

Mini Review of Soil Carbon Sequestration (SCS): Mechanisms, Influencing Factors, Benefits

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HIGHLIGHTS

- SCS helps to improve soil fertility, structure and nutrient cycling in the soil.
- Also improves crop yields and income through carbon credits for farmers.
- Physical, chemical and biological processes involved in soil organic carbon stabilisation.
- SCS helps to lower greenhouse gases and climate change.

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ABSTRACT

Soil carbon sequestration (SCS) is a key mechanism for climate change mitigation through reducing carbon dioxide emissions to the atmosphere and enhancing soil fertility. This mini review explains the physical, chemical and biological processes that influence SCS and how they contribute to soil organic carbon stabilization. The key influencing factors consist of soil texture and structure, soil pH, land use and management practices such as cover cropping, conservation tillage and agroforestry. Climatic factors such as temperature and moisture, as well as microbial communities play a part in facilitating greater carbon storage in the soil. This SCS provides several advantages such as enhancing soil nutrients and physical properties, augmenting food production, increasing diversity and resilience of soil organisms and potentially provide an economic opportunity for farmers (with a carbon credit market) while alleviating global warming. In this review, we summarize the major drivers influencing SCS and the prospects for adopting sustainable practices to optimize SOC, along with its associated benefits for both ecology and agriculture.

1. INTRODUCTION

Soil is fundamental to carbon storage, the global carbon cycle, and mitigation of climate change through a decrease in greenhouse gas emissions (Paustian et al., 2016; Amelung et al., 2020). Soils are the largest terrestrial carbon pool, containing ~2,500 gigatons (Gt) of carbon storage compared with the atmosphere (~800 Gt) and terrestrial vegetation (~560

Gt) (Lal, 2020). SCS is a process through which atmospheric carbon dioxide (CO₂) is transferred to soil in the form of organic carbon via photosynthesis and other natural processes (Lal, 2004). This is an important contributor to soil organic matter and is a conservation, ecosystem service (Paustian et al., 2016).

Carbon sequestration in soils is a complex and dynamic process governed by biological, chemical,

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and physical processes (Lal, 2004). The properties, including soil structure and texture, pH, microbial activity, land-use practices, and climatic conditions, determine the stability and residence time of sequestered carbon (Amelung et al., 2020). Soil structure affects aeration, water retention and organic matter accumulation. These properties directly affect microbial activity and carbon stabilization (Six et al., 2002). Soil pH determines decomposition rates and the availability of nutrient resources under soil conditions, which modulates microbial processes that are pivotal for carbon sequestration (Sihi et al., 2021). Temperature and precipitation are also important climatic conditions influencing microbial respiration and carbon turnover (Wang et al., 2017).

Soil carbon sequestration has benefits at environmental, agricultural and economic levels. It enriches soil fertility by increasing nutrients availability, soil moisture holding capacity, and microbial health, thus enhancing crop productivity (Lal, 2020; Ray et al., 2025). It also plays a role in promoting soil biodiversity through diversity of microbial groups, which are needed for nutrient cycling and ecosystem resilience (Schmidt et al., 2011). Carbon credit markets promote sustainable farming practices, benefiting farmers by boosting soil productivity and lowering input costs (FAO, 2020). This literature review studies, SCS through its mechanisms, factors that may affect and its benefits.

2. MATERIALS AND METHODS

This literature review systematically analyzed 46 peer-reviewed studies on SCS sourced from Web of Science, Scopus, and Google Scholar. The search employed PRISMA guidelines (Page et al., 2021) and keywords such as “soil organic matter,” “soil microbial community,” “carbon stabilization” and “conventional tillage,” targeting studies published between 2000 and 2023. Inclusion criteria prioritized field-based experiments (e.g., Lal, 2004; Schulte et al., 2021) and meta-analyses addressing SCS mechanisms, drivers, and benefits. Studies were required to report on diverse soil types (sand, clay, loam), land uses (croplands, grasslands), and climatic variables (temperature, moisture) (Amelung et al., 2020; Wang et al., 2017), while non-peer-reviewed or non-English sources were excluded.

3. MECHANISM

SCS is a process involving physical, chemical, and biological measures to stabilize organic carbon and prevent decomposition (Figure 1). The physical mechanism involves the formation of soil aggregates, especially microaggregates in fine-textured soils (e.g., clay), which protect organic matter and constitute

organo-mineral complexes. These complexes constrain oxygen availability, inhibit microbial degradation, and increase carbon stability (Six et al., 2002; Lehmann & Kleber, 2015). The combination of soil moisture and aeration into larger carbon pools drive carbon capture, especially in water-stressed settings such as peatlands and wetlands where stagnant decomposition activity has resulted in higher carbon retention (Fener & Freeman, 2011). Erosion can destroy these aggregates, resulting in a large loss of carbon (Lal, 2003).

