



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(7): 448-456
Received: 15-04-2026
Accepted: 19-05-2026

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Soil organic carbon dynamics and sequestration across land-use systems

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7Sf.6148>

Abstract

Soil organic carbon (SOC) is a fundamental component of terrestrial ecosystems, supporting soil fertility, nutrient cycling, water retention, biodiversity, and climate regulation. This narrative review synthesizes current knowledge on SOC composition, formation, stabilization mechanisms, and dynamics across major land-use systems, including forests, grasslands, croplands, agroforestry systems, wetlands, and degraded or urban lands. It highlights the biological, physical, and chemical processes governing SOC stabilization and examines how land-use change, climate variability, soil properties, and management practices influence carbon storage and sequestration. Forests, wetlands, and agroforestry systems generally maintain higher SOC stocks, whereas intensive agriculture and land degradation accelerate carbon losses. The review further discusses sustainable land management strategies such as conservation tillage, residue retention, cover cropping, organic amendments, biochar application, and afforestation that enhance SOC sequestration while improving soil health and agricultural productivity. Strengthening SOC through climate-smart land management offers significant opportunities for climate change mitigation, ecosystem restoration, and long-term food security.

Keywords: Soil organic carbon, Carbon sequestration, Land-use systems, Climate change mitigation, Sustainable land management

Introduction

Soil organic carbon (SOC) is a central component of terrestrial ecosystem as it supports soil health, water retention, nutrient cycling and climate regulation (Ramesh *et al.*, 2019; Li *et al.*, 2025) ^[1, 2]. Soils represent the largest terrestrial carbon reservoir, storing roughly two to three times more carbon than the atmosphere and vegetation. Atmospheric carbon dioxide concentration has increased from approximately 280 ppm during the pre-industrial era to more than 425 ppm in the recent times. This has intensified the Earth's radiative forcing, resulting in a global mean temperature increase of about 1.1 °C above the pre-industrial average. These changes disrupts ecosystem functioning, reduce agricultural productivity, threaten food and water security and increase the vulnerability of natural and managed ecosystems globally (IPCC, 2023) ^[3]. SOC is a complex mixture of decomposing plant and animal residues, microbial biomass, microbial metabolites and humified organic compounds associated with soil minerals. The quantity and stability of SOC are governed by a dynamic balance between carbon inputs and carbon losses (Ito *et al.*, 2020) ^[4]. SOC dynamics are highly sensitive to land-use change, management and climate variability and together determine whether soils function as carbon sinks or carbon sources. Conversion of natural ecosystems to crop production generally causes substantial SOC loss, creating a long-term soil carbon debt, although part of this loss can be restored through improved management such as tree integration, biochar and organic amendments application along with adoption of location specific restorative practices. Differences among land-use systems are pronounced. Forests and less-disturbed systems usually retain higher SOC stocks than intensively cultivated land, while conversion to monocropping or plantation systems often reduces SOC through lower biomass inputs and greater disturbance. Labile fractions such as particulate organic carbon, microbial biomass carbon and permanganate-oxidizable carbon respond rapidly to land-use shifts, whereas more stable pools such as mineral-associated organic carbon are critical for long-term sequestration (Schmidt *et al.*, 2011; Cotrufo *et al.*, 2019) ^[5].

Improvement in SOC contributes directly to several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) through improved soil fertility and agricultural productivity, SDG 13 (Climate Action) through enhanced terrestrial carbon storage, SDG 15 (Life on Land) by restoring degraded ecosystems and reducing land degradation and SDG 12 (Responsible Consumption and Production) by promoting sustainable land management. These multiple benefits highlight the central role of SOC in linking climate resilience, ecosystem sustainability and food security. Against this background, this narrative review examines soil organic carbon dynamics across land-use systems and evaluates how those dynamics influence carbon sequestration and climate mitigation outcomes.

Soil Organic Carbon: Composition and Dynamics

Soil organic carbon (SOC) is the carbon component of soil organic matter (SOM) formed by continuous inputs and microbial transformation of biological materials. Inputs include

leaf litter, crop residues, roots and exudates, animal remains, microbial biomass and organic amendments (manure, compost, biochar). These inputs decompose into a range of compounds that differ in chemistry, accessibility and turnover. SOC is preferred over SOM as a tracking metric because carbon content is measured more precisely and typically comprises 50–58% of SOM.

Composition and key contributors

- SOM includes living microbes, fresh and decomposing residues, dissolved organics, microbial products, and stabilized material. SOC reflects the carbon within these pools.
- Plant-derived compounds (carbohydrates, proteins, lipids, lignin, cellulose) dominate inputs and fuel microbial growth. Microbial residues (necromass) are now recognized as major contributors to persistent SOC because they bind readily to mineral surfaces.

