International Journal of Plant & Soil Science

Volume 37, Issue 9, Page 142-153, 2025; Article no.IJPSS.138527
ISSN: 2320-7035

A Review of Soil Organic Carbon Dynamics under Regenerative Agricultural Practices

N. Anil Kumar [a++*], Priyanka Jattan [b#],
Wankhede Dinesh Digambar [c#], Rashmi Mohapatra [d†],
Kamlesh Kumar Yadav [e‡], Charu Sharma [f]
and Sagar Chaudhary [g]

[a] Sytr Government Degree College, (Affiliated To S.K. University-Ananthapuramu,)
Madakasira -51530, Sri Sathya Sai-Dist, Andhra Pradesh, India.
[b] Department of Environmental Science, Dr YS parmar UHF Nauni, India.
[c] Department of Botany, N.E.S Science College, Nanded. S.R.T.M.U Nanded, Maharashtra, India.
[d] Centre for Indigenous Knowledge on Herba75 00l Medicines and Therapeutics, Kalinga Institute of Social Sciences (KISS), Deemed to be University, Bhubaneswar, Odisha - 751024. India.
[e] Department of Agricultural Sciences, School of Agricultural Sciences and Engineering IFTM University Moradabad Uttar Pradesh-244102 India.
[f] Department of Soil Science and Water Management, Dr Y.S Parmar University of Horticulture and Forestry Nauni, Solan, India.
[g] Oas Division ICAR IIFSR, Modipuram, Meerut, India.

Author's contribution

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i95693

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/138527

Review Article

Received: 30/04/2025
Published: 23/08/2025

[++] *Lecturer in Botany;*
[#] *Research Scholar;*
[†] *Associate Professor (Botany), Head;*
[‡] *Assistant Professor;*
**Corresponding author: E-mail: drnaikanilkumar@gmail.com;*

Cite as: *Kumar, N. Anil, Priyanka Jattan, Wankhede Dinesh Digambar, Rashmi Mohapatra, Kamlesh Kumar Yadav, Charu Sharma, and Sagar Chaudhary. 2025. "A Review of Soil Organic Carbon Dynamics under Regenerative Agricultural Practices". International Journal of Plant & Soil Science 37 (9):142-53. https://doi.org/10.9734/ijpss/2025/v37i95693.*

ABSTRACT

Regenerative agriculture represents a holistic approach to restoring degraded soils and enhancing soil carbon sequestration through ecologically informed land management practices. Unlike conventional systems that often degrade soil over time, regenerative practices aim to increase soil carbon, improve water cycles, and support ecosystem services. The philosophy centres on continuous improvement and resilience, integrating ecological design with production efficiency. Soil organic carbon dynamics under regenerative agricultural practices. Scientific evidence on the principles, mechanisms, practices, and outcomes associated with regenerative systems emphasises their role in enhancing soil organic carbon (SOC) across diverse agroecological zones. Key practices, including conservation tillage, cover cropping, organic amendments, diversified crop rotations, agroforestry, and managed grazing, have demonstrated the capacity to improve SOC through physical protection within soil aggregates, chemical stabilisation via mineral associations, and biological stabilisation through microbial processing. Long-term trials and meta-analyses indicate that regenerative practices can sequester carbon at rates ranging from 0.2 to 1.5 Mg C ha^{-1} yr^{-1}, with notable co-benefits such as improved water retention, enhanced biodiversity, and increased nutrient efficiency. Empirical case studies from semi-arid, humid, and tropical regions confirm that site-specific adaptation of regenerative techniques can yield positive outcomes for both productivity and ecological resilience. Despite these benefits, challenges persist, including high initial labour and material costs, limited access to organic inputs, insufficient extension support, and potential short-term yield declines during the transition phase. These constraints underscore the need for integrated policies, farmer-centric research, knowledge-sharing platforms, and financial incentives to facilitate the transition toward regenerative farming. The use of direct carbon measurement methods, remote sensing technologies, and modelling tools such as Century, RothC, and COMET-Farm further supports the quantification and validation of SOC gains. Widespread adoption of regenerative practices, underpinned by robust empirical data and institutional support, is critical to restoring soil carbon sinks, enhancing agroecosystem services, and ensuring long-term agricultural sustainability under climate variability. The integration of scientific knowledge with policy support, extension services, and market incentives is essential to scale regenerative models. Accelerating their adoption can significantly contribute to carbon neutrality goals, sustainable agriculture, and food security under increasingly variable climatic conditions.