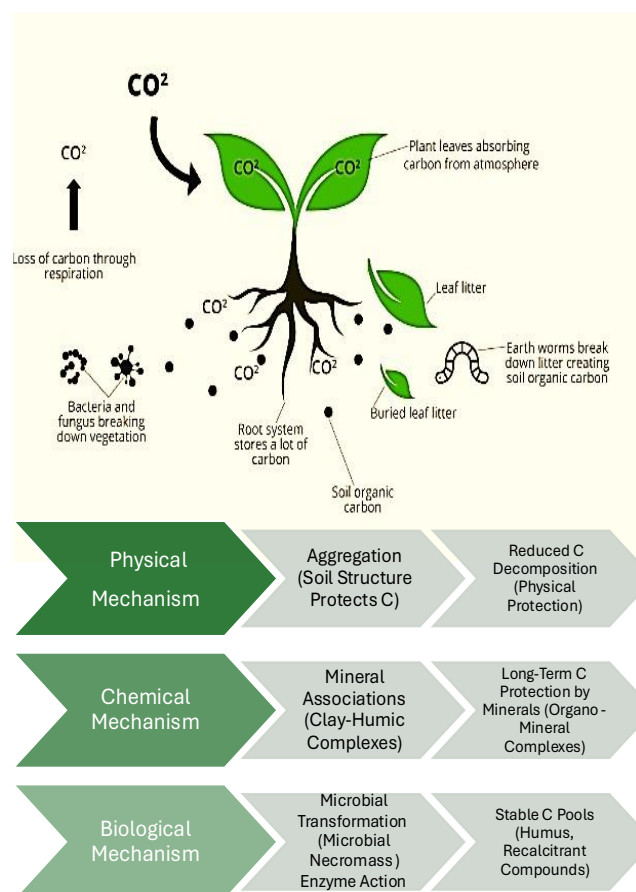


Figure 1. Summary of SCS mechanisms (1) physical protection via soil aggregates, (2) chemical bonding with Fe/Al oxides, and (3) biological stabilization through microbial necromass and root exudates (Adapted from Green Element’s group, 2020 blog on Soil Carbon Sequestration)

Chemical mechanisms include the interaction of soil organic carbon with oxides of minerals like iron (Fe) and aluminum (Al) through adsorption and ionic bonding (Kleber et al., 2015). The retention of chemically resistant constituents such as biochar and lignin as well as high molecular weight organic compounds help to improve the long-term stabilization of organic matter and carbon (Schmidt et al., 2011). Soil pH, cation exchange capacity (CEC), and mineral composition are among soil properties

that have a critical influence on the strength of these interactions (Sihi et al., 2021). Through microbial action, the biological mechanism stabilizes organic carbon. Microbial necromass is a significant component of stable carbon, specifically in mineral-associated fractions (Cotrufo et al., 2013). Root exudates promote microbial activity and the process of aggregation, important in stabilizing carbon (Jones et al., 2009). Mycorrhizal fungi, which associate symbiotically with plant roots, enhance soil aggregation and drive carbon transport deeper into the soil profile (Rillig et al., 2019). Soil microbial extracellular enzymes control carbon fluxes through decomposition. They are limited by soil nutrients, temperature, and moisture (Allison et al., 2010). These mechanisms collectively stabilize soil organic carbon but it depends on environmental and management factors, including soil texture, pH, and land-use practices, which are explained in the following section.

4. INFLUENCING FACTORS

4.1. Soil texture and structure

Soil texture and structure, for instance, directly interact with the physical mechanisms of SCS discussed earlier. As shown in Table 1, clay-rich soils exhibit the highest SCS rates (1.2–2.0 t C/ha/year) and the lowest decomposition rates (0.02–0.05 g C/kg/day), making them more effective in long-term carbon storage compared to sandy soils (0.2–0.5 t C/ha/year, 0.05–0.10 g C/kg/day) (Lal, 2004). Soil structure also plays a crucial role in regulating water retention, aeration, and root penetration. Well-aggregated soils enhance carbon stability, while compaction and erosion accelerate carbon loss through mineralization and leaching (Pan et al., 2024). A study conducted in Maintaining soil structure through conservation tillage and organic amendments is essential for optimizing SCS (Smith et al., 2020).

