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Role of Soil Organic Carbon Sequestration in Climate Change Mitigation and Sustainable Agriculture: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

A significant method for reducing greenhouse gas emissions while enhancing the environmental quality and profitability of agricultural systems is through the process of soil organic carbon (SOC) sequestration. This review assesses the effects of SOC on climate mitigation, the sustainability of food production and the enhancement of soil health. Globally soils are estimated to store about 1500 to 2400 Gigatons of carbon which represents three times more carbon than exists in the atmosphere or all plant biomass; therefore, the maintenance of SOC is an important mechanism for controlling the climate. This review integrates what is currently known about the mechanisms of SOC, the influence of various factors on SOC, the management practices which can increase SOC, and the quantitative reduction of greenhouse gas emissions possible from SOC sequestration in a variety of agroecosystems. Results show that conservation agriculture, agroforestry, cover cropping and biochar additions can result in the sequestration of 0.3 to 2.0 metric tons of C/ha/year, although large variability exists among soils and climates based upon management practices. In addition to the reduction of greenhouse gases, SOC-enhancing management practices have many additional benefits including improved water retention, improved nutrient cycling, improved biodiversity, and improved crop yields. However, to achieve global greenhouse gas emission reductions will require the adoption of these practices over billions of ha of land and will need to be implemented within a supportive regulatory framework, economic incentive program, and innovative technology. This review presents a complete assessment of the literature for those who would like to develop policies, practice and research related to SOC sequestration for reducing greenhouse gas emissions and improving the sustainability of agricultural systems.

Keywords: Soil organic carbon; climate change mitigation; sustainable agriculture, carbon sequestration; soil management; agroforestry; conservation agriculture; greenhouse gas emissions.

1. Introduction

The accelerating impact of climate change necessitates swift policy action across every aspect of the economy; however, agriculture and land use represent perhaps the greatest opportunities for both carbon sequestration and reduced emissions globally (Shipman et al., 2021). As the largest terrestrial carbon pool, soils store at least 1500 to 2400 gigatons of carbon within the top meter of their profile — greater than the entire atmospheric carbon pool and combined plant biomass carbon (Jackson et al., 2017). Due to its sheer scale, carbon sequestration via soil organic carbon (SOC) is a transformational approach toward mitigating climate change impacts while simultaneously supporting food system resilience under increasing climate uncertainty and global population pressures. An increasing body of research emphasizes that substantially increased levels of terrestrial carbon sequestration will be required to meet the Paris Climate Agreement's goals of limiting global warming to 1.5 – 2.0°C, and that soils are among the most feasible and cost-effective means of achieving this goal.

Soil organic matter (SOC), primarily comprised of carbon, provides a multitude of essential services to soils that are critical to maintaining soil health and function and extends far beyond simply storing carbon. SOC improves the physical properties of soil such as soil fertility, biological activity, structure, water holding capacity, and resistance to compaction, leading to improvements in crop yields in a wide range of climates and soil types (Brady & Weil, 2017; Saritha et al., 2025). It plays an essential role in maintaining ecosystem services and agricultural sustainability. SOC acts as a major reservoir of carbon in terrestrial ecosystems and contributes significantly to the global carbon cycle (Lal, 2004). In recent years, increasing attention has been given to SOC due to its potential role in mitigating climate change. Agricultural soils have the capacity to sequester carbon and reduce atmospheric CO_2 concentrations through appropriate management practices (Smith et al., 2008). However, the extent of carbon sequestration is influenced by various factors, including soil type, climate, land use, and management practices (Paustian et al., 2016). The biological and chemical processes facilitated by SOC provide nutrients for plants, act as a microorganism habitat, and retain pollutants in ecosystems — ultimately contributing to the resilience of ecosystems and their ability to produce food. In many parts of the world where agricultural activities have been practiced intensively for centuries, particularly in tropical and subtropical regions, and formerly forested or degraded lands — SOC contents have declined by as much as 50 – 75% (Hussain et al., 2021; Du et al., 2023; Khenrab et al., 2025). Rebuilding these lost carbon reserves represents a tremendous opportunity for simultaneous climate mitigation and agricultural productivity gains — therefore, SOC sequestration presents a “win-win” opportunity for addressing intertwined environmental problems.

Agricultural practice is linked to climate change through several interrelated pathways, including both greenhouse gas emissions and carbon sequestration. Agricultural soils emit large amounts of nitrous oxide (N_2O, ~310 times the global warming potential of CO_2) and methane (CH_4), especially when associated with wet rice paddy fields and grazing systems — in contrast, there is considerable opportunity for sequestering carbon dioxide through better management (Hou, 2021). When farmers implement practices that increase SOC accumulation and reduce emissions of other greenhouse gases — the agricultural sector can shift from a net emitter of greenhouse gases to a net carbon sink. This review distills the existing literature on SOC sequestration into actionable strategies for climate mitigation and sustainability, synthesizing scientific knowledge on the mechanisms, potential, and applications of SOC sequestration to support decision-making by policymakers and agricultural practitioners.

2. Mechanisms and Processes of Soil Organic Carbon Sequestration

2.1 Fundamentals of Soil Carbon Cycling and Sequestration Pathways

Carbon Sequestration is the process in which Carbon Dioxide from the atmosphere is captured by vegetation using the process of Photosynthesis. The Carbon is then moved to the Soil via Roots of the Plant and Plant Residues, and is stored in Mineral Formations in the Soil that are resistant to Decomposition (Gupta et al., 2022).

Photosynthesis converts CO_2 into Organic Compounds. A portion of the Organics is contained in Biomass of the Plant; once the Plants die, the Biomass can be Returned to the Soil in the form of Above-Ground Litter (Crop Residue, Fallen Leaves), or Below-Ground Resources (Root Exudates, Dead Roots) (Batista-Silva et al., 2018). In the Soil, the Organic Materials decompose with Microorganisms in the Soil releasing a portion of the Carbon as CO_2 (Respiration Process) and incorporating another portion into Stable Soil Organic Matter through Humification and Mineral-Organic Interactions (Batista-Silva et al., 2018). Stable Organic Matter is created through several Chemical, Physical, and Biological Processes working together to Store Carbon in the Soil for Long-Term Storage. Chemically, Organic Matter undergoes Polymerization and Condensation Reactions forming Complex Humic Substances that are Resistant to Microbial Degradation (Don et al., 2024). Physically, Organic Matter becomes Encapsulated within Soil Aggregates that limit Microbial Access (Don et al., 2024). Biologically, Organic Matter Forms Associations with Soil Minerals (Clay Particles, Iron/Aluminum Oxides) creating Complexes that Remain in the Soil for Decades to Centuries (Don et al., 2024). Rates of Carbon Sequestration depend upon the Balance of Inputs (Primary Productivity, Crop Residue Returned) and Outputs (Respiration Rates by Roots and Microorganisms), with Management Practices serving to Shift this Balance towards Net Accumulation. Depth Distribution of Stored Carbon Varies Significantly among Soils managed Under Different Systems with Important Implications for Permanence and Accessibility to Oxygen (Rodriguezs et al., 2023). In Undisturbed Soils, Carbon is Stored Throughout the Soil Profile, with Significant Stocks occurring in Depths greater than 50 cm (Rodriguezs et al., 2023). The Lower Temperatures, Reduced Oxygen Availability, and Limited Microbial Activity result in Reduced Decomposition Rates in these Deeper Depths.

In Conventionally Tilled Agricultural Soils, Carbon is Stored in the Upper 10-20 cm of the Plow Layer, where Disturbance Increases Decomposition Rates and Exposure to Oxidizing Conditions (Hussain et al., 2021). However, Conservation Agriculture and No-Till Practices allow Carbon to be Stored at Greater Depths, where it is More Stable and Less Susceptible to Rapid Decomposition, Making these Management Systems particularly Effective for Long-Term Sequestration (Hussain et al., 2021).

2.2 Carbon Saturation Concept and Sequestration Limits

In addition to limiting the amount of SOC that may be accumulated within a particular soil, the idea of soil carbon saturation has been recognized as a key limitation to the quantity of SOC that may ultimately be accumulated in a specific soil; the saturation capacity of a soil is generally controlled by clay content, mineral type and soil texture (Zhao et al., 2021). In general, soils possessing high clay contents and/or diverse mineral surfaces (such as iron and aluminum oxides), which are capable of protecting organic matter through organo-mineral associations, generally achieve greater saturation capacities than do coarse-textured soils having low surface areas where organic matter may associate. A significant practical implication of carbon saturation is that as a soil reaches near-saturation capacity of carbon, the rate at which additional carbon is accumulated will decrease dramatically and essentially approach zero when saturation is reached (Maringgal et al., 2020). Thus, the carbon sequestration potential of any particular soil is considered to be finite; therefore, while SOC-enhancing practices may provide substantial short-term mitigation benefits they will also eventually plateau.

