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Soil Carbon Sequestration as a Climate Change Mitigation Strategy: A Review

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The concept of soil carbon sequestration (SCS) has become a key element in the worldwide approaches to reduce the effects of climate change since soils can retain huge amounts of organic carbon that is produced by plant residues, organic fertilizers, and the management system. The given review provides an overview of a complex range of advantages and issues that relate to SCS as a tool to not only reduce climate change but to also improve the condition of soil, its production, and its resilience. The key part of the discussion is the innovative agricultural methods that exemplify conservation tillage, cover cropping, agroforestry, and organic amendments, which in totality help in raising the stocks of soil organic carbon (SOC). Another important part of the manuscript is the analysis of technological innovations, such as remote sensing, isotope tracing, digital agriculture, which enhance the precision of soil carbon measurement and monitoring. These instruments help to determine viable carbon accounting systems, to participate in carbon market and to direct policy interventions. In addition to technological advances, the review also mentions the best practices that are region-specific and consider the local types of soil, climate conditions, and socio-economic aspects to maximize the potential of sequestration and achieve wide implementation. The paper also critically evaluates the current technical, socio-economic and institutional obstacles including soil heterogeneity, land tenure factors, implementation costs and low awareness of stakeholders that hinder scale up of SCS initiative. Moreover, it highlights the need to have an interdisciplinary approach, which integrates the natural sciences, social sciences and policy frameworks in the creation of effective and sustainable solutions. Identified directions into the future are the exploitation of digital agriculture, building stakeholder partnerships, enhancing measurement and monitoring guidelines, and effective policy and incentive development. The review highlights that SCS has great potential, but to achieve its potential, making long-term investments, innovation, and cross-sector cooperation are important. This paper highlights the relevance of SCS as an implementation measure in wider climate-smart agriculture and sustainable land management paradigms and points out its co-benefits to include better soil fertility, water retention, biodiversity, and socio-economic benefits. Overall, the review summarizes the existing body of scientific evidence, demonstrates the gaps in the research and provides strategic recommendations on how soil carbon sequestration can be utilized to regulate climate change and enhance sustainable development objectives. It will be a useful guide to researchers, policymakers and practitioners who are interested in utilizing the complete potential of soils as a natural climate solution.

Keywords: Carbon, sequestration, soil fertility, carbon storage, greenhouse gas, climate change mitigation, soil health, sustainable agriculture, remote sensing, agroforestry.

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INTRODUCTION

The concentration of atmospheric carbon dioxide (CO_2), a major greenhouse gas (GHG), has risen substantially since the beginning of the industrial period, largely due to human activities such as the combustion of fossil fuels, intensive land use, land-use transformation, and deforestation (Yoro & Daramola, 2020). This unprecedented growth of CO_2 has had a profound impact on global warming and climate variability, with far-reaching implications for ecosystems, agricultural yields, and the livelihoods of people (Khan, 2024). This review focuses on providing a synthesis of the latest advances in science and in society for soil carbon sequestration (SCS). It highlights innovative measurement technologies, region-specific management practices, socio-economic barriers, and policy instruments that are important in scaling up SCS practices. Considering the current challenges, including technical, socio-economic, and policy-related barriers, and finding out directions for future research, this review offers a holistic picture of the role of SCS towards climate change mitigation and sustainable land management. The paper is divided into sections covering technological developments, regional management strategies, socio-economic and policy considerations, and future research need to aid in the effective implementation of SCS worldwide. Soil plays a central role in the terrestrial carbon cycle and has been known as an important carbon sink to sequester more carbon than both the atmosphere and terrestrial vegetation combined. Soil Carbon Sequestration (SCS) is the capture and long-term storage of soil organic carbon (SOC) and soil inorganic carbon (SIC) (Figure 1) from the atmosphere as carbon. This primarily occurs by the process of photosynthesis in plants, where CO_2 is taken up by plants and then transferred to the soil via leaf litter, root exudates, crop residues, and organic amendments. Once in the soil, this carbon becomes stabilized through a number of biological, chemical, and physical mechanisms and becomes resistant to decomposition for very long periods of time (Batool et al., 2024).

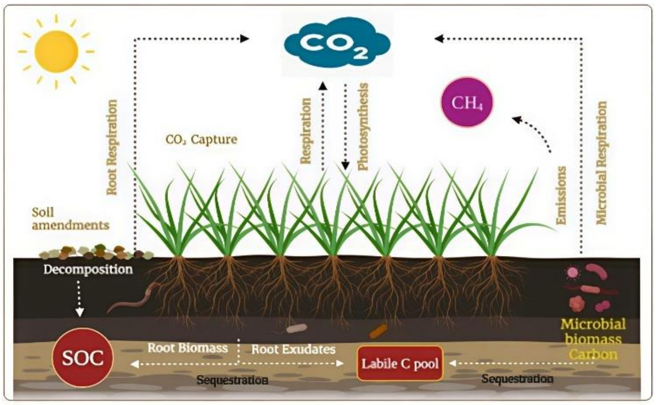

Figure 1. Image of carbon sequestration (Source: Nazir et al., 2024).