Table 1: Drivers of SOC Dynamics

Driver	Main Effect on SOC	Evidences
Land-use change	Usually causes major SOC redistribution or loss	Natural-to-agricultural conversion created a global 133 Pg C debt, and forest-to-plantation conversion reduced SOC in tropical systems (Sanderman <i>et al.</i> , 2017) ^[6]
Management practices	Can raise or lower SOC depending on residues, trees, and amendments	Residue retention, reduced tillage, perennial systems, biochar, and organic agriculture increased SOC in syntheses (Beillouin <i>et al.</i> , 2023) ^[7]
Climate	Warming and drying tend to accelerate SOC loss	Climate change was the largest contributor to SOC dynamics across much of China, and warming increased decomposition risk (Li <i>et al.</i> , 2022) ^[8]
Soil properties	Texture, drainage, and initial SOC constrain sequestration potential	Clay content, soil water condition and initial SOC strongly modified SOC responses across regions and land uses (Li <i>et al.</i> , 2025; Fu <i>et al.</i> , 2024) ^[2, 9]

Operational fractions commonly measured

- Particulate organic carbon (POC): coarse particles >53 µm; sensitive to tillage and residue management.
- Mineral-associated organic carbon (MAOC): organic matter adsorbed on clays and Fe/Al oxides; major long-term reservoir.
- Microbial biomass carbon (MBC): living microbes; controls transformation rates.
- Light fraction (LFOC) and heavy/mineral-bound fraction (HFOC): indicators of recent inputs and stabilized carbon, respectively.

Table 2: Functional Pool of Soil Organic Carbon

SOC pool	Major constituents	Turnover time	Stability	Ecological significance
Active	Fresh plant residues, root exudates, dissolved organic compounds, microbial biomass	Days to 5 years	Low	Supplies energy for microbes; regulates nutrient mineralization; responds rapidly to land-use and management changes (Six <i>et al.</i> , 2002) ^[10] .
Slow	Partially decomposed residues, microbial products, aggregate-protected organic matter	20–50 years	Moderate	Maintains soil structure; provides sustained nutrient release; contributes to medium-term storage (Lehmann & Kleber, 2015) ^[11] .
Passive	Mineral-associated organic matter, microbial necromass, organo-mineral complexes	Centuries to millennia	High	Principal long-term reservoir; underpins sequestration and climate regulation (Cotrufo <i>et al.</i> , 2013) ^[12] .

Formation and Transformation of Soil Organic Carbon

Carbon fixed by photosynthesis is routed to soil through multiple pathways, with a substantial fraction (commonly 40–60%) allocated belowground. The high belowground allocation enhances contact between plant-derived carbon, soil minerals and aggregates; and promotes processes that favor SOC stabilization (Jackson *et al.*, 2017)^[13]. Root exudates simple bioavailable compounds such as sugars, amino acids and organic acids that influences the rhizosphere microbial activity and subsequent carbon transformation (Kuzakov & Razavi, 2019)^[14]. Soil fauna fragment plant residues and increase substrate accessibility, while bacteria and fungi enzymatically decompose organic inputs. Microbes respire a portion as CO and converts the remainder into microbial biomass and

extracellular products. The fate of assimilated carbon therefore depends critically on microbial carbon-use efficiency (CUE); higher CUE channels more carbon into biomass and necromass that can be stabilized, whereas lower CUE increases respiratory losses (Cotrufo *et al.*, 2013; Liang *et al.*, 2019)^[12].

Mechanisms Governing Soil Organic Carbon Stabilization

Soil organic carbon (SOC) persistence depends on the amount of carbon inputs and how effectively that carbon is protected from microbial decomposition. Stabilization comprises biological, physical, and chemical processes that limit microbial and enzymatic access and thereby extend carbon residence time. Stabilized SOC is dynamic in which mineralization process continues, but losses are slower than inputs, so soils can act as