Studies examining the saturation of SOC in different types of soils have shown that saturation thresholds of SOC typically vary between approximately 35 Mg C / ha to 95 Mg C / ha depending upon the texture and mineralogy of the soils studied and clay soils generally exhibit the greatest saturation capacity for SOC (Siddique et al., 2023). The duration required for a soil to reach a state of saturation will vary from 10 to 40 years depending on the magnitude of the management-induced organic matter input into the soil and the inherent properties of the soil; however, because the absolute saturation capacity of coarse-textured soils is less than that of fine-textured soils, coarse-textured soils will tend to reach saturation more quickly. To realistically assess the mitigation potential of SOC-enhancing practices, understanding the dynamics of carbon saturation is critical; whereas the initial rate of carbon sequestration associated with SOC-enhancing practices may range from 1-2 metric tons C / ha annually, this rate typically diminishes over time as the soil approaches saturation (Lustriane et al., 2018); nonetheless, as long as SOC-enhancing management practices continue to be implemented, the elevated SOC levels of individual fields remain permanently elevated, thereby providing continued climate benefit.

2.3 Climate and Edaphic Factors Controlling SOC Dynamics

In addition to differences in how much carbon is produced, there are significant variations in how long that carbon remains in the soil across different climates. Temperature and rainfall are two of the most important factors that control how quickly plants grow, as well as how fast organic matter decomposes. High temperatures and adequate moisture levels can promote rapid growth of plants and therefore large amounts of carbon entering into the soil system. However, at the same time, these same environmental conditions can accelerate the breakdown of organic matter in the soil by thermophilic organisms, leading to increased carbon release back into the atmosphere. As a result, the net carbon accumulation in the soil tends to be less in these types of systems compared to other systems where decomposition rates are slower (Hao et al., 2025).

On the other hand, temperate regions with moderate temperatures and adequate moisture will tend to have higher SOC concentration values than would be expected based solely on their productivity, primarily because decomposition rates are generally slower in these environments than they are in tropical ecosystems. This allows for a greater accumulation of carbon in the soil even if the primary productivity is lower (Siddique et al., 2023). Arctic and desert regions provide a paradox in this respect. Desert systems have low productivity, which limits the amount of carbon that enters into the soil. However, the low moisture and biological activity in these systems also results in low decomposition rates, thereby increasing the amount of carbon that accumulates in the soil relative to its productivity. This phenomenon has been reported in various studies in arid and semi-arid regions (e.g. Hussain et al., 2021).

As previously mentioned, the chemical properties of the soil can also have a significant impact on SOC dynamics. One of the most important ways in which soil chemistry impacts SOC is through the way it influences microbial populations within the soil ecosystem. Soil pH can affect microbial communities through several mechanisms, such as changing the availability of essential nutrients needed for microbial activity, or altering the type of soil minerals that microbes interact with. In addition, changes in soil pH can also impact the physical and chemical structure of organo-mineral complexes, thereby affecting the degree to which they are able to stabilize SOC. Acidic soils ($pH < 5.5$) often have high SOC concentrations due to the formation of recalcitrant organic compounds that are stabilized by interaction with aluminum ions. However, acidic conditions tend to suppress plant productivity and limit the availability of nutrients needed for plant growth (Batista-Silva et al., 2018). Soils with neutral to slightly alkaline pH (6.5 – 7.5) are generally considered to be optimal for plant productivity and decomposition, making them ideal for SOC accumulation (Jost et al., 2021). Highly alkaline soils (pH > 8.0), while capable of supporting some plant productivity and decomposition, often have reduced SOC values. This reduction can occur due to the fact that highly alkaline soils tend to support high rates of decomposition and low plant productivity in many regions. While the overall response of the SOC pool to soil pH may vary depending on the local geology, climate, and vegetation, highly alkaline soils generally do not accumulate as much SOC as soils with pH values closer to neutral.

3. Soil Organic Carbon in Different Agricultural and Natural Ecosystems

3.1 SOC Stocks and Dynamics in Croplands

SOC has been greatly reduced in many of the world's agricultural soils since they were converted to crops. Data on SOC reductions show that the concentration of SOC in intensively farmed soils is now typically 25-75% less than before farming began. The greatest decreases occurred when forested land was converted to agriculture. In addition to those historical declines in SOC concentration, current SOC stocks in cropland soils worldwide range between 40-60 Mg C/ha, which is significantly less than SOC found in undisturbed ecosystems such as grasslands (120-200 Mg C/ha) and forests (150-250 Mg C/ha). These large differences represent a legacy effect of past agricultural practices, and also create a large potential for SOC restoration through proper use of the soils' saturation capacities. For example, if cultivated soils could be managed to reach their SOC saturation capacities, there is potential to remove hundreds of gigatons of CO2 from the atmosphere.

The mechanisms responsible for SOC decline in croplands are well understood and include: (1) removal of protective cover (i.e., deforestation and grassland conversion); (2) removal of crop residue that would have returned to the soil through the harvesting process; (3) increased decomposition rates resulting from soil disturbance and/or tillage, which exposes protected organic matter to microbial decay and oxidation; and (4) decreased root growth due to monoculture cropping practices and removal of perennial species (Hussain et al., 2021). The magnitude of each factor contributing to SOC decline differs depending on location, but typically tillage induced decomposition is the dominant mechanism of SOC decline in temperate and subtropical agroecosystems, whereas removal of native vegetation is the largest contributor of SOC decline in tropical ecosystems where agroconversion occurs (Francaviglia et al., 2023). Understanding the mechanisms behind SOC decline is critical to developing strategies to mitigate SOC decline and restore SOC in agricultural systems.

3.2 Carbon Dynamics in Perennial and Forest-Agricultural Systems

The mechanism that supports SOC sequestration in agroforestry is based on:

(1) Continuous litter inputs from woody elements are added to the above ground litter inputs from annual crop residues;
(2) The root systems of woody elements reach into and recycle the deeper soil layers as a result of their greater depth than those of annual crops;
(3) Annual crop roots are less disturbed than annual crops grown in monoculture because of the presence of other plants;
(4) Diverse organic substrates provided by the various types of plants promote the accumulation of different types of organic matter (Gelaye & Getahun, 2024).

SOC stocks in silvopastoral systems can vary significantly, depending largely upon the extent of grazing practiced and how it is managed (Siddique et al., 2023). In general, light to moderate grazing in forest/grassland mosaics will increase SOC content when they create conditions favoring an increase in both litter production and feces produced by animals and retain a sufficient amount of woody canopy to protect against erosion. However, where the level of grazing is high, it may lead to significant SOC loss in silvopastoral systems. The loss of SOC results from the reduction in plant growth that leads to lower amounts of litter being produced, the soil compaction resulting from the grazing animals' hooves, and the higher rate of decomposition of organic matter due to the grazing animals consuming the plant material (Hussain et al., 2021). As such, the ability to optimize the SOC content in silvopastoral systems in order to maximize the SOC content in the long term, will require careful management to ensure that the desired level of productivity is achieved without compromising the SOC content of the soil.

3.3 SOC in Grasslands, Wetlands and Marginal Lands

The world's soils have stored and will continue to store the largest amount of carbon, and they do so primarily as a result of organic carbon in the soil that has been generated by plant roots. Soils in native grasslands can be expected to store between 100 and 200 Mg C/ha; however, these values can vary significantly depending on factors such as climate and precipitation (Jackson et al., 2017). The extensive root system of perennial grasses generates significant amounts of carbon below ground in the form of continuous input of organic matter into the soil, protecting it from decomposition deeper in the soil profile where it is difficult for microorganisms to break down the organic matter (Marks et al., 2009). Grassland to cropland conversion results in a rapid decline in SOC (typically a 50-75% decline in SOC over 20-40 years) and demonstrates why grassland conservation should be an important focus of climate mitigation efforts (Hussain et al., 2021). However, restoring degraded croplands to grassland or native vegetation through restoration programs provides the opportunity for SOC to recover rapidly; although the recovery trajectory is much longer (it may take 10-30 years for SOC to reach near original levels after degradation) compared to the rate of the initial loss (Hassan et al., 2022).

Wetland soils including marshes, swamps, and organic peatlands store disproportionate amounts of carbon relative to their global areal extent, with peatlands alone holding an estimated 600 gigatons of carbon (approximately 40% of all global soil carbon and 3% of the global land surface) (Batista-Silva et al., 2018). Anaerobic conditions in wetland soils create environments in which decomposition rates are reduced dramatically, thereby enabling organic matter to accumulate at rates similar to those of primary production (Marks et al., 2009). The climate importance of wetland carbon is further enhanced by the possibility of sudden loss of carbon when wetlands are drained or disturbed; when peatlands are drained, they produce substantial emissions of CH_4 and CO_2; when intact, peatlands produce CH_4 (a potent GHG) as a result of anaerobic microbial processes (Hou, 2021). Therefore, management of wetlands for climate mitigation focuses on preserving and restoring wetland areas to maintain anaerobic conditions and thus to avoid catastrophic loss of carbon.