4.2. Soil pH

As highlighted in the chemical mechanisms section, soil pH influences ionic bonding and adsorption dynamics between organic carbon and minerals like Fe/Al oxides. This interaction determines whether carbon is stabilized or rapidly decomposed, making pH a pivotal factor in SCS efficiency. As evidenced by table 2, acidic soils (pH < 5.5) limit microbial decomposition (0.03–0.06 g C/kg/day), leading to moderate soil organic carbon (SOC) stocks (12–15 g C/kg) (Kemmitt et al., 2006). In contrast, highly alkaline soils (pH > 7.5) accelerate microbial respiration (0.06–0.12 g C/kg/day), increasing CO₂ emissions and reducing SOC stocks (10–13 g C/kg) (Kemmitt et al., 2006). Optimal SCS

occurs in slightly acidic to neutral soils (pH 5.5–7.5), where enhanced microbial diversity and humus stabilization result in peak SOC stocks (18–22 g C/kg) and the highest sequestration rates (1.0–1.5 t C/ha/year) (Sollins et al., 1996; von Lützow et al., 2006). In comparison, acidic soils sequester carbon at lower rates (0.5–1.0 t C/ha/year), while highly alkaline soils experience the fastest organic matter decomposition and the lowest sequestration rates (0.2–0.6 t C/ha/year). pH also affects the bioavailability and solubility of important micronutrients like copper, iron and zinc, which necessary for microbial enzyme activity in SOC conversion. According to recent studies, the availability of these micronutrients availability strongly related to pH and Electrical conductivity and organic carbon, all of which jointly influence microbial activity and the potential for carbon stabilization in dryland soils (Gudla et al., 2021; Gudla et al., 2024) These findings highlight pH management as a critical strategy for maintaining SOC stocks and enhancing long-term soil health.

Table 1. Soil Texture and its Impact on Carbon Sequestration and Decomposition Rates (Six et al., 2002)

Sub-factor	Carbon Sequestration Rate (t C/ha/year)	SOC Stock (g C/kg soil)	Carbon Decomposition Rate (g C/kg/day)
Clay-rich soils	1.2 – 2.0	20 – 30	0.02 – 0.05
Loam soils	0.6 – 1.1	15 – 25	0.03 – 0.06
Sandy soils	0.2 – 0.5	10 – 15	0.05 – 0.10

Table 2. Effects of Soil pH on Carbon Sequestration and Microbial Activity

Sub-factor	Carbon Sequestration Rate (t C/ha/year)	SOC Stock (g C/kg soil)	Carbon Decomposition Rate (g C/kg/day)	Reference
pH < 5.5	0.5 – 1.0	12 – 15	0.03 – 0.06	Kemmitt et al., 2006
pH 5.5–7.5	1.0 – 1.5	18 – 22	0.05 – 0.10	Sollins et al., 1996
pH > 7.5	0.2 – 0.6	10 – 13	0.06 – 0.12	Kemmitt et al., 2006

4.3. Land use and management practices

Land management practices, such as tillage and cover cropping, directly alter the biological mechanisms of SCS. For example, no-tillage systems preserve soil aggregates (a physical mechanism) and protect microbial necromass (a biological stabilization pathway), whereas conventional tillage disrupts these processes. Additionally, temperature and moisture are important regulators of microbial decomposition and carbon stability. Table 2 shows that conventional tillage disrupts soil aggregates, increasing microbial respiration and decomposition rates (0.06–0.08 g C/kg/day), leading to SOC losses (12–18 g C/kg) (West & Post, 2002). In contrast, no-tillage systems preserve aggregates, reducing decomposition (0.04–0.07 g C/kg/day) and enhancing SOC stocks (20–25 g C/kg) (West & Post, 2002). Organic amendments such as compost, manure, and biochar improve soil structure and promote long-term carbon storage (Poeplau et al., 2017). Similarly, cover cropping enhances SOC by adding organic matter through biomass and plant residues (Sa et al., 2017). Agroforestry systems further contribute to carbon stabilization by improving soil aggregation and fostering belowground carbon inputs. Combining organic inputs like vermicompost and farmyard manure (FYM) with synthetic fertilizers greatly increase crop yields, nutrient usage efficiency and soil organic carbon levels (Gudla et al., 2024). Sustainable agricultural practices are, therefore, crucial for maximizing soil carbon sequestration and mitigating climate change impacts.