SCS not only helps slow down the pace of climate change due to reduced levels of net atmospheric CO_2, but it also improves soil structure, enhances nutrient and water retention and contributes to agricultural sustainability. Because of its potential, SCS is being mainstreamed into global climate agendas, e.g. the "4 per 1000" initiative, which demands a 0.4% per annum increase in global soil carbon stocks to cancel out anthropogenic emissions (Nagothu, 2022). Agricultural soils both function as areas where carbon can be stored and as sources of carbon and are an important component of the planet's carbon cycle (Liu et al., 2022). In the last century, the combination of agriculture intensification and the resulting deforestation, abuse of land, and unsustainable soil use have led to a sharp decrease in the level of soil organic carbon (SOC). This decrease in SOC has been attributed to higher releases of greenhouse gases (GHGs) and decrease in soil fertility, water retention capacity and biodiversity (Lal, 2015). Soil has lost about 50% to 70% of their initial carbon stock since the advent of modern agriculture primarily because of soil degradation processes such as soil erosion, decomposition and mineralization (Abbas et al., 2020). The emission of carbon from the soils into the atmosphere as CO_2 strengthens global warming therefore creating a self-perpetuating feedback loop that results in the further exacerbation of ecosystems. Still, there is also a chance for a solution in this problem (Sanaullah et al., 2022); by restoring soil degradation and enhancing SOC agricultural soils can become very effective carbon sinks that can sequester and store atmospheric carbon dioxide. Nevertheless, deforestation and changes in land use such as clearing forests for the establishment of agricultural lands releases a large quantity of carbon in the form of carbon sequestered in vegetation and soil into the atmosphere, leading to drastic reductions in soil organic carbon (SOC) content. Conventional tillage also makes things worse through oxidizing soil organic matter, thus accelerating decomposition and CO_2 emissions (Bossio et al., 2020). Furthermore, activities such as mono-cropping and bareness of fields for long durations reduce organic carbon inputs and are susceptible to erosion. Agrochemical intense farming with extensive applications of synthetic pesticides and fertilizers also suppresses the diversity of microbes in soils and interferes with important processes of carbon stabilization.

This review aims to examine the processes, activities, possibilities, and limitations of soil carbon sequestration within different agroecosystems. It also evaluates the enabling conditions, such as policy environment, incentive mechanisms, and technological advances needed to realize the full potential of SCS as a viable option for climate change mitigation in the context of sustaining long-term soil fertility and productivity. Some of the technological options for soil carbon sequestration for different regions and cropping systems are provided in Table 1.

Table 1. Technological options for soil carbon sequestration.

Technology	Cropping System	Region
1. Green Manuring	Sugarcane	Tropical
	Rice-wheat	Northwestern
	Rice	Tropical
	Rice	Tropical
	Rice-wheat	Northern
	Rice-wheat	Punjab
2. Mulch Farming/ Conservation Tillage	Rice-wheat	Punjab
	Pearl millet	Arid
	Soybean-wheat	Central
	Arable land	Northern
	Arable land	Northern
	Sugarcane	Tropics
	Sugarcane	Tropics
3. Afforestation/ Agroforestry	Silviculture	Northern
	Acacia nilotica	Central
	Agroforestry	Tropical
4. Grazing Management/ Ley Farming	Grassland	U.P.
	Grassland	M.P.
	Mixed farming	Arid
5. Integrated Nutrient Management/ Manuring	Arable land	Tamil Nadu
	Rice-wheat	Northwest
	Cotton	Central India
	Arable land	Northeast
	Rice-rice	Northern
	Maize-wheat-cowpea	Semi-arid
	Rice-wheat	Northern
	Arable	Northern
	Wetland rice-wheat	Northern
	Maize-wheat	Northern
6. Cropping Systems	Pearl millet	Arid
	Fallowing/ecological	Humid/sub-humid
	Mint-mustard	U.P.

(Source: Murali et al., 2023)

Soil carbon dynamics and sequestration mechanisms**:** Soil organic carbon (SOC), as the main building block of soil organic matter (SOM), plays a crucial role in maintaining soil fertility, enhancing water holding capacity, microbial functioning, and biogeochemical cycling (Gerke, 2022). It is both a sink and a source of atmospheric carbon depending on the management of the soil. It is important to know the dynamic behavior of SOC to exploit its potential for climate change mitigation by carbon sequestration. For maximizing SOC stocks, management should be focused on increasing the amount of carbon inputs and reducing the losses due to microbial respiration and erosion (Bhattacharyya et al., 2022). The role of soil management in the moderation of the global carbon cycle is shown in Figure 2.

Active (labile) pool**:** This pool consists of easily degradable organic matter such as root exudates, microbial biomass and newly deposited plant residues. This pool is characterized by a fast turnover (several days up to several years), significant importance for nutrient cycling as well as lower stability with respect to long-term C storage.

Slow (intermediate) pool**:** This pool consists of compounds which have undergone partial breakdowns, such as lignin and cellulose and is more stable than the active pool with turnover times of decades to centuries. It is a temporary period in the process of decay (Crow & Sierra, 2018).

Passive (recalcitrant) pool**:** This pool contains highly stabilized organic matter such as humic matter and mineral bound carbon aggregates and soil conglomerates. The pool is the basis for long-term C sequestration with turnover times of centuries to millennia (Crow & Sierra, 2018).

Increased photosynthetic carbon sequestration**:** The initial fixation of CO_2 through the process of photosynthetic fixation in the plant atmosphere is the major mechanism for carbon accumulation in soil (Janzen et al., 2022). Through land use management practices such as cover cropping, agroforestry, afforestation and silvopasture there is the potential to increase total biomass yield and carbon addition to soil. Deep root perennial species not only retain more carbon but also entrap it deeper within the soil profile which is less likely to be disturbed or broken through decomposition. One approach to maximizing carbon inputs is to increase carbon net primary productivity (NPP) of ecosystems.

