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Soil Carbon Sequestration in Agro-ecosystems: Mechanisms, Management, and the Role in Climate Change Mitigation

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***Abstract*— *Soils represent one of the largest terrestrial carbon reservoirs, and the improved management of soil organic carbon (SOC) offers considerable potential for mitigating climate change, enhancing soil health, and improving agricultural productivity. This review synthesizes current knowledge on the dynamics and mechanisms of SOC storage, key environmental and land-use factors influencing it, agronomic and chemical management strategies for enhancing sequestration in agro-ecosystems, the limitations and uncertainties in quantifying its role for greenhouse-gas (GHG) mitigation, and the policy and research outlook for scaling up soil-based climate solutions. While the potential is significant, the saturation risk, measurement challenges, trade-offs, and context-specificity must be recognized. For semi-arid and dryland systems in particular, integrating SOC-based management into sustainable intensification pathways will require region-specific calibration, long-term monitoring, and alignment with socio-economic incentives.*

Keywords*— *Soil organic carbon, sequestration, climate change mitigation, agro-ecosystems, semi-arid, soil health, management practices

I. INTRODUCTION

The global climate challenge demands multiple mitigation avenues that extend beyond energy and land-use change. Among nature-based solutions, soils play a pivotal role: the top meter of global soils holds up to three times as much carbon as the atmosphere [1, 2]. Agricultural soils represent both a risk [3] and FAO (2017, 2022) have emphasized soil carbon management as a crucial land-based strategy for achieving sustainable climate solutions.

This review updates current knowledge, summarises management strategies for enhancing soil carbon storage, identifies limitations, and offers perspectives for dryland and semi-arid agro-ecosystems under climate variability.

II. MECHANISMS OF SOIL CARBON SEQUESTRATION

SOC accumulation is governed by input, transformation, and stabilization processes [4, 5].

- Inputs: Plant residues, root exudates, and organic amendments such as manure and compost contribute to carbon inputs [6, 7].
- Transformation: Microbial decomposition, aggregation, and biochemical stabilization determine carbon turnover rates [8, 9].
- Stabilization: SOC is retained through physical protection within aggregates, chemical adsorption to minerals, and biochemical recalcitrance [1, 4].

Biochar has gained attention as a recalcitrant amendment that adds stable carbon pools and modifies microbial activity [10, 11, 12]. Mineral–organic associations also play critical roles in long-term stabilization [4].

III. FACTORS INFLUENCING SOC STORAGE

SOC storage potential varies with several biophysical and management factors

[13, 1].

- Climate: Temperature and moisture regulate decomposition; warmer, drier conditions enhance mineralization and carbon loss [14, 15].
- Soil texture and mineralogy: Clay-rich soils protect SOC more effectively than sandy soils [5, 4].
- Land use and disturbance: Conversion of forests or grasslands to cropland often reduces SOC by 25–50%, whereas restoration or reduced tillage can recover part of this loss [16].
- Management intensity: Fertilization, irrigation, residue handling, and cropping diversity influence SOC inputs and turnover [17, 18].
- Saturation and residence time: Soils reach an equilibrium carbon level beyond which sequestration slows—termed "carbon saturation" [4].
- Climate feedbacks: Rising temperatures may reduce SOC stability, potentially converting soils from sinks to sources [19].

Table 1. Average Soil Organic Carbon Sequestration Potential under Various Land Uses and Climatic Conditions

Land use / System	SOC Sequestration Potential (Mg C ha^{-1} yr^{-1})	Climate Zone	Major Mechanism	Reference
No-till cropping	0.3 – 0.6	Temperate	Reduced disturbance, aggregate stability	Jian et al. (2020); Pittelkow et al. (2015)
Cover cropping	0.4 – 0.8	Humid-subtropical	Enhanced biomass and root carbon input	Joshi et al. (2023)
Manure application	0.2 – 0.5	Semi-arid	Organic carbon addition	Ghosh et al. (2024)
Agroforestry	1.0 – 3.0	Tropical	Tree litter, deep roots	Lal (2020); Pandao et al. (2024)
Biochar amendment	0.3 – 1.2	Semi-arid	Stable carbon addition, microbial modulation	Bekchanova et al. (2024); Gross et al. (2021)
Enhanced rock weathering	0.5 – 2.0	Humid-temperate	Mineral carbonation and CO_2 capture	Beerling et al. (2025)

IV. MANAGEMENT STRATEGIES FOR ENHANCING SOIL ORGANIC CARBON (SOC) IN AGRO-ECOSYSTEMS

Sustainable soil carbon management requires a combination of agronomic, biological, and ecological practices that enhance carbon inputs while minimizing losses through decomposition and erosion. The following management interventions have been widely recognized as practical approaches to increase SOC sequestration and improve soil health.

4.1 Conservation Tillage and No-Till Systems

Conservation tillage, particularly no-till farming, has emerged as one of the most effective methods for retaining soil organic matter and improving carbon stabilization. By minimizing soil disturbance, these systems protect soil aggregates and reduce the exposure of organic matter to oxidation [18, 20]. Global meta-analyses indicate that no-till practices can significantly enhance SOC concentrations, especially in the upper 0–10 cm soil layer, where residues accumulate and microbial activity is high [20]. These benefits are particularly evident in temperate and humid regions, where soil moisture is more conducive to biological activity. However, some studies suggest that while surface SOC increases, the total profile carbon may remain unchanged due to vertical redistribution of carbon [1]. The long-term adoption of reduced tillage also enhances soil structure, improves water infiltration, and facilitates nutrient cycling, thereby further supporting ecosystem resilience under changing climatic conditions.

