Soil Carbon Sequestration in Ecosystems: Processes, Mechanisms, and Climate Significance

Abhishek Kumar*

Research scholar, Department of Agronomy, School of Agriculture,
Lovely Professional University, Phagwara, Punjab, India, 144411

Corresponding Author
Abhishek Kumar
Email: abhishek8626890182@gmail.com

OPEN ACCESS

Keywords

Soil Carbon Sequestration, Ecosystem Carbon Cycling, Climate Change Mitigation

How to cite this article:

Kumar, A. 2026. Soil Carbon Sequestration in Ecosystems: Processes, Mechanisms, and Climate Significance. *Vigyan Varta* 7 (04): 240-243.

ABSTRACT

Soil carbon sequestration (SCS) is a critical natural process through which atmospheric carbon dioxide (CO_2) is captured by vegetation and stored in soil organic matter. With global soils estimated to hold between 1,500 and 2,400 petagrams of carbon, they represent the Earth's largest terrestrial carbon reservoir. This article reviews the key mechanisms of SCS—including microbial processing, organo-mineral interactions, and physical protection within soil aggregates—and examines how these processes operate across forest, grassland, and wetland ecosystems. The threats posed by land-use change and climate warming, as well as management strategies to enhance soil carbon storage, are also discussed. Understanding and harnessing SCS is essential for achieving global climate change mitigation targets.

INTRODUCTION

The growing concentration of greenhouse gases in the atmosphere has intensified the global search for viable carbon dioxide removal strategies. Among these, soil carbon sequestration stands out as both ecologically significant and practically achievable at scale. Soils store more carbon than the atmosphere and all above-ground vegetation combined, making them indispensable regulators of the global carbon cycle (Kaur *et al.*, 2025). Between 2012 and 2021, terrestrial ecosystems absorbed approximately 11.4 gigatonnes of CO_2 per year—about 31% of total anthropogenic emissions—with soils playing a central role in this uptake (World Ocean Review, 2024).

Soil organic carbon (SOC) is not merely a climate variable; it is a cornerstone of soil health, influencing fertility, water-holding capacity, structural stability, and biodiversity. Decades of conventional agriculture, deforestation, and wetland drainage have significantly depleted global SOC stocks, while simultaneously accelerating atmospheric CO_2 accumulation. Restoring and maintaining soil carbon is therefore both a climate imperative and an agricultural necessity (Villat & Nicholas, 2024). This article examines the processes underlying SCS, how they vary across ecosystems, and what strategies can be employed to maximize the contribution of soils to climate change mitigation.

1. Mechanisms of Soil Carbon Sequestration

Carbon enters the soil primarily through plant photosynthesis: organic compounds are transferred belowground via root turnover, root exudates (rhizodeposition), and the decomposition of above-ground litter. Once in the soil, this carbon is subjected to a spectrum of biological and chemical transformations that determine whether it is rapidly mineralized back to CO_2 or incorporated into stable, long-lived soil organic matter fractions (Sarker *et al*., 2025).

Microbial communities are the primary architects of SCS. The microbial carbon pump (MCP) theory describes two pathways through which microorganisms regulate carbon stabilization: the ex vivo modification pathway, in which plant residues are chemically transformed and transported into the soil matrix, and the in vivo turnover pathway, through which microbial biomass carbon—upon cell death—is entombed in the persistent SOC pool (Chen *et al*., 2025). Research using ^{13}C isotope labeling has demonstrated that dissolved labile carbon substrates contribute significantly to the particulate organic carbon (POC) pool via microbial biomass intermediates, challenging earlier assumptions about the primary drivers of stable carbon formation (Wei *et al*., 2024).

A second major stabilization pathway involves organo-mineral interactions. Mineral-associated organic carbon (MAOC) forms when microbially derived organic molecules adsorb electrostatically or covalently onto clay particles and metal oxides (iron and aluminum hydroxides), creating structures highly resistant to microbial degradation. The mineral carbon pump (MnCP) theory complements the MCP by describing how labile plant carbon is transformed through abiotic redox reactions and polymerization into stable aromatic macromolecules bound to mineral surfaces (Chen *et al*., 2025). Fine-textured clay-rich soils offer greater mineral surface area, and therefore have a higher capacity for MAOC formation than coarse sandy soils.

Management practices such as no-till farming preserve aggregate integrity: studies show macro-aggregate proportions are maintained at 51–54% under reduced tillage compared to ~44% under intensive conventional tillage, with significant consequences for SOC retention (USDA, 2024).

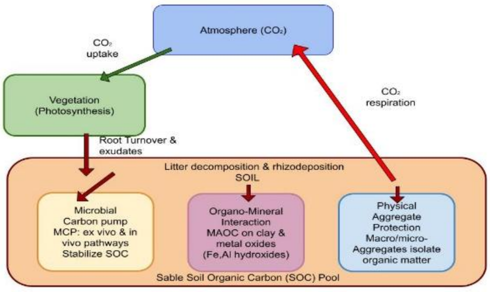

Figure 1. Mechanisms of Soil Carbon Sequestration

2. Soil Carbon Sequestration Across Ecosystems

Forest ecosystems harbor the largest terrestrial carbon stocks. High above-ground biomass, continuous litter inputs, deep root systems, and rich microbial communities combine to sustain substantial SOC accumulation. Research has shown that plant rhizodeposition is a key driver of stable SOC formation, with root-derived carbon more efficiently stabilized in mineral-associated fractions than shoot-derived litter (Villarino *et al*., 2021). Ectomycorrhizal fungi, dominant in boreal and temperate forests, further enhance carbon storage by suppressing decomposition of organic matter in the forest floor.