Biomass returns to soil on increase**:** The most direct method to increase SOC is the inclusion of above ground and below ground plant biomass. Agroforestry methods such as crop residues retention, green manure application, composting and organic mulch enhance the quantity and quality of recycling organic matter into the soil (Rosenzweig et al., 2016). A further reason why root biomass is important is that it tends to be a slow decomposer, and the association with soil minerals is also better. These inputs are important in resourcing labile and slow SOC pools and the initiation of the humification process (Nair et al., 2021).

Stable organo-mineral complexes formation**:** Microbial decomposition of organic matter leads to the formation of humic substances, which adsorb on mineral constituents of soils (clays, iron and aluminium oxides) to form organo-mineral complexes. The complexes do not allow organic matter to be later broken down by microbes by either encapsulation within aggregates of soil or adsorption onto the surfaces of minerals. The basis of stable carbon buildup in soils is the physical and chemical protection of organic matter (Christensen, 2020).

Soil microbial and faunal interactions**:** Microflora (bacteria, fungi, actinomycetes) and macrofauna (earthworms, termites, ants) are significant in the decomposition and transformation of the organic matter, as well as its stabilization. Their

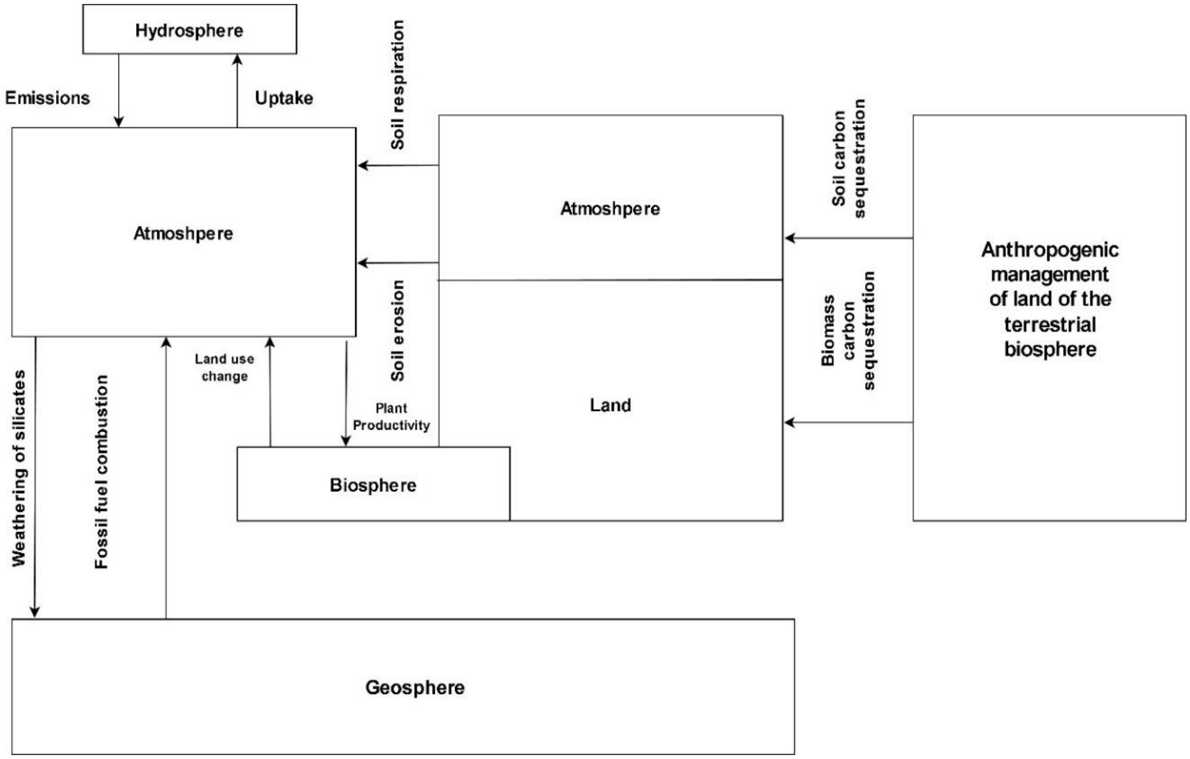

Figure 2.The role of soil and its management in moderating the global carbon cycle.

SOC is commonly divided into three broad fractions

metabolic products, including glomalin-related soil proteins (GRSPs), mucilage, and polysaccharides, are binding agents that stabilize soil aggregates and retain carbon. Dead microbial biomass (Microbial necromass, AMB) is also gaining more significance as a source of stable SOC because it is strongly attached to mineral particles (Kästner et al., 2021)

***Carbon storage in deep soil*:** The recent studies have given particular emphasis on the deep soil horizons (more than 30 cm) that serve the purpose of carbon storage. These layers would have been overlooked in the past; however, they may contain large volumes of carbon, especially where the root systems of perennial plants and /or trees are deep-rooted. The deep carbon is more resistant and not easily perturbed and mineralized and has a longer residence period (Sharma et al., 2022).

Their understanding and support need a combined strategy that should be grounded on site-specific management, enhanced expertise in soil biology, and sustainable land-use. Carbon sequestration in the soil is extremely climate and soil sensitive and is variable between vegetation and ancient management processes. However, it is highly possible that the desired manipulation of the processes can balance environmental sustainability and agricultural sustainability with climatic objectives.