4. Impact of Agricultural Management Practices on Soil Organic Carbon Sequestration

4.1 Soil Disturbance and Tillage Effects on Carbon Dynamics

Soil Tillage, an Agricultural Practice That Affects Carbon Sequestration Through Mechanisms of Physical Protection of Organic Matter and Soil Oxidation Rates. Conventional tillage (such as moldboard plowing and discing) significantly increases SOC oxidation rates through four different mechanisms: (1) physical protection of organic matter is broken down when soil aggregates are destroyed, (2) the increased exposure of the soil surface to microbial decomposition, (3) increased soil aeration, and (4) rapid decomposition of new additions of organic matter (Hassan et al., 2022). Long term studies comparing SOC accumulation between tilled and no-till soils consistently show that SOC accumulation rates under conventional tillage are 50-80% lower than those observed in non-tilled soils receiving the same amount of organic matter (Wang et al., 2020).

Carbon Dynamics Following Conversion from Conventional Tillage to Reduced or Zero Tillage Are Relatively Well Defined and Follow These General Trends: Immediately After Adoption of No-Till Practices, SOC Accumulation Rates Typically Increase By 0.5-2.0 Mg C/ha/year Depending on the Amount of Residue Returned and Soil Type (Maringgal et al., 2020). However, This High Rate of Carbon Sequestration Is Not Sustainable Indefinitely; As Soils Approach Their Saturation Capacity (Typically In 20-30 Years), The Rate at Which Carbon Is Sequestered Declines Significantly (Silveira Nicoloso et al., 2020). Despite This Reduction in Sequestration Rate Over Time, Long Term Studies Spanning Greater Than 30 Years Have Shown That Non-Tilled Soils Maintain SOC Concentrations 15-35% Higher Than Conventionally Tilled Soils, Providing Permanent Climate Benefits for as Long as the Conservation Practice is Maintained (Yuan et al., 2023). Additionally, The Depth Distribution of Sequestered Carbon Also Differ Dramatically Between Tillage Systems with Zero Tillage Systems Sequestering Carbon Throughout the Soil Profile While Conventional Tillage Results in Surface-Concentrated Carbon (Francaviglia et al., 2023).

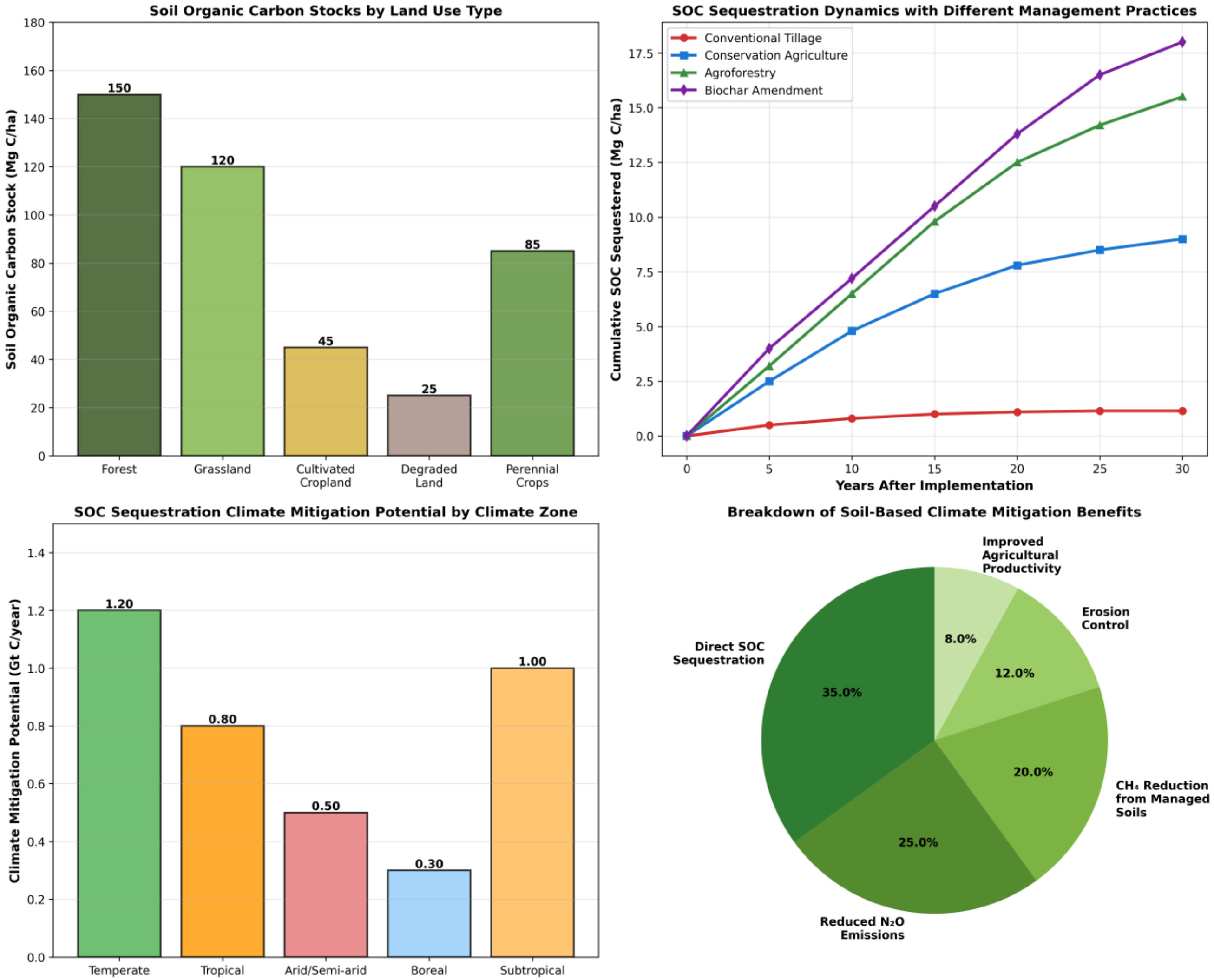

Fig. 1. Different agricultural systems are able to produce substantially varying amounts of SOC sequestration

The graph illustrates how different agricultural systems are able to produce substantially varying amounts of SOC sequestration as a result of the way in which each system is managed; it also shows that agroforestry and Conservation Agriculture (CA) have significantly higher rates of SOC sequestration than traditional farming systems. This graph was developed by combining data from numerous long term research projects with similar management strategies. It highlights the size of SOC sequestration and the duration of SOC sequestration for several types of agricultural systems.

4.2 Organic Matter Input and Residue Management Strategies

The amount, type, and timing of organic material inputs into soils have been identified as key factors controlling the capacity of soils to store SOC; and agricultural practices specifically designed to enhance the return of organic materials to the soil surface have been shown to be highly effective at promoting SOC accumulation (Siddique et al., 2023). Crop residue retention is considered to be one of the most direct methods to increase organic material inputs to the soil. It involves leaving crop residue (stubble, stover, etc.) in the field instead of taking it away for use as animal feed or for energy production. Studies have shown that this practice can promote an additional 0.3-0.8 Mg C/ha/year of SOC sequestration (Wang et al., 2020). However, there are many variables that determine how well crop residue retention will perform to enhance SOC sequestration, including rate of decomposition of the crop residue, which is determined by the carbon-to-nitrogen (C:N) ratio of the residue, the amount of lignin present, and the environmental conditions (Hassan et al., 2022). For example, residues with high C:N ratios and/or high lignin content (e.g., cereal crop stalks) tend to break down slowly and protect stored carbon for longer periods of time, whereas residues with low C:N ratios and/or low lignin content (e.g., legume residues) tend to break down quickly (Jackson et al., 2017).

In addition to crop residue retention, another way to increase organic material inputs to the soil is to implement cover cropping (planting non-cash crops to maintain soil cover and add organic material to the soil) during off-season periods (fallow), between cash crops, or both (Hussain et al., 2021). In particular, cover crops, especially those that fix atmospheric N (nitrogen-fixing legumes), contribute to the soil system in two ways: they can provide supplemental N for subsequent crops through biologically fixed N and they can provide additional organic material to the soil (Yuan et al., 2023). The effect of cover cropping on SOC sequestration can vary significantly (from 0.2 to 0.6 Mg C/ha/year) based upon the species selected, duration of growth, and how the cover crop is incorporated into the soil (Wang et al., 2020). Integrated crop-livestock systems (ICLS) also incorporate the benefits of crop production with the added benefit of using residues more efficiently in the food chain and extending the productive life cycle of plant production, often producing higher net SOC accumulation compared to either sole crop production or livestock production (Siddique et al., 2023).

