). N_2O is around 300 times stronger than CO_2, while CH_4 is about 40 times more potent, when considering its ability to cause global warming (Chataut et al., 2023). Notably, compared to CO_2 emissions, N_2O emissions from grassland ecosystems are usually far lower, often spanning many orders of magnitude lower (Laubach et al., 2023). It must be acknowledged that the agricultural industry bears a heavy burden of global responsibility (Himu & Raihan, 2023; Raihan & Himu, 2023). It is responsible for approximately 25% of all GHG emissions on Earth, with systems for raising livestock being particularly influential in this regard (Raihan, 2023y; 2023z). The management of grasslands to maximize soil carbon sequestration is shown in Figure 7.

Obstacles and Prospects of SOC Sequestration

Soil carbon sequestration has its limits when it comes to reducing GHG emissions, as discussed by Moinet et al. (2023). Soil carbon sequestration has a lot of untapped potential, but the authors point out a few things that might make it hard to predict how effective it will be. A crucial component is soil carbon saturation, which occurs when the rate of soil carbon accumulation slows down to a quasi-equilibrium state. Longitudinal studies exhibit this saturation tendency, with the exception of certain instances such as peat formation. It is essential to take saturation effects into account while evaluating various management approaches for SOC increase. If this is not done, the potential for carbon sequestration may be overestimated. A total reduction of about 3000 Gt CO_2 emissions is necessary to keep the world's temperature rise to 1.5 ◦C by 2100, as stated in the Paris Agreement. According to Moinet et al. (2023), by 2100, soil carbon sequestration is expected to account for 4% to 1% of the world's emissions, at the very most. Aligning with recent estimates from other angles, this work gives a quantitative view of the function of SOC sequestration in reducing climate change. It also stresses the need for realistic evaluations. Another drawback is that, depending on factors like weather and soil microbes, grasslands may experience greater carbon loss than sequestration. The depletion of productive soil profile layers, which may take a long time to mix with the stored C, is another important limitation that can affect SOC sequestration. Restoring soil systems to their original C-storage equilibrium can take anywhere from a few years to several decades. The dynamics of SOC sequestration and its equilibrium constant in attaining a sustainable green environment in accordance with the UN's SDGs require additional research, nevertheless.

To lessen the impact of climate change on farming, it is essential to manage natural resources carefully and implement farming practices that increase soil carbon sequestration. The impact of shifting weather patterns on this industry is substantial (Raihan & Voumik, 2022a; 2022b). There is a direct correlation between soil carbon sequestration and a win-win strategy for dealing with climate change adaptation and mitigation. This method safeguards soil-based carbon stores from soil microbes that might discharge carbon into the environment by transferring CO_2 from the atmosphere into the soil. One way to restore soil and trap carbon from the air is to switch from traditional tillage to no-till farming methods and turn degraded or marginal lands into perpetual land use. Improved soil health, more sustainable ecosystems, more efficient use of water and nutrients, and substantial sequestration of atmospheric CO_2 are all benefits of no-till farming. The key to achieving these benefits is a combination of zero- or no-tillage and keeping crop residues in the field. SOC accumulation rates at different soil depths can be increased through crop rotation, which is an additional potentially useful technique for soil regeneration and carbon sequestration, especially in conservation agriculture systems. The stability of soil aggregates, water retention capacity, fertility condition of soil, and food security are all enhanced by agricultural management approaches that encourage carbon sequestration. Soil carbon sequestration should be considered as a means to mitigate climate change due to these additional benefits. There is a lack of knowledge on the dynamics and security of soil carbon cycles across various regions of the world, despite the fact that agricultural methods have a huge potential for carbon sequestration. Predicting the broad adoption of carbon sequestration technologies in agriculture is problematic due to the varying patterns of land management. In spite of this ambiguity, knowing the full extent of soil carbon is crucial and shouldn't wait for a perfect grasp of sequestration capacity. Conservation tillage strategies seem to be more effective than other atmospheric drawdown approaches, and they can be improved upon soon. Soil quality and carbon sequestration are both improved by this approach, and it does so with little downsides.

Conclusion

Through the use of carbon inputs and the reduction of SOC losses, agricultural management practices have the potential to improve soil carbon sequestration. Methods for increasing carbon inputs include using cover crops, crop rotation, agroforestry, deep-rooting crops, or applying compost or biochar, which are external carbon sources. By keeping agricultural residues in the field and preventing soil erosion with practices like no-tillage and cover crops, farmers can reduce SOC losses. It is critical to weigh the benefits and drawbacks of various approaches, though. For instance, the accessibility of organic fertilizers such as compost, manure from farms, or biochar, as well as the additional CO_2 emissions that come with transporting them, are limitations. Although mineral fertilizers can help sequester carbon, the extra CO_2 emissions from processes like irrigation pumping and manufacturing can sometimes cancel each other out. We need long-term solutions that weigh the pros and cons of these activities. Downsides include more weeds, altered soil pH, decreased nutrient availability, and leaching from irrigation. Furthermore, the mineralization of SOM or denitrification of nitrogen-applied fertilizers' ammonia or nitrate contents are both accelerated by GHG emissions linked to soil activities. We need further studies and field trials with longer time periods to see how effective new management approaches are at sequestering carbon, such as applying inorganic carbon. In spite of these obstacles, SOC sequestration is essential for soil health, soil fertility, and ecosystem services through preserving soil productivity, reducing the effects of climate change, and providing ecosystem functions.

To maximize the potential for carbon sequestration, overcome limitations, and create effective strategies for preserving soil fertility and health while reducing the effects of climate change in agriculture, ongoing research and the adoption of sustainable agricultural practices are essential. The growing interest in soil carbon sequestration indicates that agricultural soils are likely to play an important role in stabilizing the atmospheric concentration of CO_2 and to do so by means that are consistent with sustainable and climate smart agriculture. Future research directions for climate change mitigation and agriculture sustainability through soil organic carbon involve expanding practices on a large scale, preserving areas with high carbon density, increasing soil organic carbon through modified management or land use in areas with low carbon density, and enhancing land management activities that maintain or enhance soil organic carbon. Additionally, forthcoming studies should prioritize enhancing climate resilience by means of carbon sequestration, monitoring, and maintenance in soils. Furthermore, it is imperative for future research to prioritize the augmentation of sustainable agricultural methods in order to enhance resilience and adaptability to climate change.

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Authors contribution: Asif Raihan contributed to conceptualization, visualization, methodology, reviewing literature, extracting information, synthesizing, and manuscript writing.

Data availability: The author confirms that the data supporting the findings of this study are available within the article.

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