***Agricultural management practices that enhance soil carbon sequestration*:** Sustainable agriculture has been identified as one of the most important factors that lead to the strengthening of the soil organic carbon (SOC) contents; thereby providing solutions to climate change and improvement of soil health. The management practices aim at maximizing organic carbon to the soil and minimizing the loss of carbon through respiration, erosion, and disturbance (Deb et al., 2015). Such practices of climate-smart agriculture have synergistic benefits that do not only result in additional carbon sequestration, but also in enhanced soil fertility, water retention, biodiversity, and farm resilience when implemented in a holistic way and modified to suit agroecological conditions locally (Altieri et al., 2015). They require capacity building, stimulative economic and favorable policy environments to be successfully implemented to realize large-scale adoption by farmers, particularly in smallholder and resource-constrained systems (Bottrell & Schoenly, 2018). The major land management practices that have been established to enhance soil carbon sequestration in different agroecosystem include:

***Conservation tillage*:** Reduced tillage and no-till systems (conservation tillage) cause less physical disturbance of soil thereby preserving soil structure, microbial habitat as well as organic matter (Bezboruah et al., 2024). This approach lowers CO_2 emission and enables soil aggregation and stabilization with the reduction of aeration and oxidation of soil organic matter, which is critical to long-term carbon sequestration. Conservation tillage reduces soil erosion and improves the water infiltration and retention (Ahmad & Wang, 2023). Conservation tillage has restricted or none of the mechanical disturbance of the ground, thus reducing the soil under plowing (Carter, 2017). No-till, strip-till, and reduced-till systems preserve the organization of the soil, retain the organic matter, and reduce the carbon emissions of the soil (Blanco & Lal, 2023). The mechanism of such systems is that crop residues remain on the soil surface and act as a cover to prevent soil erosion and enable organic carbon to be built up (Hussain et al., 2021). The primary advantages are enhanced soil structure that is achieved by reduction in compaction and enhancement in porosity leading to deeper penetration of roots. Also, there is an increase in water conservation due to low surface runoff and high infiltration to guarantee increased soil moisture conservation. Conservation tillage also leads to a stable environment which fosters the growth of microbes to support the growth of the beneficial microorganisms that are involved in the stabilization and accumulation of soil organic carbon (SOC).

Cover cropping**:** The use of cover crops, such as legumes, grasses, and brassica during the fallowing phase increases the biomass, root exudation, and provides a protective layer cover on the soil against erosion and temperature changes (Kocira et al., 2020). The cover crops take into the ground, and on the surface, organic matter, which causes microbial activity to develop and expand both active and inactive SOC pools. Carbon storage is also encouraged through fixation of nitrogen available in the air through leguminous cover crops, which helps to increase plant productivity indirectly. Cover crops are beneficial in capturing carbon dioxide in the atmosphere through photosynthesis and when they decompose, the biomass contributes to the soil organic matter storage significantly. Cover crops have multi-fold ecological and agronomic benefits. These are the leguminous cover crops that can fix biologically nitrogen that enriches the soil with plant-available nitrogen and as such reduces the use of synthetic fertilizers. Besides, cover crops are nutrient scavengers; they absorb residual nutrients in the soil, which is mainly nitrogen, thereby preventing leaching and groundwater pollution. By retaining this nutrient in the biomass, cover crops help in ensuring their gradual release to soil to facilitate nutrient cycling and increase soil fertility (Poeplau & Don, 2015).

Besides the management of nutrients, cover crops also improve soil structure, reduce erosion, keep-off weeds and increase the microbial diversity also contributing to long-term soil health and enhancing the soil potential to sequester carbon (Vukicevich et al., 2016).

Agroforestry systems**:** Agro forestry entails the use of woody perennials (trees and bushes) with annual crops or livestock systems that lead to an increase in carbon input due to increased biomass production and deep root systems. Carbon is stored in above ground biomass in trees in woody biomass and below ground biomass in root biomass. The SOC also contributes to leaf litter as well as pruned residues. Moreover, agroforestry improves microclimatic condition and erosion, which also leads to the retention of carbon (Jinger et al., 2022).

Agroforestry can be defined as the purposeful co-location of bushes and trees in agricultural areas, a combination of forestry and farming in a bid to promote sustainable land use (Raj et al., 2019). The trees in agroforestry contribute to the sequestration of carbon in their biomass, in addition to the increase of the soil organic carbon by means of the deposition of leaf litter and root residues (Swarup et al., 2019). Agro forestry introduces a multistrata system by combining woody perennials with crops or livestock, which mimics natural ecosystems and, therefore, enhances the level of biodiversity and PTA. Figure 3 provides different ways of carbon sequestration.

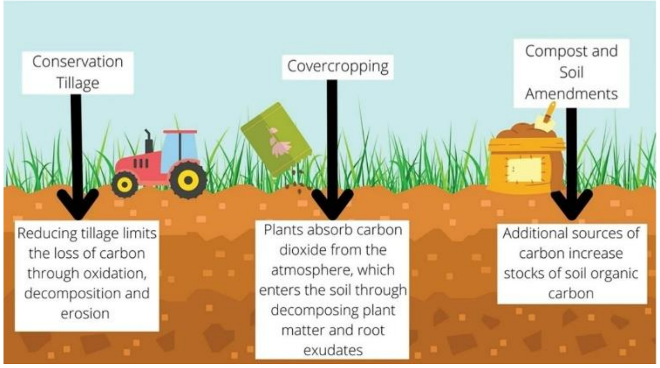

Figure 3. Different methods of carbon sequestration
(Source: Barbato & Strong, 2023)

Application of organic amendments**:** When organic amendments such as compost, farmyard manure, crop residues, green manure, and biochar are added the SOC content is greatly increased due to the amendments of the labile and stable carbon fractions. Compost and manure promote growth of microbes and cycling of nutrients where biochar which is rich in carbon and is a product of pyrolyzed biomass is highly resistant to decomposition and contributes to passive SOC pool. These amendments improve the soil structure and nutrient retention and water holding capacity (Zaib et al., 2023).