Table 3. Impact of Soil Management Practices on Carbon Sequestration and Decomposition (West & Post, 2002)

Management practices	S C S Rate (t/ha/year)	SOC Stock (g C/kg soil)	Carbon Decomposition Rate (g C/kg/day)
Conventional Tillage	-0.2 – 0.5	12 – 18	0.06 – 0.08
No-tillage	0.5 – 1.0	20 – 25	0.04– 0.07

4.4. Climate

Climatic conditions modulate the microbial activity described earlier. High temperatures accelerate enzymatic decomposition (a biological mechanism), while moisture extremes alter oxygen availability, thereby influencing physical and chemical stabilization pathways. High temperatures (>25°C) accelerate microbial respiration, increasing

decomposition rates (0.1–0.2 g C/kg/day) and leading to carbon loss (Davidson & Janssens, 2006) showed it in Table 4. However, decomposition rates vary across ecosystems and soil types (Wang et al., 2017). Moisture extremes also disrupt SCS. Waterlogging creates anaerobic conditions, limiting oxygen availability and increasing methane (CH₄) emissions, which reduces SOC storage (Lal, 2004). Conversely, drought restricts microbial movement, slowing the formation of stable carbon compounds (Kätterer et al., 2019). Moderate climates (≈15°C) and adequate moisture balance decomposition (0.05–0.10 g C/kg/day) while enhancing carbon stabilization (Kirschbaum, 1995; Wang et al., 2017) and Low temperatures (≈5°C) slow microbial activity, reducing decomposition rates (0.01–0.05 g C/kg/day), which can lead to carbon storage (Davidson et al., 2006) as presented in table 4. These factors significantly influence microbial community dynamics and the balance between carbon sequestration and greenhouse gas emissions (Schimel et al., 2007).

Table 4. Temperature Effects on Soil Carbon Decomposition Rates

Sub-factor	Carbon Decomposition Rate (g C/kg/day)	Reference
5°C	0.01 – 0.05	Davidson et al., 2006
15°C	0.05 – 0.10	Conant et al., 2011
25°C	0.1 – 0.2	Davidson & Janssens, 2006

4.5. Microbial activity

The role of microorganisms in SCS bridges biological mechanisms and external influences. Microbial community composition influenced by soil pH and land use, determines whether carbon is stabilized as mineral-associated organic matter or released as CO₂. Fungi and bacteria break down organic matter into mineral-associated organic matter (MAOM), contributing 30–60% of stable SOC (Liang et al., 2017) as indicated in Table 5. Mycorrhizal fungi enhance SOC stabilization by producing glomalin, which contributes 5–15% of SOC retention in soil aggregates (Rillig et al., 2019), while bacterial extracellular polymeric substances (EPS) help protect SOC from decomposition by improving soil aggregation, leading to a 20–40% increase in aggregate stability and preventing carbon loss (Crowther et al., 2016). Microbes also interact with soil minerals, forming stable carbon-mineral complexes that persist for centuries (Kleber et al., 2015) as evidenced in table

5. However, land-use changes and climate stress can shift microbial community composition, altering the

balance between carbon sequestration and greenhouse gas emissions (Cotrufo et al., 2013).

Table 5. Role of Microbial Activity in Soil Carbon Sequestration and Stabilization

Microbial Group	Contribution to SCS	SOC Stabilization (%)	References
Fungi & Bacteria	Decomposes organic matter into mineral-associated organic matter (MAOM)	30–60%	Liang et al., 2017
Mycorrhizal Fungi	Enhances SOC stabilization through glomalin production	5–15%	Rillig et al., 2019
Bacterial EPS (Extracellular Polymeric Substances)	Protects SOC from decomposition by enhancing soil aggregation	20–40%	Crowther et al., 2016
Microbial-Mineral Interactions	Forms stable carbon-mineral complexes	Long-term (>100 years)	Kleber et al., 2015
Microbial Community Shifts	Alters balance between carbon sequestration and greenhouse gas emissions	Variable	Cotrufo et al., 2013

5. BENEFITS OF SOIL CARBON SEQUESTRATION

5.1. Mitigating climate change

Soils are an immense carbon sink and SCS mitigates atmospheric carbon dioxide and other greenhouse gases (GHGs) (Lal, 2004). SCS enhances soil structure, water holding capacity, nutrient cycling, and resilience to harsh climatic events (Lal, 2020). It enhances nitrogen use efficiency and thereby also minimizes nitrous oxide (N₂O) emissions and minimizes methane (CH₄) emissions from agricultural lands (Paustian et al., 2016). As shown by research, soil is capable of sequestering carbon dioxide through regenerative agricultural practices from a rate of 0.2–1.3 metric tons/ha/year (Minasny et al., 2017). Also, grazing and manuring the land with livestock in the Cropland integrated system may increase soil carbon sequestration and help reduce overall emissions (Machmuller et al., 2015).