4.2 Cover Crops and Crop Rotations

The inclusion of cover crops and diversified crop rotations plays a vital role in maintaining continuous carbon inputs into the soil system. Cover crops—especially legume-grass mixtures—enhance root biomass production, stimulate microbial activity, and improve soil aggregation, collectively contributing to greater soil carbon sequestration [17, 8]. Long-term experimental data indicate annual SOC gains ranging from 0.3 to 0.6 Mg C ha^{-1} yr^{-1} under well-managed cover cropping systems [17]. In addition to carbon sequestration, diversified rotations reduce pest and disease pressure, improve nutrient-use efficiency, and stabilize crop yields—key benefits for sustainable agroecosystem functioning.

4.3 Organic Amendments and Residue Management

The addition of organic amendments—such as farmyard manure, compost, and crop residues—directly increases both labile and recalcitrant carbon fractions in soils. These inputs enrich microbial habitats, enhance nutrient availability, and foster aggregate formation [6, 7]. Residue retention on the soil surface reduces evaporation and erosion while promoting moisture conservation and energy flow within the soil food web. However, the C:N ratio of residues must be balanced through appropriate nitrogen management to prevent immobilization and maintain crop productivity. The long-term integration of manure or compost with mineral fertilizers has been shown to enhance soil carbon stability and resilience against degradation.

Table 2. Representative SOC management practices and co-benefits

Practice	SOC impact	Co-benefits	Limitations
No-till	Moderate SOC gain in surface layers	Improved infiltration, erosion control	Potential yield variability
Cover crops	High SOC potential	Soil structure, biodiversity	Water competition in dry areas
Organic amendments	Direct C addition	Improved fertility	Cost and logistics
Agroforestry	Large, long-term SOC	Biodiversity, shade, income	Land competition
Biochar	Long-term stable C	Water holding, yield	Production costs
Enhanced weathering	CO_2 removal via minerals	Nutrient enrichment	Scaling uncertainty

4.4 Agroforestry and Perennial Systems

Agroforestry and perennial cropping systems serve as highly efficient biological sinks for atmospheric carbon. Integrating trees, shrubs, and deep-rooted perennials into farmlands not only enhances belowground carbon storage but also promotes litter deposition and soil biodiversity [21, 9]. Empirical studies suggest that well-designed agroforestry systems can sequester between 1 and 3 Mg C ha^{-1} yr^{-1}, depending on tree species composition, soil type, and climatic conditions [1]. Moreover, the long-term presence of perennials stabilizes soil structure, improves nutrient recycling, and mitigates the impacts of extreme weather events, aligning with climate-smart agricultural principles.

4.5 Biochar and Advanced Carbon Amendments

4.6 Biochar, a carbon-rich product derived from the pyrolysis of biomass, represents a promising technology for long-term carbon sequestration in soils. Its high stability and porous structure contribute to improved soil aeration, water-holding capacity, and nutrient retention [10, 11]. Meta-analytical evidence shows mean SOC increases of 18–30% following biochar application, depending on feedstock and application rate [12]. Additionally, biochar enhances microbial habitat quality and may reduce nitrous oxide emissions, providing a dual benefit for climate change mitigation and improving soil fertility.

4.6 Enhanced Rock Weathering

Enhanced rock weathering [22, 23, 24]. This emerging strategy not only captures atmospheric CO_2 but also releases essential nutrients, such as calcium, magnesium, and potassium, which can enhance soil fertility. ERW offers a potentially scalable and durable pathway for carbon removal; however, uncertainties remain regarding its large-scale feasibility, energy costs, and potential ecological impacts. Further long-term field studies and life-cycle assessments are needed to evaluate its integration into sustainable farming systems.

V. LIMITATIONS, UNCERTAINTIES, AND RESEARCH GAPS

Despite the promise, SOC sequestration faces key challenges:

Saturation and permanence: Carbon gains slow as soils approach equilibrium, and reversal can occur due to land-use change or erosion [4, 1].

Measurement challenges: SOC changes are slow, spatially variable, and costly to monitor accurately [5].

Trade-offs: Some practices may increase N_2O emissions or require additional inputs [1].

Timescales: Detectable carbon increases often take 10–20 years [9].

Climate feedbacks: Warming may accelerate decomposition, especially in semi-arid regions [14, 19].

VI. POLICY AND OUTLOOK FOR SEMI-ARID AGROECOSYSTEMS

Integrating SOC sequestration into national climate policy aligns with land degradation neutrality and SDG 13 [25, 26].

In India's semi-arid regions, soil carbon enhancement must complement productivity goals and climate resilience [9]. Incentive mechanisms—such as carbon credit schemes and payments for ecosystem services—can motivate adoption of carbon-positive practices [2, 27].

Emerging technologies [28]. Long-term adoption depends on capacity building, farmer engagement, and integration of soil health indicators into policy frameworks [5, 1].

VII. CONCLUSIONS

Soils are vital components of the global carbon balance and a cornerstone of sustainable agriculture. Enhancing SOC offers co-benefits of improved fertility, resilience, and climate mitigation. However, sequestration potential is finite and context-dependent. Region-specific approaches, particularly for dryland and semi-arid systems, are essential. Future efforts must combine agronomic innovation, digital monitoring, and enabling policy to achieve meaningful and lasting soil carbon gains.

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