Grasslands, covering approximately 40% of Earth's land area, store roughly one-third of global terrestrial carbon stocks, almost entirely in the soil rather than in biomass (Bai & Cotrufo, 2022). Plant species diversity is a key driver of grassland SOC: greater diversity produces richer and more varied root inputs, stimulates complex microbial communities, and improves soil structural stability. FAO estimates suggest that grasslands alone could contribute up to 17% of the 4p1000 initiative's global sequestration target of 3.5 Pg C per year (Dondini *et al*., 2023).

Wetland ecosystems are the most carbon-dense terrestrial systems per unit area, storing 20–30% of the global soil carbon pool despite covering only 5–8% of Earth's land surface (Yu *et al*., 2025). However, wetland carbon stores are acutely vulnerable: drainage restores aerobic conditions, triggering rapid SOC oxidation and large greenhouse gas emissions. Global wetland area has declined by 35% since 1970, representing a significant and largely irreversible loss of carbon storage capacity (Yu *et al*., 2025).

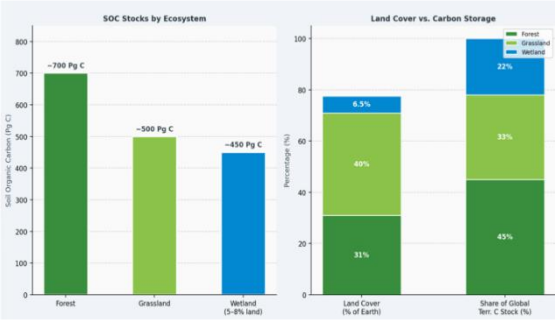

Figure 2. Soil Carbon Storage Across Ecosystems

3. Management Strategies and Challenges

A suite of evidence-based land management practices can substantially enhance SCS. In agricultural systems, regenerative practices including no-till farming, cover cropping, agroforestry, compost amendments, and reduced synthetic inputs have demonstrated consistent SOC gains across diverse climatic zones (Villat & Nicholas, 2024). In U.S. croplands, the adoption of these practices contributed to a 58% increase in mineral soil carbon stocks between 1990 and 2022, with these soils offsetting roughly 10% of total agricultural greenhouse gas emissions (USDA, 2024). Biochar application—produced by pyrolysis of organic biomass—offers an additional strategy, introducing a highly stable, biologically recalcitrant carbon form into soils while improving fertility and water retention.

Protecting and restoring ecosystems at risk is equally critical. Avoiding deforestation, preserving peatlands, and rewetting drained wetlands prevent the release of centuries-old carbon stocks that cannot be rebuilt on human timescales. Restoration of degraded ecosystems has real but ultimately limited potential: global modeling estimates suggest ecosystem restoration can sequester a maximum of 96.9 Gt C by 2100, equivalent to just 3.7–12.0% of anticipated cumulative anthropogenic emissions (Cook-Patton *et al*., 2025).

Reliable measurement and monitoring of SOC changes remain technically demanding, though remote sensing and machine learning tools are advancing rapidly. Finally, emerging threats such as microplastic contamination may impair soil microbial communities and aggregate stability, subtly undermining long-term sequestration capacity (El-Ataar, 2025).

CONCLUSION

Soil carbon sequestration is an irreplaceable component of any credible climate change mitigation strategy. Through microbial processing, organo-mineral stabilization, and physical aggregate protection, soils across forests, grasslands, and wetlands sequester and store vast quantities of atmospheric carbon. While natural sequestration processes are powerful, they are also fragile: land-use change, climate warming, and poor management can rapidly reverse carbon gains accumulated over centuries. Realizing the full climate mitigation potential of soils requires the integration of ecosystem protection, sustainable agriculture, and evidence-based policy. Soils are not merely a passive reservoir—they are an active, manageable, and vital partner in the global effort to stabilize the climate.

REFERENCES

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377(6606), 603–608.

Chen, Z., Wang, X., & Liu, Y. (2025). Current progress and future trends in carbon sources and sinks in farmland ecosystems. PMC.

Cook-Patton, S. C., *et al*. (2025). Limited carbon sequestration potential from global ecosystem restoration. Nature Geoscience. z

Dondini, M., Martin, M., De Camillis, C., Uwizeye, A., Soussana, J.-F., Robinson, T., & Steinfeld, H. (2023). Global assessment of soil carbon in grasslands. FAO Animal Production and Health Paper No. 187.

El-Ataar, A. (2025). Harnessing soil carbon sequestration to address climate change challenges in agriculture. Journal of Umm Al Qura University for Applied Sciences.

Kaur, P., *et al.* (2025). Understanding soil carbon sequestration: Mechanistic insights, management approaches, and future challenges. Discover Soil.

United States Department of Agriculture (USDA). (2024). Documentation of literature, data, and modeling: Soil organic carbon in cropland ecosystems.

Villarino, S. H., Pinto, P., Jackson, R. B., & Piñeiro, G. (2021). Plant rhizodeposition: A key factor for soil organic matter formation in stable fractions. Science Advances, 7, eabd3176.

Villat, J., & Nicholas, K. A. (2024). Quantifying soil carbon sequestration from regenerative agricultural practices. Frontiers in Sustainable Food Systems, 7, 1234108.

Wei, X., *et al.* (2024). Dissolved carbon flow to particulate organic carbon enhances soil carbon sequestration. SOIL, 10, 441–453.

World Ocean Review. (2024). Forests, grasslands and soils as carbon stores. World Ocean Review 8.

Yu, Z., *et al*. (2025). Carbon sequestration potential of wetlands and regulating strategies response to climate change. Environmental Research, 270, 120924.