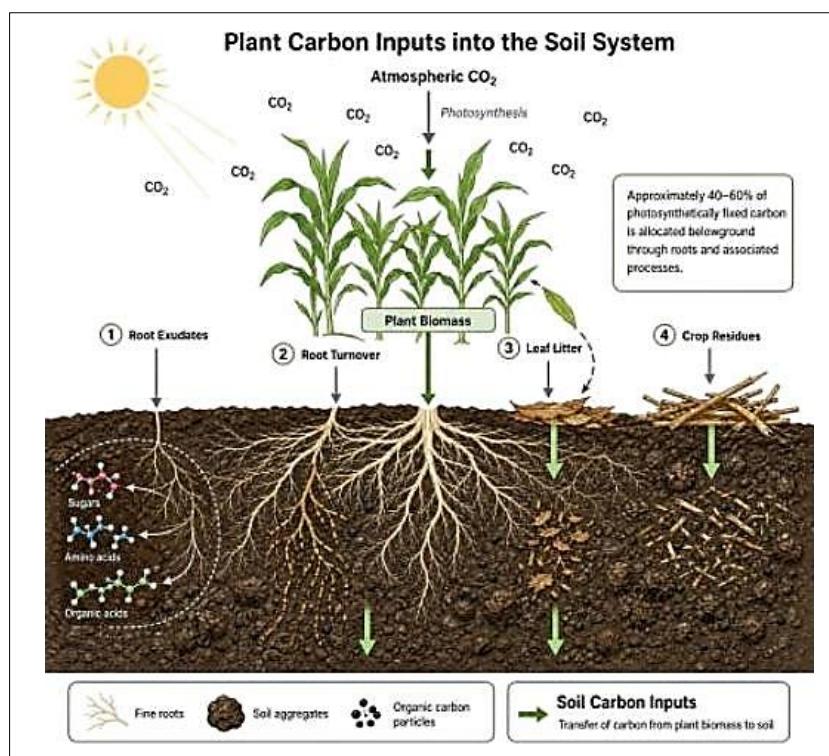


Fig 1: Plant Carbon Inputs into the Soil System

persistent, yet transient, carbon reservoirs (Six *et al.*, 2002; Schmidt *et al.*, 2011) ^[10, 5].

The traditional humification view that plant residues become chemically recalcitrant humic substances which alone explain persistence has been superseded. Current evidence shows most organic compounds are degradable if they are accessible; therefore persistence depends more on constraints to microbial access and activity than on intrinsic molecular resistance (Lehmann & Kleber, 2015) ^[11]. These mineral-associated products form a major, long-lived SOC fraction (Cotrufo *et al.*, 2019).

Three interacting pathways govern stabilization

- **Biological:** conversion of plant carbon into microbial biomass and necromass that can become protected
- **Physical:** occlusion of organic matter within soil aggregates, which limits microbial and enzymatic access.
- **Chemical:** adsorption and complexation of organic compounds onto reactive mineral surfaces (clays, Fe and Al oxides).

These pathways operate together. Microbial transformation creates compounds that adsorb to minerals and become occluded within aggregates, producing multiple, complementary forms of protection. Stabilization efficiency is shaped by soil texture and mineralogy, aggregation, microbial community composition, vegetation, climate, hydrology, and management. Finetextured, mineral-rich soils generally retain more stable carbon because of greater surface area and reactive sites. Management that increases belowground inputs, enhances aggregation, reduces disturbance, or improves microbial carbon-use efficiency increases stabilization. Conversely, intensive tillage, erosion, residue removal and practices that accelerate mineralization reduce stabilization and shorten SOC residence times.

3.1 Physical Stabilization

Physical stabilization works by restricting decomposer access. Organic matter becomes occluded within aggregates, limiting oxygen diffusion, pore connectivity and enzyme penetration, which slows decomposition even of chemically labile material (Six *et al.*, 2002; Schmidt *et al.*, 2011) ^[10, 5]. Soil macroaggregates (>250 µm) form around fresh residues, roots and hyphae and microaggregates (53–250 µm) develop within macroaggregates during decomposition. As aggregates form, fresh carbon is progressively transferred into physically protected fractions with longer residence times (Tisdall & Oades, 1982) ^[15].

Biological agents such as fine roots, fungal hyphae, microbial exudates (EPS) and soil fauna such as earthworms initiate and stabilize aggregation. Mycorrhizal fungi contribute glomalin-related proteins that reinforce long-term aggregate stability. Management strongly controls aggregate dynamics. Tillage disrupts macroaggregates and exposes previously protected carbon, accelerating mineralization; conservation practices (reduced tillage, residue retention, cover crops, agroforestry, organic amendments) enhance aggregation and long-term carbon protection (Lal, 2016) ^[16]. Effectiveness depends on texture and climate. Clay-rich soils form more stable microaggregates and retain more physically protected carbon than sandy soils. Climatic cycles such as wetting–drying and freeze–thaw can build or break aggregates, so physical protection acts as aggregate occlusion and couples with mineral associations to produce layered stabilization.

3.2 Chemical Stabilization

Chemical stabilization occurs when organic compounds bind to reactive mineral surfaces, forming mineral-associated organic carbon (MAOC) that is less accessible to microbes. The capacity for chemical stabilization depends on the abundance and characteristics of clay minerals, Fe and Al oxides, pH, and mineral surface area. Binding mechanisms include ligand exchange, cation bridging, electrostatic attraction, hydrogen

bonding, and van der Waals forces (Lehmann & Kleber, 2015)^[11]. Chemical stabilization complements physical and biological pathways. Microbial transformation generates compounds that adsorb onto mineral surfaces, while aggregates physically protect these organo-mineral complexes from disturbance. Organo-mineral complexes are often enclosed within aggregates, producing multiple protection layers that together determine long-term SOC persistence.