Finally, external organic material inputs such as compost and manure can provide a mechanism for enhancing SOC sequestration in soils that have lost significant amounts of their SOC pool (degraded/depleted soils) (Silveira Nicoloso et al., 2020). Compost applications can lead to rapid increases in SOC sequestration, up to 2-4 Mg C/ha/year in the year following application when applied at 10-20 Mg/ha (Silveira Nicoloso et al., 2020). However, the sustainability of these types of approaches will depend on the ability to identify reliable and cost-effective sources of feedstocks for compost production. Biochar addition (the application of thermally treated organic materials to soil) provides a new mechanism for achieving long-term SOC sequestration through the high chemical stability of biochar, with the potential for achieving permanent carbon storage levels greater than conventional organic matter (Schmidt et al., 2019).

4.3 Crop Diversification and Integrated Management Systems

The three most important ways to increase your ability to capture and store Carbon Dioxide (CO2) in soils as a result of the methods used in agriculture is by implementing crop rotation and polyculture systems, and also by using Intercropping Systems. When you have crop rotation and polyculture systems, they allow you to take advantage of several different methods for increasing CO2 storage in soils. They include the use of a greater variety of Organic Matter, more efficient use of resources, and lower levels of chemical inputs than traditional farming methods. As an example, Hassan et al. (2022) states that in comparison to the levels of CO2 stored in soils when the same land was planted continuously in one type of crop (monoculture), crop rotation systems which included legumes were able to capture up to 0.4 - 0.9 MgC / ha / year.
The primary reasons for the increases in CO2 storage resulting from crop rotation systems and polyculture systems include:

(1) Greater variety of carbon sources support a greater variety of decomposers that break down organic matter at slower rates,
(2) Increased allocation of carbon underground due to the presence of symbiotic relationships (i.e., mycorrhizal associations),
(3) Improved physical properties of soils that protect organic matter.

Agroforestry systems, which incorporate trees into cropping systems (and/or grazing systems), are capable of achieving the greatest level of CO2 storage in soils of all types of agricultural systems. Agroforestry systems may be capable of storing between 0.8 – 2.5 Mg C / ha / yr under the best management practices (Sharma et al., 2019). Agroforestry achieves such high levels of CO2 storage as a result of four main factors:

(1) Multiple layers of vegetation produce a continuous flow of organic matter into soils,
(2) Trees are able to access and incorporate carbon from deeper in the soil profile because of their extensive root systems,
(3) Sustained production of organic matter continues throughout the year even when annual crops cannot be grown,
(4) Annual cropping typically disrupts the structure of soils much more than agroforestry systems do

In addition to being able to store large amounts of CO2 in soils, agroforestry systems also contribute to carbon sequestration in the form of above-ground tree biomass, adding another 1 – 3 Mg C / ha / yr to total carbon sequestration (Roy et al., 2022). Due to this combination of effects, agroforestry systems offer a potentially highly effective means of mitigating climate change.

Integrative Soil-Crop-Livestock Systems are considered to be the most sustainable way to manage the natural world as it relates to agriculture. Integrative Systems combine the complementary production functions of crops, livestock, and other forms of living organisms to create an efficient, closed-loop system that minimizes reliance on external inputs, while maximizing carbon storage in soils. Within these systems, the relationship between each component is mutually beneficial: Crops grow to provide feed and residue for livestock; Livestock graze and consume crops to provide nutrient-rich manures to fertilize crops; All three components work together to maintain a stable, self-sufficient ecosystem (Francaviglia et al., 2023). Long-term studies of integrative systems indicate that these systems exhibit both higher SOC sequestration and higher sustainability than individual component systems, indicating that as long as there is sufficient diversity within a system, there will be sufficient carbon storage (Hassan et al., 2022).

Table 1. Comprehensive summary of SOC sequestration rates and key characteristics of various management practices, providing quantitative guidance for system selection and optimization

Management Practice	SOC Sequestration Rate (Mg C ha−1 yr−1)	Key Characteristics & Optimization	Equilibrium Duration	References
No-Till (NT)	0.20 – 0.57	Minimal soil disturbance; most effective when paired with residue retention. Effectiveness depends on soil texture.	15 – 20 years	West & Post (2002)
Cover Crops	0.32 – 0.58	Increases biomass input and reduces erosion. Legume covers add N, potentially enhancing humification.	20 – 40 years	Bolinder et al. (2020)
Agroforestry	0.21 – 1.22	Deep-rooting trees capture subsoil carbon; high spatial variability based on tree species and density.	40 – 60 years	Mayer et al. (2022); Kim et al. (2024)

Management Practice	SOC Sequestration Rate (Mg C ha−1 yr−1)	Key Characteristics & Optimization	Equilibrium Duration	References
Biochar Application	0.50 – 1.10	Recalcitrant carbon with long-term persistence (>100 years). Acts as a direct C-sink and soil conditioner.	$100+$ years	Gross et al. (2021); Lehmann et al. (2025)
Organic Amendments	0.40 – 0.80	Includes compost and manure. High initial rates, but limited by availability and transport costs.	30 – 50 years	Bolinder et al. (2020)
Afforestation	0.60 – 1.00	Land-use change from crop to forest. High potential in temperate and tropical zones.	50 – 100 years	Bolinder et al. (2020)
Improved Grazing	0.30 – 0.50	Rotational grazing and increasing perennial species. Helps stabilize grassland carbon pools.	25 – 40 years	Sanderman et al. (2024)

This table summarizes both qualitative and quantitative information about a variety of peer reviewed publications in the scientific literature describing SOC sequestration, the time it takes for SOC sequestration to be at maximum (saturation), the cost to implement different conservation practices, and the benefits and limitations associated with each practice. The term "saturation" is defined as the point at which SOC sequestration rates are significantly reduced by achieving the soil's SOC saturation capacity. The cost of implementing these conservation practices represent typical costs of implementing those practices and do not reflect any potential opportunity costs resulting from changing land use. Co-benefits to the farmer extend beyond carbon sequestration into improvements in soil health, crop yield, and other ecosystem functions and services. Limitations indicate practical constraints that can affect the ability of farmers to adopt certain practices or the effectiveness of such practices in certain situations. This review provides a basis for determining which conservation practices would best fit in with the goals of a producer or the needs of a particular region in terms of reducing greenhouse gas emissions and sequestering atmospheric CO_2.

5. Soil Organic Carbon Sequestration Potential for Climate Change Mitigation

5.1 Global Sequestration Capacity and Regional Variability

The global potential for SOC sequestration in agricultural soils and degraded lands has been estimated to be around 0.5 – 1.8 GtCO2-eq/year; this estimate depends on the rate of adoption of new SOC-enhancing management practices, the level of management intensity that will be applied, and the initial SOC concentration (Jackson et al., 2017). This SOC sequestration potential varies significantly by region because of the different climates, soil characteristics, the degree of initial SOC depletion as a result of past land use activities, and current land uses found in each region. Regions with tropical climates contain about 60 percent of the world's agricultural land; however, they have suffered the greatest losses of SOC as a result of deforestation and intensive farming, therefore have the greatest potential for large-scale SOC sequestration if their agriculture can be managed appropriately (Shipman et al., 2021). Realizing the SOC sequestration potential in tropical climates is highly dependent upon managing the agricultural system to maximize SOC sequestration, which is challenging for several reasons. First, the timeframes over which SOC is sequestered in tropical climates tend to be much shorter than those found in temperate climates (Sommer & Bossio, 2014). For example, when using conservation tillage and cover crops in tropical climates, SOC sequestration can occur in 15-25 years; in contrast, SOC sequestration tends to require 30-50 years in temperate climates. Second, because of the warmer temperatures in tropical climates, the decomposition of SOC tends to be faster than in cooler climates, resulting in lower potential for SOC sequestration.

Regions with temperate and boreal climates tend to have smaller total agricultural areas than tropical regions; however, they tend to have higher SOC sequestration rates per unit area because the rates of SOC decomposition tend to be slower than in tropical climates and the ability to store SOC is generally higher (Hassan et al., 2022). SOC sequestration in temperate climates has been estimated to range from 0.1 to 0.3 GtCO2-eq/year (Yuan et al., 2023). Temperate climates have an advantage over tropical climates in terms of longer SOC sequestration timescales (30-50 years) that provide more sustainable climate benefits. Semi-arid and arid climates represent another set of paradoxical opportunities. While the SOC storage potential in these climates is limited because of low crop yields and limited SOC inputs, the SOC sequestration potential per unit of water or fertility input can be high because of the slow rate of SOC decomposition in these climates under dry conditions (Jost et al., 2021). Therefore, optimizing SOC sequestration in these climates can be accomplished by implementing appropriate irrigation and/or input management practices. However, the magnitude of SOC sequestration varies widely across regions due to differences in soil texture, climate, and management practices (West and Post, 2002).

Regional assessments of SOC sequestration must account for these contrasting dynamics to develop optimal SOC sequestration mitigation strategies for each agroecological context. Fig. 2 socfactorsaffecting.png represents the complex interplay between climate (temperature, precipitation), soil (texture, pH), and management (conservation tillage, cover cropping) factors on SOC dynamics. The figure provides a synthesis of SOC sequestration data from multiple climatic zones and soil types and provides a useful framework for developing location-specific SOC management practices that will enhance SOC sequestration.