Crop rotation and diversification**:** Diversified crop rotations and intercropping systems enhance the biomass below the ground and generate a variety of root architectures and exudates that select a variety of microbial communities. The rotation of deep to the shallow root crops facilitates the carbon input at disparate soil layers and boosts the overall carbon storage in the soil (Zhang et al., 2024). Crop diversification also discontinues the pest and disease cycle, reducing the use of chemical inputs, which otherwise may be detrimental to the microbial health of the soil.

***Improved grazing management*:** Adaptive grazing management activities such as rotational grazing and deferred grazing as well as controlled stocking rates are applied in pastures and rangelands to encourage forages and root biomass development. Efficient grazing prevents overgrazing, maintains ground cover and encourages addition of carbon by litter fall and root turnover. Properly rested grazing systems allow further productivity and high SOC accretion in the long-term (Chen et al., 2015).

***Integrated nutrient and water management*:** Although not specifically mentioned, effective nutrient (especially nitrogen) and water management also improves the process of SOC sequestration by promoting the growth of healthy vegetation and carbon capture through photosynthesis. Greenhouse gas emissions can be reduced with the help of effective irrigation technologies (e.g., drip irrigation) and prevent carbon loss due to leaching and runoff (Wu & Ma, 2015).

***Soil carbon sequestration potential across ecosystems*:** The potential of soil carbon sequestration (SCS) varies across a broad spectrum across various ecosystems due to the history of land use, climate, soil type, vegetation cover, and land management practices. The ability of every ecosystem to hold carbon is the main step in formulating certain interventions that maximize climate reduction as well as enhance soil health. Lastly, sequestration in soils has a high possibility in various ecosystems but holds a lot of promise as a natural climatic remedy. The croplands and degraded regions have a great potential of SOC returning in terms of improved and better management and restoration, but grasslands and forests are vital in the stabilization of carbon and its permanent storage (Bai & Cotrufo, 2022). A landscape-scale mechanism of ecosystem-specific measures will help to maximize carbon sequestration impacts, enhance biodiversity, improve soil fertility and water retention, and improve resilient agricultural and natural systems (Loewen, 2020). The allocation of the possibility of soil carbon sequestration in the major ecosystems is summarized as below:

***Croplands*:** Croplands cover a large part of the planet's land surface and are frequently under intensive farming operations involving repeated tillage, monoculture, and excessive chemical inputs. These intensive methods result in high SOC depletion. In spite of this, croplands have high carbon gain potential if sustainable and regenerative practices are adopted. Currently, the soils that have been covered with crops are found to have low SOC levels due to frequent disturbance and biomass removal at harvesting time. However, it has been noted that croplands have the capacity to sequester 0.1 to 1.0 megagrams of carbon per hectare per year (Mg C ha^{-1} yr^{-1}) depending on the type of soil, climate, and level of management.

The conservation tillage, cover crops, incorporation of organic amendments, diversified crop rotation, and precision nutrient application are promising practices that can be used to improve SOC in croplands (Francaviglia et al., 2023). As an example, the International Maize and Wheat Improvement Center (CIMMYT) conducted long-term experiments in India showing that zero-till with crop residue retention may increase SOC by 20-30% over 20 years have given solid emphasis on the impact of conservation agriculture (Somasundaram et al., 2020).

***Grasslands*:** Grasslands cover approximately 40 percent of the land surface in the world and have moderate to high potential in terms of sequestration of carbon in the soil due to the vast root mat and resistant to degradation. In grasslands, the majority of the SOC is not only below the surface and is tied with root biomass but also turnover is the important driver of carbon addition (Bai & Cotrufo, 2022).

The current day grasslands have been moderately degraded due to overgrazing, frequent fires and other conversion activities which have reduced the carbon level in the soils. It has been realized that in well-managed grasslands (that is, temperate regions), 0.2 to 0.5 Mg C ha^{-1} yr^{-1} of carbon is sequestered. The use of sustainable practices such as rotating grazing, reseeding of disturbed land, balancing the nutrient of soil and controlling fire in these systems can help in enhancing the carbon storage in soil. Maintenance of ground cover and promotion of intact root systems help in SOC accumulation in the long run (Lal, 2015).

***Forests*:** One of the largest terrestrial carbon reservoirs on the earth is forests with over 70 percent of terrestrial carbon in the form of above-ground biomass and soil organic carbon. The older forests will have higher SOC content, but there are a lot of possibilities of sequestration by sustainable forestry and restoration management.

The major carbon sinks on the planet are tropical and boreal forests, which are threatened by deforestation and degradation of forest, thus affecting their capacity to store and capture carbon. The amount of C that can be stored in soils of forests as a consequence of leaf litterfall, dead wood, and root rot can range between 0.05 and 0.5 Mg ha^{-1} yr^{-1}. Some of the effective strategies to add carbon content in forest ecosystem soils include afforestation, reforestation, assisted natural regeneration, agro forestry systems and reduced-impact logging. Restoration of marginal (or abandoned agricultural lands) to forest by afforestation is also a very promising approach to long-term carbon sequestration as well as rehabilitation of ecosystems.

***Degraded lands*:** Degraded lands are those soils that are afflicted with salinity, erosion, loss of nutrients and structural degradation making them very poor SOC stock in terms of landscape. They offer excellent SOC recovery chances through holistic rehabilitation interventions. The degraded land is likely to be poor in terms of soil structure and fertility rate, and decreased diversity which will result in decreased carbon stocks today. The rehabilitation operations are capable of sequestration of 0.3-1.2 Mg C ha^{-1} yr^{-1}, based on degradation and form of rehabilitation (Powlson et al., 2011). The restoration activities include- organic amendments (such as compost, manure, biochar), vegetative cover (grasses or trees), soil conditioning (amendments such as gypsum or lime), and erosion control structures (Rathi et al., 2024). An example of this is in China, in the Loess plateau, afforestation and ecological recovery have resulted in SOC increases of an incredible magnitude, reduced dust storms and increased agricultural output is an example of how carbon sequestration can be co-beneficial in livelihoods and climate mitigation.