3.3 Biological Stabilization of Soil Organic Carbon

Biological stabilization recognizes microorganisms as principal agents transforming plant-derived carbon into persistent SOC. During decomposition, microbes assimilate substrates into biomass and generate residues (necromass), extracellular polymers, and metabolites that become stabilized via physical protection and mineral association. Microorganisms thus regulate both carbon loss (respiration) and storage (biomass and necromass), making them central to SOC dynamics (Cotrufo *et al.*, 2019). Microbial carbon use efficiency (CUE) is the proportion of assimilated carbon converted to biomass *versus* respired and it largely determines the fraction of carbon retained in soil. High CUE favors biomass production and necromass formation; low CUE increases respiratory losses. Substrate quality, nutrient availability, moisture, and temperature strongly influence microbial metabolism and the balance between sequestration and mineralization.

SOC Dynamics in Major Land-Use Systems

Soil organic carbon (SOC) dynamics vary markedly among forests, grasslands, croplands, agroforestry systems, wetlands, and degraded or urban lands. Whether a soil functions as a carbon sink or source depends primarily on the magnitude and quality of organic inputs, the frequency and intensity of disturbance, and the efficiency of biological and physicochemical stabilization under a given climate and soil type (Beillouin *et al.*, 2022; Ramesh *et al.*, 2019)^[17, 1]

Forest Ecosystems

Forest store approximately 45–50% of global terrestrial carbon in vegetation and soils, with soils often containing larger and more persistent pools than aboveground biomass, particularly in temperate and boreal regions where cool conditions slow decomposition (Pan *et al.*, 2011)^[18]. Consequently, forests play a dual role in climate regulation by simultaneously removing atmospheric CO₂ through photosynthesis and storing significant quantities of carbon belowground as stable soil organic carbon. Continuous inputs from litterfall and coarse woody debris, combined with substantial belowground carbon from root turnover and rhizodeposition, sustain high SOC stocks (Clemmensen *et al.*, 2013; Jobbágy & Jackson, 2000)^[19, 20]. Litter quality decides decomposition and stabilization. Broadleaf litter, with lower lignin and narrower C:N ratios, decomposes more rapidly than coniferous litter rich in lignin and phenolics, which promotes thick organic horizons and large SOC stocks in boreal forests despite lower productivity. Fungal-dominated decomposition, mycorrhizal associations, and microbial necromass formation are central to SOC formation, with microbial residues adsorbed onto clay minerals and Fe/Al oxides contributing substantially to mineral-associated organic carbon (MAOC) (Cotrufo *et al.*, 2019). Physical protection within aggregates and chemical organo-mineral interactions extend carbon residence times from decades to centuries (Lehmann & Kleber, 2015; Six *et al.*, 2002)^[11, 10].

Equally important are belowground inputs derived from root turnover, fine-root mortality, and rhizodeposition. Root-derived carbon enters directly into the soil matrix, increasing the likelihood of interaction with mineral particles and aggregate formation, thereby contributing more efficiently to stable SOC than surface litter alone (Jobbágy & Jackson, 2000; Clemmensen *et al.*, 2013)^[20, 19]. Climate exerts strong control over SOC dynamics under forest land use system. Tropical forests exhibit high productivity but rapid decomposition, limiting long-term SOC accumulation, whereas boreal forests accumulate large stocks under cold, often waterlogged conditions (Jobbágy & Jackson, 2000; Pan *et al.*, 2011)^[20, 18]. Deforestation, logging, and fire reduce inputs and expose soils to erosion and mineralization, while afforestation, reforestation, and sustainable management restore inputs and stabilization, enhancing long-term sequestration.

Grassland Ecosystems

Grassland ecosystems allocate 40–80% of photosynthetically fixed carbon belowground through dense fibrous root systems, continuous root turnover, and rhizodeposition. Grassland soils frequently contain SOC stocks comparable to or exceeding those of forest in surface horizon (Jobbágy & Jackson, 2000)^[20]. Root-derived carbon enters directly into the soil matrix, promoting microbial biomass and necromass formation and increasing the probability of stabilization as MAOC (Cotrufo *et al.*, 2019; Kuzyakov & Razavi, 2019)^[14]

Grassland soils are generally characterized by high aggregate stability, resulting from the combined effects of dense root systems, microbial extracellular polysaccharides, and fungal hyphae. These aggregates physically protect organic matter from microbial decomposition while simultaneously promoting organo-mineral interactions that enhance long-term carbon persistence. Consequently, root-derived carbon is considered one of the most efficient contributors to stable SOC formation in grassland ecosystems (Six *et al.*, 2002; Lehmann & Kleber, 2015)^[10, 11].