5.2. Improving soil fertility and soil structure

SOC enhances soil stability, porosity, and water infiltration (Six et al., 2002) via the formation of soil aggregates (Wiesmeier et al., 2015). Microbes degrade plant residues, compost and organic matter into humus that binds soil particles together and helps form soil aggregates, which give a crumbly soil texture (Lal, 2004) and increase aggregate stability against wind and water erosion (Lal, 2020). Better management techniques increase soil nutrient indices and SOC accumulation in arid areas particularly in ground nut-based systems (Gudla et al., 2023; Gudla et al 2023). A 1% increase in SOC can improve the soil water holding capacity of sandy soils by 2–4 times

(Minasny et al., 2017). SOC improves CEC of the soils for key nutrients such nitrogen, phosphorus and potassium (NPK) required for plants growth (Lehmann & Kleber, 2015).

5.3. Boosting Agricultural productivity

Organic carbon enriched soils are more fertile, leading to increased plant growth, and crop yields. SCS promotes nutrient cycling by microbes, decreases usage of chemical fertilizers, and increases the capacity for water retention, resulting in the sustainable use of the farm (Poeplau et al., 2017). It serves as a barrier against the loss of topsoil, improves cohesive soil texture and helps to minimize land degradation and maintain agricultural productivity (Lal, 2020). Increases in soil organic carbon (SOC) can have even greater impacts, as a 1% increase in SOC can increase the moisture holding capacity of the soil by 2–4 times (Minasny et al., 2017), especially in sandy soils. SOC is therefore a contribution to the high CEC values of soils making them better at retaining nutrients (Lehmann & Kleber, 2015).

5.4. Supporting soil biodiversity and health

Increases in organic matter serve as a food source to a wide range of micro-organisms like bacteria and fungi which eventually promotes soil carbon sequestration. They play an important role in converting nutrients into usable forms. Microbial activity, diversity, and a healthy soil ecosystem is strengthened by increased organic carbon content (Lal, R. (2020). Improved biodiversity contributes to soil ecosystem stability and resilience. Soil fauna (e.g. earthworms) improve soil quality by changing soil

structure, increasing soil aeration, and increasing soil fertility (Fierer et al. 2012). Previous research indicates that crop rotation diversification and organic amendments can improve soil function and promote microbial diversity (Jansson & Hofmockel, 2020). In addition, the fungi have been shown to increase the uptake of nutrients from soil and help plants resist stress (van der Heijden et al., 2015).

5.5. Economic benefits for farmers

SCS improves soil health, crop production and reduces the need for inputs. By enhancing soil health, it helps farmers to reduce their reliance on chemical fertilizers, pesticides and irrigation which will minimize the total cost of crop production (Lal., 2015). Moreover, farmers can earn extra income from carbon credit markets, being paid for the carbon they sequester in their soils. For instance, Australia's carbon farming initiative allows farmers to earn AUD 15–30 per ton of CO₂ sequestered through practices like rotational grazing and biochar application (Smith et al., 2022). Globally, Carbon credits are worth \$15–\$30 per ton of CO₂ sequestered globally (FAO, 2020), making it a powerful economic incentive for the adoption of sustainable soil management. According to research, soil health investment would still achieve greater overall farm profitability of 10-15% in the long run, due to increasing yield and decreasing input costs. Federal initiatives, from the USDA Conservation Reserve Program (CRP) to the EU Common Agricultural Policy (CAP) support farmer participation in carbon sequestration practices (Schulte et al., 2021). Additionally, studies indicate that these practices can boost net farm profits by 20-25% over a decade, primarily through improved soil fertility and reduced dependency on purchased inputs (Giller et al., 2021).

6. CONCLUSION

SCS is a diverse process influenced by physical, chemical, and biological mechanisms, with soil texture, pH, land management, and climate acting as key drivers. While SCS offers significant benefits such as climate mitigation, enhanced soil fertility, and economic incentives. Despite its potential, SCS adoption faces barriers such as high initial costs for cover cropping seeds and limited farmer awareness of carbon markets. Current research exhibits limitations, including a geographic bias toward temperate regions and a lack of long-term field data. Future studies should focus on underrepresented ecosystems (e.g., tropical peatlands) and evaluate the socio-economic barriers to adopting SCS practices, such as upfront costs for farmers. Policymakers must integrate SCS

into climate action frameworks to scale its global impact.

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