Wetlands and peatlands**:** Wetlands and peatlands may harbor a disproportionate percentage of carbon per unit area, which is primarily in the form of peat a highly condensed form of partially decomposed vegetal material (Osman, 2018). Although most wetlands contain very high carbon density, they are endangered by drainage, agricultural conversion and development of infrastructures which release carbon stored in them to the atmosphere. The peatlands alone can hold a number of several hundred megagrams of carbon per hectare. These ecosystems should be conserved and restored through wetting down, encouraging the practice of paludiculture (agriculture in wetlands) and protecting against fire and drainage so as to avoid further emission of carbon and trigger sustained carbon accretion. Peatlands have low rates of carbon accumulation but because of their unique carbon density, conservation of peatlands is of priority during soil carbon sequestration. Co-benefits regarding soils carbon sequestration.

Soils carbon sequestration co-benefits**:** Although soils carbon sequestration (SCS) plays a crucial role in reducing climate change through the sequestration and trapping of atmospheric carbon dioxide, the benefits of the practice go far beyond carbon storage (Rodrigues et al., 2023). The positive effects of practices that accumulate soil organic carbon are many in relation to the health of soils, processes in the ecosystem and agricultural yield. In general, the carbon sequestration of soils offers various synergies that help create resilience agroecosystems, improve farm livelihoods, and general environmental sustainability goals (Franzluebbers & Hendrickson, 2024). SCS contributes to the quality of soil and water, as well as diversity and reduced chemical dependence, leading to long-term productivity and sustainability of agricultural landscapes, making it a pillar innovation of climatic smart agriculture. The most precise estimates of the carbon stocks and fluxes of soil are obtained by higher-strength measurement and monitoring systems that include direct sampling, remote sensing, and modelling (Xu et al., 2025). To ensure the promotion of SCS as a scalable and verifiable climate change mitigation strategy, it is crucial to overcome the challenges with the help of standardized protocols, technological breakthroughs, and capacity development (Luu et al., 2025). These are the co-benefits that promote the importance of SCS as a holistic approach to sustainable land management:

Enhanced soil fertility and structure**:** Soil organic carbon increments lead to improvement in fertility of soil through the provision of sustained supply of nutrients due to the decomposition of the organic matter. SOC improves the aggregation of soil, solidifies soil, reduces compaction and encourages root growth. This improved physical environment can improve nutrient retention and delivery, reduce nutrient loss and maximize plant growth and yield capacity (Gerke, 2022).

Better water retention and drought resilience**:** Soil organic matter has so much water-holding capacity, improving the retention of soil water in case of drought. Soils with a high amount of organic carbon act like sponges and enhance the infiltration of water as well as reducing the surface runoff. Such shock-absorbing capacity enhances crop and pasture drought resistance thereby enhancing the systems in the agricultural industry to be resistant to climatic variation and extreme weather conditions (Kumar et al., 2020).

Increased biodiversity and microbial activity**:** As the SOC levels increase, it offers improved environments to soil microbial communities, fungi as well as fauna to operate hence initiating soil functions such as nutrient cycling, decomposition of organic matter and even suppressing disease. Enhanced microbial diversity results in the stability and resilience of the soil ecosystem where plants can develop in a healthy environment and reduce the vulnerability of crops to pathogens and pests.

Lower requirement for chemical inputs**:** Due to the increase of soil fertility and the inherent cycling of natural nutrients, less and less synthetic fertilizers and pesticides will be needed. This decrease in chemical input lowers the production costs of farmers, lessens the environmental pollution, and lowers the production and use of greenhouse gases in the manufacture and uses of fertilizers. Moreover, healthier soil can be used in the sustainable agricultural intensification without undermining natural resources.

Soil carbon measurement and monitoring**:** The success of the soil carbon sequestration (SCS) activities depends on measurement and continuous monitoring of the amount of soil organic carbon (SOC) stock. Good quality data are important to calculate carbon gain or loss, guide land management practice, certify carbon credits and guide policy processes. Various methods and technologies are employed, and all are at advantage and disadvantage.

Soil direct sampling and laboratory analysis**:** This is an ancient and widely used technique that involves the use of soil samples at varying depths using standard procedures to determine the SOC vertical distribution. Carbon concentration is measured by laboratory analysis by the use of dry combustion (elemental analysis) or wet oxidation. Time-series sampling allows tracking changes of the SOC concentrations. Although this is true, the technique is lengthy, costly and subject to sampling errors as a result of the heterogeneity of the soil.

Remote sensing and geographic information systems (GIS) technologies**:** The progress of remote sensing technologies, including satellite images and drones, hyperspectral sensors, and others, enables SOC estimation at a large scale in an indirect manner through monitoring vegetation cover, soil reflectance, and land use. GIS assists the process of coalescing information layers of spatial data and modeling the SOC distribution with a higher resolution and pace. These technologies are highly beneficial at the landscape scale, but they have to be ground-trusted with ground-truth soil samples to get reasonable estimates.