High aggregate stability, maintained by roots, fungal hyphae, and microbial polysaccharides, physically protects organic matter and facilitates organo-mineral interactions, making root carbon a particularly efficient pathway to stable SOC (Lehmann & Kleber, 2015; Six *et al.*, 2002)^[11, 10]. Grazing intensity regulates these dynamics: moderate grazing can stimulate productivity and root turnover, whereas overgrazing reduces cover, increases compaction and erosion, and accelerates SOC loss. Fire effects depend on frequency, intensity, and post-fire recovery.

Agricultural Croplands

Conversion of natural ecosystems to cropland has depleted 20–60% of original SOC globally, driven by tillage, residue removal, monocropping, and intensive harvesting that accelerate decomposition and reduce inputs (Guo & Gifford, 2002)^[21]. SOC dynamics in croplands reflect the balance between inputs from residues, roots, cover crops, and organic amendments, and losses via respiration, erosion, and disturbance.

Root-derived carbon is as important as residue carbon, with fine-root turnover and rhizodeposition stimulating microbial activity and supporting formation of stable microbial necromass, particularly under systems with extensive root biomass or perennials (Cotrufo *et al.*, 2019). Conventional tillage disrupts aggregates, exposes protected organic matter, and increases aeration, accelerating mineralization; reduced and

no-tillage preserve structure and residue cover, slowing decomposition and promoting SOC retention, especially near the surface (Six *et al.*, 2004; West & Post, 2002) ^[10, 22].

Diversified rotations, including legumes and deep-rooted crops, increase input diversity and quantity, improve nutrient cycling, and transport carbon to subsoils with higher stabilization potential, whereas continuous monocultures often accelerate SOC decline (Lal, 2016) ^[16]. Cover crops maintain living roots during fallow periods, increasing annual inputs, improving aggregation, and promoting MAOC formation, with meta-analyses showing gradual SOC gains alongside agronomic benefits. Organic amendments (manure, compost, biochar) supply both labile and stable carbon fractions, enhance aggregation and microbial activity, and sustain higher SOC than mineral fertilizers alone (Jeffery *et al.*, 2011; Lal, 2016) ^[23, 16]. Microbial carbon-use efficiency, shaped by management, determines whether assimilated carbon is respired or incorporated into stable biomass and necromass.

Agroforestry Systems

Agroforestry integrates trees with crops and/or livestock, generating diverse and continuous organic inputs from tree litter, pruning residues, crop residues, and root systems, while reducing disturbance relative to conventional agriculture (Jose, 2009) ^[24]. Perennial trees contribute woody litter and deep root biomass, transporting carbon to subsoil horizons where decomposition is slower and mineral associations stronger, enhancing long-term stabilization (Lorenz and Lal, 2014) ^[25]. Coexistence of trees and crops creates heterogeneous microhabitats that support diverse microbial and mycorrhizal communities, stimulating microbial biomass and necromass formation and promoting MAOC and aggregate stability. Tree canopies moderate soil temperature and moisture, reduce erosion, and improve nutrient cycling, indirectly supporting sustained microbial activity and reducing SOC losses (Jose, 2009) ^[24]. In India, systems such as poplar-wheat, eucalyptus-based configurations, *Prosopis cineraria*-crop systems, and homegardens consistently show higher SOC than adjacent monocultures, contributing to both productivity and sequestration (Kumar and Kunhamu, 2021) ^[26].

Wetlands and Peatlands

Wetlands and peatlands occupy 6-8% of terrestrial area but store nearly 30% of global SOC, owing to waterlogged, anaerobic conditions that suppress decomposition and allow organic matter to accumulate over centuries to millennia. Peat-forming vegetation such as Sphagnum produces phenolic-rich litter that resists decay, while sedges and reeds contribute substantial belowground biomass under oxygen-limited conditions. Anaerobic decomposition proceeds via nitrate, iron, and sulfate reduction and methanogenesis, which are less efficient than aerobic respiration and slow organic matter breakdown but generate CH₄, creating a trade-off between carbon storage and greenhouse gas emissions (IPCC, 2023) ^[3]. In peatlands, persistence depends primarily on environmental protection (saturation, low oxygen, acidity, low temperature) rather than organo-mineral interactions (Lehmann and Kleber, 2015) ^[11]. Drainage, peat extraction and climate change expose organic soils to oxygen, accelerating decomposition, oxidation, subsidence, and fire risk, converting sinks into major CO₂ sources. Rewetting and hydrological restoration reduce oxidation, slow decomposition, and reestablish long-term

accumulation, while conserving biodiversity and water regulation functions.

Degraded and Urban Lands: Degraded and urban lands exhibit reduced SOC due to erosion, vegetation removal, compaction, salinization, mining and soil sealing, which limit inputs, weaken biological activity and destabilize aggregates. Microbial biomass and carbon-use efficiency decline under poor substrate availability, moisture deficits, and physical constraints. Despite low baseline stocks, these systems have high relative sequestration potential. Afforestation, revegetation with perennials, conservation agriculture, controlled grazing, biochar and compost application, and mined-land rehabilitation with topsoil replacement and native vegetation can substantially rebuild SOC and restore ecosystem functions (Lal, 2016) ^[16]. Urban green spaces such as parks, gardens, urban forests, green roofs, can accumulate appreciable SOC where management minimizes disturbance and maintains vegetation, contributing to local sequestration and co-benefits such as heat island mitigation and biodiversity support.