5.2 Co-benefits and Synergies with Sustainable Agriculture

Climate change mitigation via SOC sequestration is greatly amplified by several co-benefits for enhancing food security, agriculture productivity and ecosystem services (Hao et al., 2025). In addition to increasing crop productivity, increased levels of SOC also improve the ability of soils to retain water; specifically, an increase of 1 percent in SOC may result in a corresponding increase of 10-15 percent in the available water capacity of a soil, directly beneficial in water-limited areas (Jost et al., 2021). Improved water availability will be especially important in those regions that are expected to experience increasing frequency and severity of droughts as a direct consequence of climate change (Roy et al., 2022). As well as improving the physical properties of the soil, such as its water-holding capacity, increased levels of SOC have been shown to positively impact the structure of the soil, allowing roots to penetrate further into the soil profile and improving aeration and trafficability, thus limiting the negative impacts of soil compaction on crop productivity (Wang et al., 2020).

In addition to these two primary co-benefits, the process of increasing SOC has been shown to positively impact the nutrient cycle within the soil system, specifically increasing the amounts of nitrogen, phosphorus and other micronutrients made available to crops, thereby reducing the need for fertilizers (Jackson et al., 2017). The reduction in fertilizer use not only reduces the amount of energy required to produce fertilizers, but also decreases greenhouse gas emissions associated with the production, application and degradation of N2O (indirect climate benefit), while also improving the overall quality of surface waters by decreasing the flow of excess nutrients into them (Hussain et al., 2021). Further, reducing the number of fertilizers applied to land reduces the cost to farmers (Hussain et al., 2021). Another important co-benefit of SOC enhancement is biodiversity enhancement. Higher levels of SOC support greater numbers of soil microorganisms, invertebrates and larger fauna, all of which work together to promote a more balanced relationship between pests and their natural predators, pollinators and ecosystem resilience (Beattie et al., 2025).

The increases in crop productivity provided by SOC enhancement are especially large in degraded or low-input agricultural systems, where increases in SOC can lead to increases in crop yields of up to 20-50% (Roy et al., 2022). These increases in crop yield convert SOC enhancement from a cost of mitigating climate change to a source of net revenue, significantly improving the financial incentives for adopting SOC-enhancing practices (Francaviglia et al., 2023). Therefore, when considering the combined effects of increased crop productivity, lower input costs, increased resistance to extreme weather conditions and climate change mitigation, it becomes clear that there are compelling arguments for the adoption of SOC-enhancing practices based on both environmental and economic grounds (Siddique et al., 2023).

5.3 Permanence and Reversibility Issues in Carbon Sequestration

SOC permanence has been a major concern for its use as a method for climate mitigation. Because SOC is a biological system, it is always at risk of being oxidized if soil conditions change. Therefore, the permanence of SOC is heavily dependent upon continued management practice and not merely the accumulation of carbon over time. If current management practices are terminated and the land is returned to conventional tillage or high intensity management, significant amounts of accumulated carbon can be lost within 5-10 years (Hassan et al., 2022). This raises questions about the necessity for instituting both institutional and policy measures to ensure long term commitment to management practices (Jackson et al., 2017).

The depth distribution of carbon that is sequestered in soil influences its permanence. Carbon that is stored below 50cm of the soil profile is much more resistant to rapid oxidation and physical disturbances than surface carbon. Thus, the deeper the sequestration the more durable the sequestration (Rodriguezs et al., 2023). Similarly, the organic matter composition influences its permanence. Mineral-stabilized organic matter (i.e., occluded within aggregates or complexed with minerals) generally shows longer term stability than particulate organic matter located on the surface of aggregates (Don et al., 2024). In this regard, biochar and other highly stabilized organic matter provide very good permanence and have the potential for carbon to reside in the soil for thousands of years without undergoing active decomposition (Torri et al., 2014). Given these differences in permanence, it is necessary for mitigation assessments to differentiate between short-term (10-20 yr) and long-term (50+ yr) sequestrations, using discount rates to account for the reversibility risks associated with each (Sommer & Bossio, 2014).

Climate change also presents paradoxical implications for SOC permanence. Warming temperatures and altered precipitation regimes may cause the decomposition of accumulated SOC to occur more rapidly, particularly in areas that were previously cool or wet, thereby creating a positive feedback loop that accelerates climate change (Hao et al., 2025). Consequently, SOC sequestration in the most vulnerable locations (high latitude peatlands, mountainous regions) may offer lower permanence and more uncertain climate benefits than sequestration in more stable climates (Hou, 2021). However, even temporary SOC sequestration (20-50 yr) offers significant climate mitigation benefits by delaying carbon release, and providing the opportunity for reductions in atmospheric CO_2 concentrations via other methods (Beattie et al., 2025).

6. Constraints, Challenges and Barriers to Implementation

6.1 Biophysical Constraints on SOC Sequestration

The potential for soil organic carbon (SOC) sequestration is technically large, but a number of biological and physical constraints can limit the amount of carbon that can be sequestered on a global scale (Jackson et al., 2017). The most basic biological constraint is the carbon saturation concept, which states that at some point, soils will become saturated with respect to their ability to store additional carbon, thereby making further sequestration ineffective indefinitely (Siddique et al., 2023). In soils that are already saturated (which are typically sandy soils or those with low mineral surface area), there are inherently limitations to the additional amounts of carbon that can be stored through sequestration (Silveira Nicoloso et al., 2020). Second, the hydrological cycle imposes a second set of biological constraints: in areas that are water deficient, increasing plant productivity to support additional sequestration requires supplemental irrigation; however, irrigation is often expensive and/or environmentally damaging (Roy et al., 2022). Third, there are also geographic-based constraints associated with the location of agricultural land: the greatest remaining opportunity for SOC sequestration is in tropical regions, where high decomposition rates result in rapid saturation levels and therefore long-term impacts of SOC sequestration are limited (Smith et al., 2014). Fourth, as mentioned previously, the relationship between SOC sequestration and the provision of other ecosystem services creates tradeoffs: for example, the slower decomposition rates that allow for SOC accumulation can also decrease available nutrients unless an adequate level of fertilizers are added through management (Marks et al., 2009). Fifth, and finally, the time frame in which SOC sequestration takes place (i.e., 20-50 years to achieve saturation) does not align well with the urgency of reducing greenhouse gas emissions to mitigate climate change, such that the potential of SOC sequestration as a viable strategy to address near-term climate goals is questionable (Hao et al., 2025).

6.2 Socioeconomic and Institutional Barriers

Technical and biological limitations alone do not explain why most SOC-enhancing practices have yet to be adopted by many smallholder farmers in developing countries (Yuan et al., 2023). Short-term studies often report inconsistent results, emphasizing the need for long-term experiments (Powlson et al., 2011). There are also significant economic and social barriers. The economic assessment of SOC sequestration has revealed an important asymmetry: the advantages of sequestration (i.e., avoided future climate-related damage) are distributed widely, but they occur far into the future, and they are very difficult to quantify at the farm level. In contrast, the costs and risks associated with adopting new practices (e.g., lower yields in the short run, need for new equipment or training, loss of income from diversification) are highly localized, immediate, and easy to observe (Francaviglia et al., 2023). This asymmetry results in what economists refer to as a "commons dilemma" - i.e., farmers' individual interests are not aligned with the public good of mitigating global warming, so there will be little voluntary effort to implement these practices unless some external incentive or regulation is provided (Siddique et al., 2023).

There are also institutional obstacles to implementing these practices over long periods of time - e.g., in regions where land ownership is insecure, commodity prices are unstable, or there are frequent changes in government policy (Hussain et al., 2021). If a farmer is unsure whether he/she will continue to own a particular piece of land, s/he will not be able to commit to the 20-30 years required to adopt and maintain SOC-enhancing practices (Hassan et al., 2022). If a farmer's economic situation deteriorates (e.g., due to a decrease in crop price), it will no longer be economically viable for him/her to continue with these practices (Hassan et al., 2022). Furthermore, the institutional challenges associated with verifying the implementation of SOC-enhancing practices, measuring the actual amount of carbon stored in soils, and ensuring the long-term permanence of this stored carbon have hindered the widespread adoption of these practices even further (Jost et al., 2021).

6.3 Knowledge Gaps and Technical Implementation Challenges

While the technical feasibility of SOC-enhancing practices suggests that their adoption could lead to large-scale reductions in greenhouse gas emissions, significant knowledge gaps remain regarding the optimal combination of soil type, climate condition, and commodity production system (Jackson et al., 2017). General principles (e.g., minimize disturbances to soils, maximize inputs of organic matter, grow multiple crops) have been identified that can improve SOC levels, but site-specific optimization requires an understanding of how various management practices interact with the characteristics of specific locations (Wang et al., 2020). Thus, knowledge about SOC-enhancing practices needs to be developed on a regional basis, creating a need for a high degree of extension service activity, which is often limited in developing regions (Roy et al., 2022). Technical challenges to the implementation of SOC-enhancing practices include: (a) ensuring adequate supplies of organic residues while allowing for other uses (e.g., livestock feed, biofuel feedstocks); (b) controlling pest and disease infestation in residue-rich systems; and (c) addressing the temporary declines in yield during the transition period after SOC-enhancing practices are initiated until yields recover due to the improved SOC status of the soils (Francaviglia et al., 2023).