Modeling approaches**:** Process-based and empirical models describe the SOC dynamics as a mixture of such factors as climate, soil properties, land management, and vegetation inputs. The Century, RothC, and DNDC are some of the developed models that simulate carbon fluxes, decay rates and sequestration potential under different conditions. Models seal gaps in data, make predictions of long term trends and evaluate the impact of management regimes. The quality of input data and assumptions used to make model predictions is of great importance, therefore, it needs to be carefully validated.

Measurement and monitoring challenges**:** SOC changes significantly with soil texture, land use history and with microclimate gradient on short distances that require large scale sampling in order to provide a proper representation of an area. SOC is not equally distributed in depth and absence of equitability in sampling depth across studies may produce comparable data. Changes in SOC take decades or centuries and cannot be monitored in the long term so that it would be possible to detect meaningful changes (Batjes & Wesemael, 2015). Sophisticated technological equipment and frequent sampling might be costly, especially in areas where resources are scarce. Connecting data among different approaches and levels is still difficult yet tforrre is a need of comprehensive monitoring systems.

Policy and economic instruments**:** The development of enabling environments to enhance soil carbon sequestration (SCS) needs to be achieved by effective policies and economic incentives. Such frameworks encourage farmers, land stewards, and other stakeholders to work towards climate-resilient agricultural production practices in terms of reduced financial risks, increased benefit, and sustainability. Well-developed policy frameworks with well-structured economic tools offer an enabling environment in which ambitious adoption of soil carbon sequestration practices takes place. These actions not only help to meet the mitigation goals of climate change but also sustainable development of agriculture, rural lives, and ecosystems. Critical instruments required to develop SCS at local, national, and international levels are follow-ups:

Carbon credit mechanisms**:** Carbon markets are also financial incentives which involve assigning financial value to carbon sequestered in soils. Through such systems, landowners are able to get carbon credits, which they can sell either in voluntary or compliance markets as a way of getting payment of ecosystem services. The agricultural farmers and projects will voluntarily enroll in activities aimed at capturing carbon and receive credit on carbon-verified storage. The regulations mean that the amount of emissions has to be mitigated where the institutions could purchase the soil carbon credits to compensate for the amount of emissions. To achieve successful implementation, powerful measurement, reporting, and verification (MRV) systems should be implemented to foster transparency and credibility. The inclusion of SCS in national systems of carbon accounting fosters market participation and the possibility of global climate finance.

Subsidies and incentives for conservation agriculture**:** Governments may encourage the use of SCS compatible practices by funding inputs (as subsidies or cost- sharing) cover crop seed, organic amendments, and no-till equipment. Economic support reduces investment barriers to entry on the part of the farmers, particularly the small scale farmers. Incentives to long-term investment are the subsidies to taxation payments or even loans with no interest as an incentive to invest in sustainable land management.

Regulatory frameworks for sustainable land use**:** Land use zoning, soil quality guidelines and environmental policies are some examples of policy instruments used to direct sustainable use and prevent degradation. Conservation tillage, lessening of deforestation and bringing about recovery of the degraded land can be achieved with the help of controls. Compliance and protection of soil carbon stocks are practiced through enforcing and monitoring measures.

Capacity building and farmer education programs**:** Knowledge and skill building are also significant to efficient uptake of SCS. Extension education, training workshops, demonstration farm and online portal can make farmers understand the benefits, best management practices and get access to incentive programs. Inclusive practices that pay attention to women, youth, and the underprivileged groups create equity and increase influence.

Alignment with large-scale climate and agrifood policies**:** SCS projects should be oriented on national climate action plans (NDCs), sustainable agriculture policies, and rural development plans to align with them and to efficiently utilize resources. Inter-ministerial coordination of inter-sectoral cooperation between agriculture, environment, finance and forestry ministries promote using co-benefits in inter-ministerial approaches.

Barriers and challenges**:** Although the potential of soil carbon sequestration (SCS) is massive and could definitely help solve the problem of climate change and improve the state of soil, it has certain significant impediments that limit its widespread utilization and effectiveness. Understanding these challenges is the key to creating the effective solutions and supportive frameworks that may be implemented in a broader way:

***Time lag for noticeable soil organic carbon (soc) increases*:** SOC sequestration is a long and slow process which is one of the primary limitations. Evident alterations in soil carbon composition have been observed to consume years to decades since biological and chemical processes regulate the stabilization of carbon. The lag can demoralize those farmers and land managers who seek short term economic returns or noticeable results.

***Lack of awareness and training among stakeholders*:** There is a deficiency in knowledge between the advantages of SC and best management practices required by most farmers especially in resource limited areas. Poor quality of extension services, training programs and unavailability of technical data are some of the problems that interfere with the undertaking of appropriate measures in managing soils.

***Policy and financial constraints*:** In the absence of clear policies, incentive and financing programs to back them, the individuals usually keep them out of investing in the soil-enhancing measures of carbon. Smallholder farmers cannot afford the high cost of shifting to conservation technologies, organic amendments or agro forestry habitats. The coordinated action is also impaired by fragmented policies and absence of sectoral integration.

***Long-term commitment and changes in management*:** SCS requires long-term land management alterations to ensure that the SOC stocks are amassed and maintained. Its lengthy time span can be challenging due to fluctuating economic periods, land tenure on issues as well as other competing farm priorities. Short term land use decision making and market operations may lead to carbon benefits reversal.

***Uncertainty in climate and soc response models*:** Soil carbon dynamics modeling uses complex interactions based on climate variability, soil, vegetation and management. The existing models are not definite when it comes to both spatial heterogeneity and temporal dynamics, which makes the determination and measurement of them difficult. This has created a doubt that it is difficult to come up with effective strategies and to authenticate carbon credit arrangements.