Carbon Sequestration Potential across Land-Use Systems

Soil carbon sequestration refers to the process by which atmospheric carbon dioxide (CO₂) is fixed through photosynthesis and transferred into the soil as soil organic carbon (SOC), where it is retained for extended periods by biological transformation and physicochemical stabilization (Lal, 2004a) ^[27, 28]. The long-term persistence of SOC depends on the interaction between carbon inputs and soil's capacity to stabilize carbon through physical protection within aggregates and chemical binding to mineral surfaces, particularly clay particles and iron- and aluminum-oxides (Six *et al.*, 2002; Lehmann & Kleber, 2015) ^[10, 11]. Environmental factors such as climate, soil texture, mineralogy and moisture regulate decomposition rates (Schmidt *et al.*, 2011) ^[5].

It is important to distinguish between SOC storage and SOC sequestration. Storage denotes the total amount of organic carbon present in soil at a given time, whereas sequestration refers to the net accumulation of SOC over time. Soils with historically low carbon content, such as degraded or intensively cultivated lands, typically exhibit higher sequestration potential because they are far from their stabilization capacity, whereas soils already rich in organic matter may have limited ability to accumulate additional carbon (Sanderman *et al.*, 2017) ^[6]. This concept of soil carbon saturation posits that mineral surfaces have a finite capacity to stabilize organic matter; beyond this threshold, additional inputs contribute less to long-term storage (Six *et al.*, 2002, Sanderman *et al.*, 2017) ^[10]. Enhancing SOC sequestration offers multiple co-benefits including climate mitigation, improved soil structure, water retention, nutrient cycling, microbial activity, and crop productivity, positioning it as a cornerstone of climate-smart agriculture. However, gains depend on practices such as intensive tillage, deforestation, drainage of wetlands, or exposure to rising temperatures and can lead to rapid losses of stored carbon (IPCC, 2023) ^[3].

Influence of Land-Use Systems on Carbon Sequestration

Different land-use systems vary widely in their capacity to sequester SOC due to differences in plant productivity, allocation of carbon belowground, frequency of soil disturbance, and the efficiency of stabilization processes (Jackson *et al.*, 2017) ^[13].

Table 3: Comparative characteristics of major land-use systems regulating soil organic carbon dynamics and carbon sequestration

Land-use system	Primary carbon inputs	Dominant biological processes	Major SOC stabilization mechanisms	Relative SOC stock	Carbon turnover rate	Sequestration potential	Major threats	Recommended management
Forest	Litter, woody debris, fine roots, rhizodeposition	Fungal decomposition, mycorrhizae, microbial necromass	Aggregate protection, organo-mineral complexes (MAOC)	Very high	Slow	Very high	Deforestation, logging, fire	Sustainable management, afforestation, reforestation
Grassland	Dense roots, root turnover, exudates	Rhizosphere microbes, rapid root cycling	Aggregate formation, root-derived MAOC	High	Moderate	High	Overgrazing, erosion, conversion	Rotational grazing, perennial grasses, restoration
Cropland	Residues, roots, cover crops, amendments	Bacterial decomposition, residue mineralization	Aggregate, mineral association	Low-moderate	Fast	Moderate-high (with conservation)	Tillage, residue burning, monocropping	No-till, cover crops, residue retention, integrated nutrient management
Agro-forestry	Tree litter, crop residues, deep roots	Diverse microbes, mycorrhizae	Aggregates, MAOC, continuous belowground inputs	High	Moderate	Very high	Tree removal, poor species choice	Diversification, residue recycling
Wetlands/Peatlands	Aquatic and peat-forming vegetation, roots	Anaerobic decomposition, methanogenesis	Environmental protection (saturation, low O ₂)	Extremely high	Very slow	Very high	Drainage, peat extraction, warming	Conservation, rewetting, hydrological restoration
Degraded/Urban	Sparse vegetation, restoration plantings.	Limited microbial activity	Weak aggregation	Low	Variable	Moderate (after restoration)	Mining, compaction, sealing	Afforestation, biochar/compost, ecological restoration

Forests are among the most effective systems for long-term carbon sequestration. Continuous litterfall, extensive root systems, and limited soil disturbance promote the accumulation of stable SOC, particularly in temperate and boreal regions where cooler temperatures slow decomposition. While mature forests may approach carbon equilibrium, afforestation and reforestation of degraded lands can significantly increase SOC stocks (Pan *et al.*, 2011) ^[18].