SOC sequestration can be measured using a variety of approaches, including: (a) laboratory analysis of soil samples; (b) remote-sensing proxies with varying degrees of accuracy; and (c) sophisticated modeling that require extensive amounts of data (Don et al., 2024). However, these approaches are costly and/or require significant expertise, limiting the ability to measure SOC sequestration and, therefore, constraining the development of carbon markets that rely on this approach (Silveira Nicoloso et al., 2020). Rapid, inexpensive, and accurate measurement technologies for SOC sequestration would greatly enhance the development of carbon markets and enable farmers to obtain timely information about the effectiveness of SOC-enhancing practices (Silveira Nicoloso et al., 2020).

7. Policy Frameworks and Implementation Strategies

7.1 Carbon Pricing and Payment Mechanisms

Pricing for carbon — through either a tax or a market — is the primary means by which to create an economic incentive for SOC sequestration (Hussain et al., 2021). Through a carbon tax or a carbon market, those responsible for emitting greenhouse gases are able to buy carbon credits, which reflect reduced emissions or enhanced SOC; this creates an economic signal for sequestration (Hou, 2021). A key determinant for how well carbon pricing drives SOC sequestration is if it achieves a carbon price sufficient enough to make sequestration economically justifiable: estimated break-even carbon prices for SOC enhancing practices vary greatly (depending on the practice, location, and cost of implementing the practice) — ranging from as low as \$15 per ton CO_2-eq. up to as high as \$80 per ton CO_2-eq (Francaviglia et al., 2023).

Subsidies for SOC enhancing practices — through direct payments from government — have proven effective at providing the necessary economic incentive for large scale practice adoption but require large sums of money from government to fund the subsidies (Siddique et al., 2023). There are hybrid approaches to subsidies that include an initial grant to support the establishment of a new practice and then performance based payments to continue the practice, and some researchers believe that these hybrid approaches may provide a better balance of short-term financial commitment with long-term commitment (Roy et al., 2022). Examples of payment programs for SOC enhancing practices that exist today include Agri-Environmental Schemes in Europe, Conservation Reserve Programs in the U.S.A., and emerging programs in developing countries — and all examples show that the use of direct payments for SOC enhancing practices has been very successful at increasing the adoption rates of these practices (Arah et al., 2016). However, the long term sustainability of direct payment programs relies heavily on both political will to maintain funding over time, and program design that ensures that payments do not result in "additionality" issues (where the payments are used to subsidize practices that were going to be implemented regardless of the presence of payments) (Sommer & Bossio, 2014). Management strategies effectiveness presents a comparative analysis of different management strategies' effectiveness in sequestering SOC and their cost-effectiveness, providing guidance for policy optimization and farmer decision-makingThe figure integrates technical effectiveness with economic feasibility, highlighting strategies offering superior cost-effectiveness.

7.2 Regulatory and Voluntary Approaches

A key advantage of the regulatory approach is that it offers a high degree of certainty to farmers about both the specific practices required to achieve SOC and the timing of the implementation (i.e., the certainty of compliance) (Yuan et al., 2023). On the other hand, regulatory mandates can be politically difficult to implement due to potential resistance from powerful farm lobby groups. In addition, as regulatory policies require all farms within a particular geographic area to adopt the same practices regardless of variations in costs among those farms, they also create inefficiencies in resource allocation (Hou, 2021). The likelihood of regulatory mechanisms being successfully implemented increases when accompanied by financial support for farmers to offset the transitional costs associated with changes in their farming practices (Hussain et al., 2021).

A key advantage of the voluntary approach is that it maximizes farmer flexibility in terms of the timing and extent of adoption of SOC-enhancing practices. Farmer autonomy is maximized through education and technical assistance provided to farmers to encourage them to adopt these practices at their own pace (Siddique et al., 2023). One of the disadvantages of this approach is that it typically results in lower adoption rates compared to regulatory or highly incentivized approaches (Siddique et al., 2023). Examples of successful voluntary programs include providing technical support and/or education to farmers to help them understand how to adopt SOC-enhancing practices and provide positive incentives (i.e., payments, recognition, and market differentiation) for farmers who do so (Francaviglia et al., 2023). An example of a certification program that verifies the use of SOC-enhancing practices and provides a means for producers to differentiate their product and receive a price premium based upon its production under these practices (organic, low-carbon agriculture) represents an example of a voluntary market-based mechanism that aligns farmer incentives with climate benefits (Roy et al., 2022).

7.3 Integration with Broader Agricultural and Climate Policies

Optimal climate and agricultural policy frameworks recognize that SOC sequestration is just one of several tools available to reduce GHG emissions from agricultural activities and enhance the overall sustainability of those activities; therefore, optimal climate and agricultural policy frameworks will include SOC strategies in combination with other complementary policy elements (Hao et al., 2025). Policies which promote both sustainable intensification (i.e. increases in productivity) and environmental benefits create "win-win" situations where climate mitigation is linked to food security improvement (Saritha et al., 2025). The integration of SOC sequestration with biodiversity conservation policies recognizes that many of the same practices which enhance SOC also provide habitat for beneficial organisms and contribute to ecosystem services (Beattie et al., 2025).

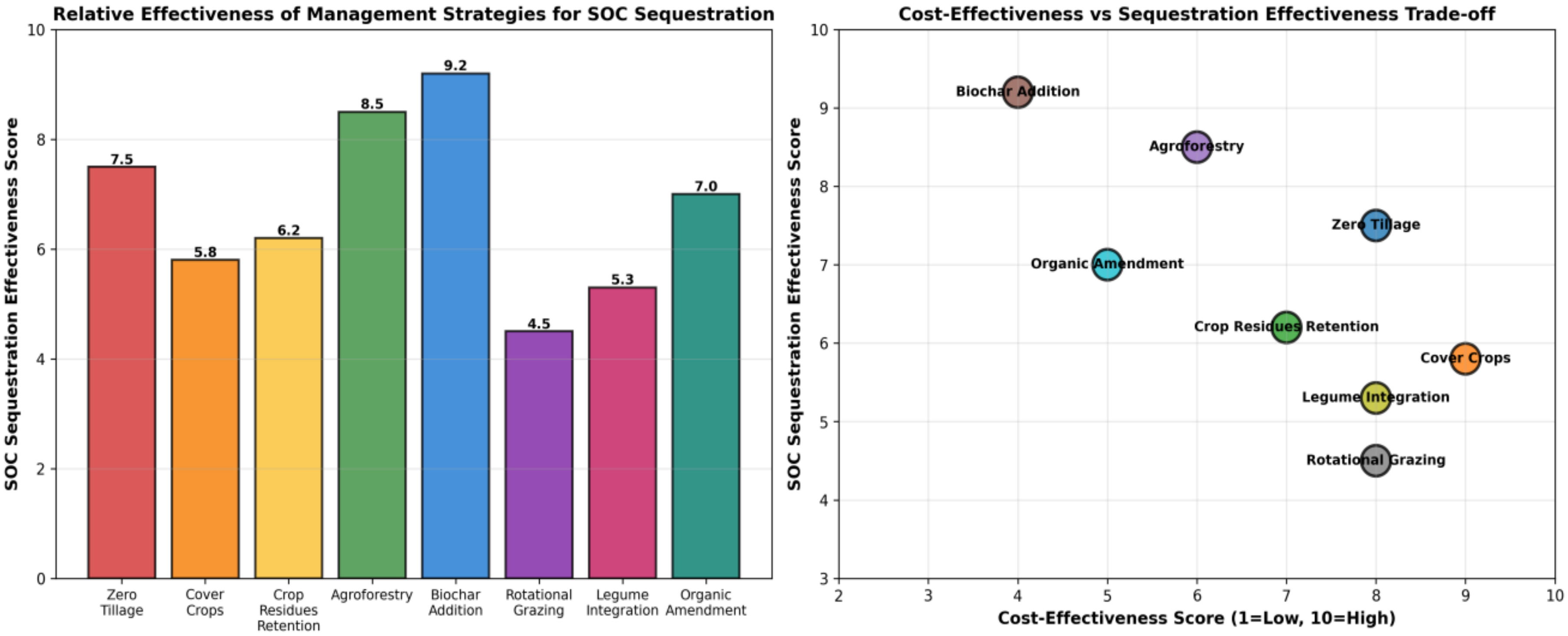

Fig. 2. Management *strategies* effectiveness presents a comparative analysis of different management strategies' effectiveness in sequestering SOC and their cost-effectiveness, providing guidance for policy optimization and farmer decision-making

The influence of global trade policy and agricultural standards on SOC sequestration is becoming increasingly important, as large markets in developed countries begin to require producers to use low-carbon or sustainable production methods (Sharma et al., 2019). The development of internationally accepted standards for carbon accounting in agriculture will ensure that carbon credits generated in developing countries are acknowledged by international carbon markets and thus provide additional economic incentive for sequestration globally (Yuan et al., 2023). However, establishing standards for carbon accounting that are both environmentally robust and economically feasible for low income farmers continues to be a challenging scientific and policy objective (Roy et al., 2022).