***Technical challenges in measurement and monitoring*:** The SOC changes cannot be reliably estimated using spatial heterogeneity of soil and site constraints of depth and frequency of sampling. They are unavailable because of low levels of affordability and technical skills required to be able to measure advanced measurement technologies such as remote sensing or isotopic tracing.

***Socio-economic and institutional barriers*:** Land fragmentation, insecurity of land tenure, cultural practices, and institutional weaknesses are some of the factors that influence the adoption of SCS practices. Gender inequality and social injustice can further disadvantage some groups by denying them the benefits or the decision process. These obstacles have to be reduced by combined efforts which will unite education, change of policies, economic motivation, innovation in research and participation of stakeholders. Addressing socio-economic and institutional constraints and technical will be core towards achieving the full potential of soil carbon sequestration in developing climate resilience and sustainable agriculture.

***Limitations and ecosystem-specific effectiveness of soil carbon sequestration mechanisms*:** Although the processes of soil carbon sequestration like photosynthesis, biomass returns, and organo-mineral complex formation are basic processes, they are not uniformly effective due to the number of ecological, soil and management factors. Photosynthesis, despite its critical role in biomass yields, leads to the production of organic contributions which in the stable soil carbon is usually insignificant due to environmental pressures, nutrient status and land management. Furthermore, fast microbial biomass breakdown, leaching and soil disruption limits the ability of biomass residues to add to soil carbon and thereby stabilize it over time. The organo-mineral complexes which have been known to stabilize organic matter are the ones that require soil mineralogy, pH and microbial activity. The development of these complexes may be hampered in soils of low mineral content or where disturbances are frequent causing them to have lower ability to stabilize carbon. Moreover, the overall contribution of these processes depends on the land use and land management that dictate the ratio between organic inputs and degradation events. Lastly, the efficacy of such mechanisms is ecosystem specific. As an example, the presence of high mineral content soils in forests is more inclined towards the formation of the organo-mineral complexes compared to the more organic-based soils in the wetlands, which are highly dependent on microbial biomass and remnants of organic substances. Knowledge of these variations and the mechanisms interactions is important to create land management strategies that achieve optimal carbon sequestration in the soil under the varying ecosystems.

***Future directions and research needs*:** To fully realize the potential of carbon sequestration (SCS) as a green and long-term climate mitigation measure, it is important that research and innovation be sped up in different areas. The following key areas of priority should be taken into consideration in the future:

***Integration of digital agriculture for precision SCS monitoring*:** Drones, remote sensing, IoT sensors, and big data analytics could change the process of managing and monitoring soil carbon. Precision agriculture technologies enable site-specific measurements of SOC, crop stress, and soil water levels to make informed customized interventions to balance carbon sequestration and productivity. Digital platforms that are easy to adopt and those that are quite broadly applicable and which farmers and land managers find simple to ensure their adoption.

Region-specific best practices development**:** Soil types, agroecological regions and socio-economic environments are diverse and a single-size-fits-all SCS recommendation may not be effective in all locations. The future studies should examine and determine the management practices that are location-specific and that result in the optimum carbon profit and the resolution of regional challenges. This includes experimenting with various options of tillage, crop rotation, organic amendment and agroforestry systems that suit regional systems of farming and climate.

Improved carbon accounting methods**:** Carbon accounting should be made more accurate and transparent to facilitate carbon markets, farmer incentives and policy. It is necessary to reduce the uncertainty by improving soil carbon modeling, use of long-term field data, and standardization of measurements protocols. Isotopic tracing and molecular characterization of soil organic matter are new techniques that can illuminate carbon dynamics.

Leveraging synergies with biodiversity and water conservation objectives**:** Future studies should explore the possibility of integrating SCS with more comprehensive environmental objectives, e.g. biodiversity and water conservation. Cover cropping and agro forestry are SCS practices, which not only sequester carbon but also enhance diversity of habitats, enhance soil health and efficiency of water use. This knowledge may be used to guide multifunctional land use planning to improve the resilience of ecosystems and human wellbeing.

Interdisciplinary research integrating soil science, climate modeling, and socioeconomics**:** To address the complex challenges of SCS, transdisciplinary approaches, including the interconnection of natural sciences with social sciences, are needed. The interrelationships between ecosystem processes, climate uncertainty, economic incentives and farmer choices can be disentangled with the help of multidisciplinary research by soil scientists, climatologists, economists and social scientists. Integrative research will also inform more effective policies, incentive plans, and adoption pathways. The key to addressing soil carbon sequestration in a scale and sustainability capable of making it a viable solution to climate change will be investment in the newest research, innovation, as well as interdisciplinary and stakeholder partnership strengthening. By emphasizing inclusiveness, technology, and ecological co-benefits, SCS will contribute greatly to global climate targets and sustainable development.

Conclusion**:** Soil carbon sequestration (SCS) is a new, inexpensive, and natural process of reducing the amount of greenhouse gases in the atmosphere to combat climate change besides improving soil health, agricultural output and ecosystem stability. By adding more organic carbon to the soils, SCS does not only reduce greenhouse gas levels in the atmosphere but also generates a number of co-benefits such as improved soil fertility, water retention capacity, and biodiversity.

Nevertheless, to achieve the full potential of SCS requires a multi-dimensional reaction of solid scientific research, enabling and adaptable policy settings, massive farmer involvement, and unanimity among governments, researchers, industry and civil society. Flexibility of the methods to certain agroecological and socio-economic environments and integration of technological innovations will be the keys to success.

Lastly, through further investment, effort and collaboration, soil carbon sequestration can become one of the major contributors to the creation of climate resilient agricultural systems and a major priority in the global sustainable development process and environmental protection endeavor.

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