Grasslands allocate a substantial proportion of photosynthetically fixed carbon belowground through dense, fibrous root systems. This root-derived carbon is efficiently incorporated into mineral-associated organic carbon (MAOC), contributing to relatively stable SOC pools despite lower aboveground biomass (Jobbágy & Jackson, 2000) ^[20]. Proper grazing management and restoration of degraded grasslands can further enhance sequestration by stimulating root growth and aggregate formation.

Croplands typically contain lower SOC stocks due to frequent tillage, residue removal, and continuous cultivation, all of which accelerate carbon losses. However, because agricultural soils cover vast areas globally and often have depleted carbon levels, they represent a major opportunity for additional sequestration. Practices such as conservation tillage, cover cropping, crop rotation, residue retention, and integrated nutrient management can increase carbon inputs and reduce losses (Paustian *et al.*, 1997) ^[29].

Agroforestry integrates trees with crops or livestock, combining the carbon storage benefits of forests with the productivity of agricultural systems. Continuous litterfall, deep-root inputs, improved aggregation, and enhanced microbial diversity promote both biomass carbon accumulation and long-term SOC stabilization. Compared to conventional agriculture, agroforestry systems consistently show higher sequestration

potential while also improving soil fertility, biodiversity, and farm resilience.

Wetlands and peatlands store the highest densities of soil carbon among terrestrial ecosystems due to waterlogged, anaerobic conditions that suppress decomposition and allow organic matter to accumulate over centuries (Gorham, 1991) ^[30]. Their primary climate mitigation value lies in conserving existing stocks rather than increasing sequestration rates. Protecting intact wetlands and rewetting drained peatlands are critical to preventing largescale carbon losses.

Degraded and urban soils, although often low in baseline SOC, can exhibit high relative sequestration potential through restoration. Afforestation, revegetation, organic amendments, and biochar application can substantially increase carbon accumulation from low starting points while restoring ecosystem functions.

Land Management Strategies for Enhancing Soil Carbon Sequestration: Enhancing soil carbon sequestration requires practices that increase organic carbon inputs, improve stabilization efficiency, and minimize losses. Although effectiveness varies by soil type, climate, and land-use context, several strategies have consistently demonstrated potential to increase SOC stocks while improving soil health and productivity (Lal, 2004^a; Paustian *et al.*, 2016) ^[27, 28, 16].

Soil Organic Carbon and Climate Change Mitigation

Climate mitigation refers to actions that reduce the drivers of climate change by lowering greenhouse gas emissions or by increasing carbon removal from the atmosphere (IPCC, 2023) ^[3]. Mitigation is closely linked to soil organic carbon (SOC) as soils can act as sink as well as source depending on the land use and management.