8. Future Perspectives and Emerging Technologies

8.1 Advanced Monitoring Technologies and Carbon Accounting

Emerging technologies for measuring and monitoring SOC could potentially significantly reduce costs associated with carbon accounting while providing increased accuracy, thus improving the feasibility of both carbon markets and farmer payments (Hao et al., 2025). Technologies employing proximal sensing such as infrared spectroscopy have been demonstrated to provide rapid, low-cost estimates of SOC in field conditions; however, the need for calibration against laboratory measurements is still an existing limitation (Jackson et al., 2017). Satellite-based remote sensing using multispectral and hyperspectral data has also been demonstrated to be effective for estimating SOC at larger scales than those typically assessed by proximal sensing technologies; however, these methods are generally limited to assessment of SOC on a per farm basis (Siddique et al., 2023). The use of combinations of sensing approaches (e.g., proximal sensing, remote sensing, modeling) may ultimately provide for cost-effective carbon accounting that will enable implementation of carbon sequestration payment programs (Roy et al., 2022).

Biological indicators of soil quality (e.g., microbial biomass, enzyme activities, community composition) offer the opportunity to quantify not only the amount of SOC but also its functional characteristics (e.g., the ability of the SOC to support crop productivity, nutrient cycling, etc.) to evaluate the permanence of SOC sequestration (Beattie et al., 2025). Biological indicators of SOC quality have also been shown to be highly correlated with both crop productivity and nutrient cycling capacity, which will allow for the integration of carbon accounting into payment programs based upon agricultural productivity metrics (Marks et al., 2009). A major barrier to the wide-spread acceptance of biological indicators as a method for assessing SOC quality is the lack of standardized protocols for measuring and interpreting these indicators (Francaviglia et al., 2023).

8.2 Innovative Management Approaches and Emerging Practices

The potential for longer term carbon storage (> 1000 years) using biochar and pyrolysis technologies is enhanced by their ability to also improve plant growth and soil health (Shyam et al. 2025). A further benefit of producing biochar from agricultural waste includes the provision of renewable energy and biofuels while creating a valuable circular economy, which enables the sequestering of carbon and provides an alternative use for waste products (Torri et al. 2014). Due to the half-life of biochar being significantly greater than traditional organic matter (500-5000 vs. 10-50 years), it has the capability to sequester atmospheric CO2 for extended periods (Schmidt et al. 2018). However, one of the major barriers to scaling up biochar production is due to the limited availability of suitable feedstock and the lack of economic feasibility for carbon capture at current carbon pricing levels; therefore, carbon pricing would need to increase or biochar production would need to be economically feasible on its own as a product (Saritha et al. 2025).

Microbial management methods are other methods that have been recently developed to manipulate soil microorganisms to create more efficient pathways to store SOC (Beattie et al. 2024). These microbial treatments may be able to reduce the rate of decomposition of organic matter in soils, thereby enhancing the rate of carbon sequestration; however, there is still considerable research required to develop these methods into a reliable, cost effective tool (Jost et al. 2021). The challenges associated with developing reliable microbial treatment include the uncertainty regarding how long the introduced microorganisms will persist in field environments and the variability in effectiveness among the different microbial species that could be used in a treatment (Hao et al. 2025). Combining microbial management methods with established agricultural practices could lead to increased levels of SOC; however, additional research is needed to translate lab based studies into reliable field based practices.

Precision agriculture has the potential to optimize the application of agronomic practices to manage the variability in soils that exist in every field (Silveira Nicoloso et al. 2020). Precision agriculture can be utilized to account for the spatial variability in soil properties, terrain features, and crop yields that exist in each field; this allows for tailored management practices to be applied to each zone of a field resulting in the reduced costs associated with optimizing SOC accumulation while improving crop productivity (Yuan et al. 2023). Remote sensing and lower cost sensor systems have improved access to the information necessary to utilize precision agriculture (detailed soil maps, yield monitoring, weather stations); therefore, precision agriculture has become a more feasible option for small scale farmers located in developing countries (Wang et al. 2020).

9. Conclusion

When the time is right to implement soil carbon sequestration (SCS), it has been identified as a "scientifically validated" way to achieve many things, such as help mitigate climate change, promote sustainable agriculture, and increase food security.

This review provides strong evidence to show that there is a huge amount of unused potential for storing carbon in soils, and that established practices can capture anywhere from .3 to 2.5 metric tons of C/ha/y; when combined with the fact that SCS generates numerous benefits including increased crop yield, better water retention, lower inputs needed for farming, and increased biodiversity (Jackson et al., 2017); the SCS potential of 0.5-1.8 Gt CO_2-eq/y represents a relatively large contribution to the climate change mitigation effort; especially considering that it has the potential to offset 10-25% of the current GHG emissions from agriculture if implemented on a large enough scale (Sommer & Bossio, 2014). To realize this potential, however, we need to overcome many of the same biophysical, socio-economic, and institutional challenges that have prevented the widespread use of SCS-enhancing practices since their inception. It appears that the most viable path forward is through the creation of a coherent policy framework that incorporates a combination of economic incentives, regulations that are enforceable, technical assistance, and investments in research (Hussain et al., 2021). Additionally, emerging technologies for carbon monitoring, new agricultural management practices, and innovative financial structures provide tools to help overcome some of the same obstacles that have previously impeded the adoption of SCS-enhancing practices (Hao et al., 2025).

Ultimately, transforming our agricultural systems to include SCS will require multi-faceted collaborative actions across the fields of policy development, farmer education, technology transfer, and long-term commitments by institutions to promoting and protecting both the health of the soil and the mitigation of climate change (Siddique et al., 2023). Because of the urgent nature of climate change, the limited timeframe of individual SCS projects needs to be considered: while each farm adopting SCS-enhancing practices helps to mitigate climate change, the time-sensitive nature of achieving saturation levels within 20-50 years means that SCS needs to occur in tandem with global efforts to reduce greenhouse gas emissions from fossil fuels and other sectors (Hou, 2021). Therefore, SCS should be viewed as one part of an integrated approach to climate change mitigation that includes reducing emissions from fossil fuels, increasing the use of renewable energy sources, and enhancing the level of biological carbon sequestration (Sommer & Bossio, 2014).

Therefore, when implemented as part of an overall transformation of agriculture to make it more sustainable, SCS has the potential to create an agriculture system that not only feeds people, but also restores degraded ecosystems, increases the resiliency of agroecosystems to climate variability, and decreases the human-induced rate of global warming (Smith et al., 2014).

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Arah, I. K., Ahorbo, G. K., Anku, E. K., Kumah, E. K., Amaglo, H., et al. (2016). Postharvest handling practices and treatment methods for tomato handlers in developing countries: A mini review. *Advances in Agriculture, 2016*, Article 6436945. https://doi.org/10.1155/2016/6436945

Batista-Silva, W., Nascimento, V. L., Medeiros, D. B., Nunes-Nesi, A., Ribeiro, D. M., Zsögön, A., et al. (2018). Modifications in organic acid profiles during fruit development and ripening: Correlation or causation? *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2018.01689

Beattie, G. A., Edlund, A., Esiobu, N., Gilbert, J., Nicolaisen, M. H., Jansson, J. K., et al. (2025). Soil microbiome interventions for carbon sequestration and climate mitigation. *mSystems, 10*(1), e01129-24. https://doi.org/10.1128/msystems.01129-24

Bolinder, M. A., Crotty, F., Elsen, A., Goss, M. J., Hanna, M., Kätterer, T., et al. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: A synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change*. https://doi.org/10.1007/s11027-020-09916-3

Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., et al. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Global Change Biology, 30*(1), e16983. https://doi.org/10.1111/gcb.16983

Du, M., Xue, P., Minasny, B., Tang, Y., McBratney, A. B., et al. (2023). Macroecological processes impact Australian soil resistomes and climatically stable regions with anthropogenic activities serve as ARG hotspots. *Journal of Environmental Management, 342*, 118132. https://doi.org/10.1016/j.jenvman.2023.118132

Francaviglia, R., Almagro, M., Vicente-Vicente, J. L., et al. (2023). Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. *Soil Systems, 7*(1), 17. https://doi.org/10.3390/soilsystems7010017

Gelaye, Y., Getahun, S., et al. (2024). A review of the carbon sequestration potential of fruit trees and their implications for climate change mitigation: The case of Ethiopia. *Cogent Food & Agriculture, 10*(1), 2294544. https://doi.org/10.1080/23311932.2023.2294544