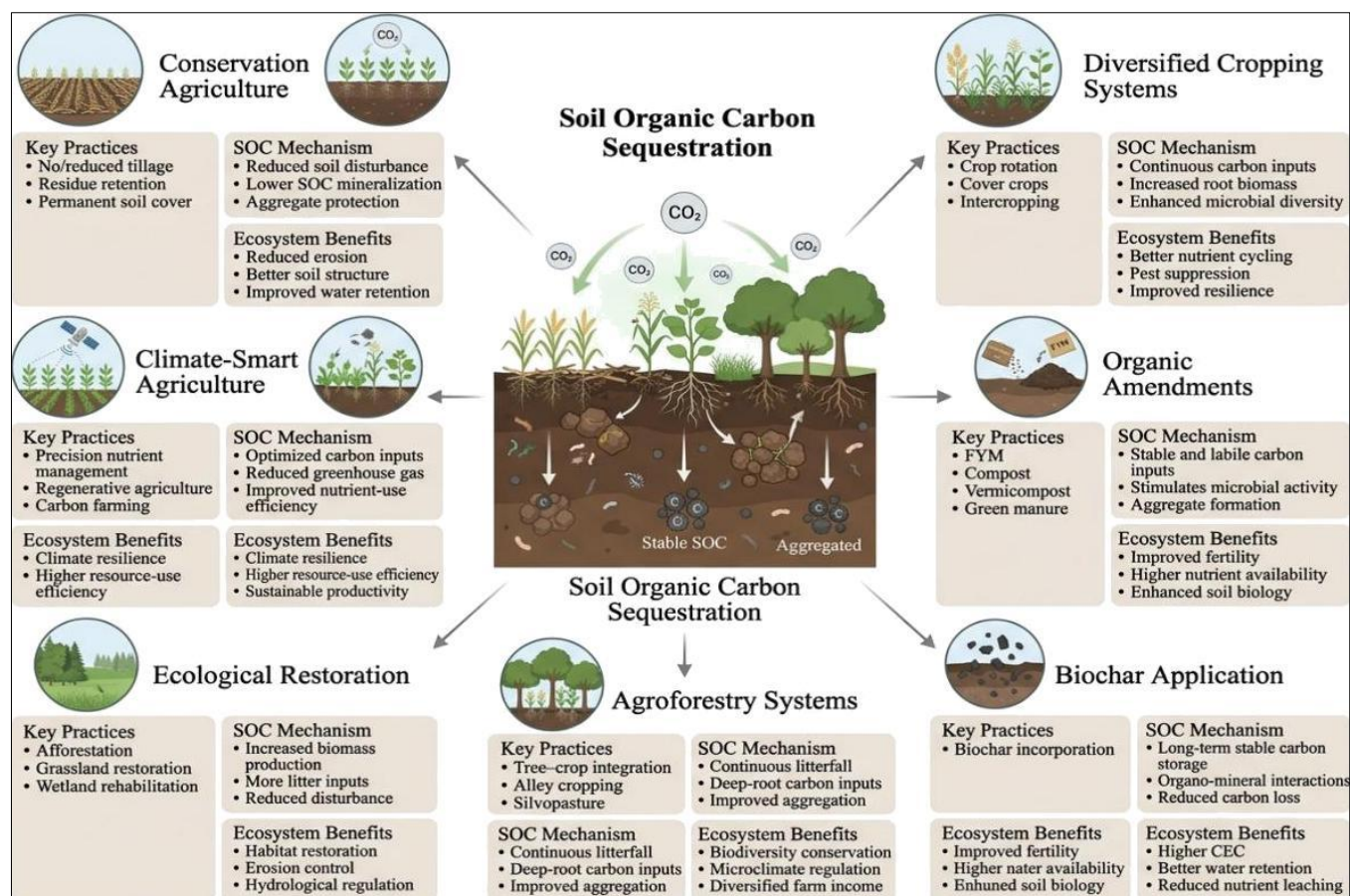


Fig 2: Land Management Strategies for Enhancing Soil Organic Carbon Sequestration

Therefore, SOC is a soil fertility indicator along with a climate-relevant carbon pool (Rodrigues *et al.*, 2023) [31]. Forests, grasslands, agroforestry systems and conservation agriculture usually maintain higher SOC because they supply continuous organic residues, root biomass, and lower disturbance. Whereas, Intensive cultivation, overgrazing, drainage of wetlands and frequent tillage often reduce SOC by augmenting decomposition and erosion (Lal, 2004^b, Six *et al.*, 2002) [27, 28]. The link between SOC dynamics and climate mitigation is direct. When soil carbon stocks increase, more atmospheric carbon is stored below ground, and net emissions decline. When SOC declines, previously stored carbon returns to the atmosphere and weakens mitigation gains (Lal, 2004^b) [27, 28]. SOC management supports climate mitigation by reducing CO₂ release, improving ecosystem resilience and strengthening the buffering capacity of land systems under climatic stress. The climate mitigation value of SOC is significant but limited. SOC sequestration is finite and may not be permanent without sustained management. Carbon enhancement should be viewed as a complementary mitigation strategy rather than a substitute for direct emission reduction. SOC and climate also interact through feedback mechanisms. Rising temperature often increases microbial activity and SOC mineralization, leading to higher CO₂ emissions, while drought, flooding, and wildfire can reduce plant inputs and disturb carbon storage. The climate mitigation value of SOC depends on several interacting controls. Temperature and moisture regulate decomposition rates, while soil texture and mineral composition influence carbon protection (Dungait *et al.*, 2012) [32]. Management intensity, fertilizer use, irrigation, drainage, and residue handling further shape SOC turnover and associated emissions.

Because of these interactions, the same land use practice can have different mitigation outcomes across regions and soil types.

Conclusion

This review examines the soil organic carbon dynamics under different land use system highlighting how different land use systems affect the soil organic carbon, sequestration and climate change mitigation. Changes in land use profoundly influence SOC storage, with forests, grasslands, wetlands, agroforestry systems and sustainably managed croplands differing considerably in their capacity to retain and sequester carbon. While intensive landuse practices often accelerate SOC depletion, conservation agriculture, residue retention, diversified cropping, agroforestry, ecological restoration and organic amendments can effectively enhance SOC stocks and improve soil health. Recent advances in soil biogeochemistry have improved our understanding of SOC stabilization, emphasizing the roles of microbial transformation, mineral-associated organic carbon and aggregate protection in determining long-term carbon persistence. Nevertheless, the potential for SOC sequestration is constrained by climatic conditions, soil properties and carbon saturation, underscoring the need for site-specific and sustainable management strategies. Emerging technologies such as remote sensing, digital soil mapping and machine learning are further improving SOC monitoring and prediction. It is essential to maintain and enhance SOC for sustainable agriculture, ecosystem resilience and climate change mitigation, making it a cornerstone of future land management and environmental conservation strategies.

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