Gross, A., Bromm, T., Glaser, B., et al. (2021). Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy, 11*(12), 2474. https://doi.org/10.3390/agronomy11122474

Gupta, K., Wani, S. H., Razzaq, A., Skalický, M., Samantara, K., Gupta, S., et al. (2022). Abscisic acid: Role in fruit development and ripening. *Frontiers in Plant Science, 13*, 817500. https://doi.org/10.3389/fpls.2022.817500

Hao, Y., Mao, J., Bachmann, C. M., Hoffman, F. M., Koren, G., Chen, H., et al. (2025). Soil moisture controls over carbon sequestration and greenhouse gas emissions: A review. *npj Climate and Atmospheric Science, 8*(1), 16. https://doi.org/10.1038/s41612-024-00888-8

Hassan, W., Li, Y., Saba, T., Jabbi, F., Wang, B., Cai, A., et al. (2022). Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: A review. *International Soil and Water Conservation Research, 10*(3), 530–545. https://doi.org/10.1016/j.iswcr.2022.01.005

Hou, D., et al. (2021). Sustainable soil management and climate change mitigation. *Soil Use and Management, 37*(2), 220–223. https://doi.org/10.1111/sum.12718

Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstić, Đ., et al. (2021). Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants, 10*(10), 2001. https://doi.org/10.3390/plants10102001

Jackson, R. B., Lajtha, K., Crow, S. E., Hugelius, G., Kramer, M. G., Piñeiro, G., et al. (2017). The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. *Annual Review of Ecology, Evolution, and Systematics*. https://doi.org/10.1146/annurev-ecolsys-112414-054234

Jost, E., Schönhart, M., Skalský, R., Balkovič, J., Schmid, E., Mitter, H., et al. (2021). Dynamic soil functions assessment employing land use and climate scenarios at regional scale. *Journal of Environmental Management, 287*, 112318. https://doi.org/10.1016/j.jenvman.2021.112318

Khenrab, S., Kour, S., Sharma, V., Rai, P. K., Kour, K., Bharat, R., et al. (2025). Soil organic carbon fractions, stocks, and management index across diverse land uses in temperate India. *Frontiers in Sustainable Food Systems, 9*, 1688664. https://doi.org/10.3389/fsufs.2025.1688664

Kim, D. G., Mayer, S., et al. (2024). Carbon sequestration potential in temperate and tropical agroforestry systems: A synthesis. *Agricultural Systems, 214*, 103812.

Lal, R., et al. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lehmann, J., Barrios, E., Devault, M., Li, L., Nelson, R., Six, J., & Trimmer, J. (2025). Biochar in the circular bionutrient economy. *Proceedings of the National Academy of Sciences of the United States of America, 122*(33), e2503668122. https://doi.org/10.1073/pnas.2503668122

Lustriane, C., Dwivany, F. M., Suendo, V., Reza, M., et al. (2018). Effect of chitosan and chitosan-nanoparticles on post harvest quality of banana fruits. *Journal of Plant Biotechnology, 45*(1), 36–44. https://doi.org/10.5010/JPB.2018.45.1.036

Maringgal, B., Hashim, N., Tawakkal, I. S. M. A., Mohamed, M. T. M., et al. (2020). Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. *Trends in Food Science & Technology, 96*, 253–267. https://doi.org/10.1016/j.tifs.2019.12.024

Marks, E., Aflakpui, G. K. S., Nkem, J., Poch, R. M., Khouma, M., Kokou, K., et al. (2009). Conservation of soil organic carbon, biodiversity and the provision of other ecosystem services along climatic gradients in West Africa. *Biogeosciences*. https://doi.org/10.5194/bg-6-1825-2009

Mayer, S., Hafner, S., Gebauer, G., Gradel, A., Heinke, J., & Luedeling, E. (2022). Agroforestry as a climate-smart economic strategy: Carbon benefits, adaptation pathways, and global evidence from smallholder systems. *Forests, 13*(2), 159. https://doi.org/10.3390/f13020159

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., Smith, P., et al. (2016). Climate-smart soils. *Nature, 532*(7597), 49–57. https://doi.org/10.1038/nature17174

Powlson, D. S., Whitmore, A. P., Goulding, K. W. T., et al. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science, 62*(1), 42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Rodrigues, C. I. D., Brito, L. M., Nunes, L. J. R., et al. (2023). Soil carbon sequestration in the context of climate change mitigation: A review. *Soil Systems, 7*(3), 64. https://doi.org/10.3390/soilsystems7030064

Roy, O., Meena, R. S., Kumar, S., Jhariya, M. K., Pradhan, G., et al. (2022). Assessment of land use systems for CO_2 sequestration, carbon credit potential, and income security in Vindhyan region, India. *Land Degradation & Development*. https://doi.org/10.1002/ldr.4181

Sanderman, J., Hengl, T., & Fiske, G. J. (2024). Soil carbon debt of agricultural lands and opportunities for global soil carbon sequestration. *Proceedings of the National Academy of Sciences, 121*(8), e2312456121. https://doi.org/10.1073/pnas.2312456121

Saritha, J. D., Nalini, N., Ramakrishna, N., Teja, C., Kumar, M. P., et al. (2025). Soil carbon sequestration in agro-ecosystems: Mechanisms, management, and the role in climate change mitigation. *International Journal of Environment, Agriculture and Biotechnology, 10*(6), 33–36. https://doi.org/10.22161/ijeab.106.5

Schmidt, H.-P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W., et al. (2019). Pyrogenic carbon capture and storage. *GCB Bioenergy*. https://doi.org/10.1111/gcbb.12553

Sharma, S. D., Rana, V. S., Prasad, H., Lakra, J., Sharma, U., et al. (2019). Appraisal of carbon capture, storage, and utilization through fruit crops. In M. Goel et al. (Eds.), *Carbon capture, storage and utilization* (pp. 114–124). CRC Press. https://doi.org/10.1201/9780429026225-11

Shipman, E. N., Yu, J., Zhou, J., Albornoz, K., Beckles, D. M., et al. (2021). Can gene editing reduce postharvest waste and loss of fruit, vegetables, and ornamentals? *Horticulture Research*. https://doi.org/10.1038/s41438-020-00428-4

Shyam, S., Ahmed, S., Joshi, S. J., Sarma, H., et al. (2025). Biochar as a soil amendment: Implications for soil health, carbon sequestration, and climate resilience. *Discover Soil, 2*(1), 18. https://doi.org/10.1007/s44378-025-00041-8

Siddique, I. A., Grados, D., Chen, J., Lærke, P. E., Jørgensen, U., et al. (2023). Soil organic carbon stock change following perennialization: A meta-analysis. *Agronomy for Sustainable Development, 43*(5), 58. https://doi.org/10.1007/s13593-023-00912-w

Silveira Nicoloso, R. da, Amado, T. J. C., Rice, C. W., et al. (2020). Assessing strategies to enhance soil carbon sequestration with the DSSAT-CENTURY model. *European Journal of Soil Science, 71*(6), 1034–1049. https://doi.org/10.1111/ejss.12938

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., et al. (2014). Agriculture, forestry and other land use (AFOLU). In O. Edenhofer et al. (Eds.), *Climate change 2014: Mitigation of climate change* (pp. 811–922). Cambridge University Press. https://doi.org/10.1017/CBO9781107415416.017

Smith, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B, 363*, 789–813.

Sommer, R., Bossio, D., et al. (2014). Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2014.05.017

Torri, S. I., Corrêa, R. S., Renella, G., et al. (2014). Soil carbon sequestration resulting from biosolids application. *Applied and Environmental Soil Science, 2014*, Article 821768. https://doi.org/10.1155/2014/821768

Wang, X., He, C., Liu, B., Zhao, X., Liu, Y., Wang, Q., et al. (2020). Effects of residue returning on soil organic carbon storage and sequestration rate in China's croplands: A meta-analysis. *Agronomy, 10*(5), 691. https://doi.org/10.3390/agronomy10050691

Weil, R. R., Brady, N. C., et al. (2017). *The nature and properties of soils* (15th ed.). Pearson. https://www.pearson.com/en-us/subject-catalog/p/nature-and-properties-of-soils-the/P200000002448/9780137516933

West, T. O., Post, W. M., et al. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal, 66*(6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930

Yuan, J., Liang, Y., Zhuo, M., Sadiq, M., Liu, L., Wu, J., et al. (2023). Soil nitrogen and carbon storages and carbon pool management index under sustainable conservation tillage strategy. *Frontiers in Ecology and Evolution, 10*, 1082624. https://doi.org/10.3389/fevo.2022.1082624

Zhao, Y., Li, B., Li, C., Xu, Y., Luo, Y., Liang, D., et al. (2021). Comprehensive review of polysaccharide-based materials in edible packaging: A sustainable approach. *Foods, 10*(8), 1845. https://doi.org/10.3390/foods10081845

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