Keywords: Regeneration; sequestration; soil; carbon; biodiversity; agroforestry; sustainability.

1. INTRODUCTION

Regenerative agriculture is a system of farming principles and practices that focuses on restoring and enhancing the health and vitality of farm soil through natural processes (Khangura *et.al.,* 2023). It emphasises biodiversity, organic matter enrichment, reduced tillage, integrated livestock, cover cropping, and agroforestry. Studies presenting economic issues mentioned that regenerative agriculture creates, e.g. ‘long-term economic sustainability’, ‘improves crop yields’, ‘improves soil productivity’ and ‘political-economic repositioning’ (Schreefel et al., 2020). Unlike conventional systems that often degrade soil over time, regenerative practices aim to increase soil carbon, improve water cycles, and support ecosystem services. The philosophy centres on continuous improvement and resilience, integrating ecological design with production efficiency. Soil carbon, particularly soil organic carbon (SOC), plays a central role in soil fertility, structure, water retention, and nutrient cycling (Han *et.al.,* 2016). It serves as a key indicator of soil health and productivity. SOC acts as a reservoir for essential nutrients like nitrogen and phosphorus, supports microbial activity, and enhances the buffering capacity of soils (Rathi et al., 2024). The SOC pool profoundly affects soil productive potential by enhancing its physical, chemical, and biological attributes, thereby contributing to a more fertile and resilient soil ecosystem. Organic amendments, including straw return and manure application, have been put forward as an efficient strategy to enhance soil aggregation, stimulate SOC turnover, and simultaneously boost SOC sequestration (Wu et al., 2024; Borah & Parmar, 2024). Studies report that for every 1% increase in SOC, water holding capacity increases by approximately 20,000–27,000 litres per hectare. Soil carbon also plays a major role in mitigating climate change by acting as a sink for atmospheric carbon dioxide through biological sequestration. Globally, soils have lost between 25–75% of their original carbon stocks due to unsustainable land use, overgrazing, and intensive cropping (Tsegay *et.al.,* 2021). FAO estimated that 33% of the world's soils are degraded, with significant carbon loss from the topsoil. The tropical and subtropical regions are particularly vulnerable due to higher decomposition rates and frequent cultivation. India's average SOC content in cultivated land is below 0.5%, which is considered critically low. Intensive monocropping, residue burning, excessive tillage, and low organic matter inputs are leading contributors to carbon loss (Purwanto *et.al.,* 2020). These depleted soils exhibit reduced productivity, water stress, and vulnerability to erosion.

2. SOIL CARBON DYNAMICS AND DEGRADATION

Soil carbon exists in two major forms: soil organic carbon (SOC) and soil inorganic carbon (SIC) (Mi *et.al.,* 2008). SOC is derived from decaying plant and animal residues, root exudates, microbial biomass, and organic amendments. It is dynamic, biologically active, and largely responsible for nutrient cycling, soil structure, and moisture regulation. SOC contributes to the formation of humus, a stable fraction essential for long-term soil fertility. SIC comprises carbonates such as calcium and magnesium carbonates, primarily found in arid and semi-arid soils. It is more stable and less responsive to biological processes, but it plays a role in buffering soil pH and interacting with SOC stabilisation. SOC dominates in humid and temperate regions, while SIC can constitute up to 50% of total soil carbon in dryland systems. Soil carbon is lost through several physical, chemical, and biological processes (Delgado *et.al.,* 2017). The major pathways include microbial decomposition, soil erosion, leaching, and volatilisation. Intensive tillage exposes organic matter to oxygen, accelerating microbial oxidation and carbon dioxide release. Erosive forces transport carbon-rich topsoil, leading to permanent loss unless redeposited in stable locations. Decomposition rates increase with temperature and moisture fluctuations, particularly in tropical zones, reducing carbon retention. Carbon losses also occur through leaching of dissolved organic carbon and emissions of greenhouse gases such as CO_2, CH_4, and N_2O from poorly managed soils. Residue burning contributes directly to atmospheric CO_2 while depleting the soil's organic inputs. High-input monoculture systems, frequent tillage, and synthetic agrochemical dependency significantly reduce SOC stocks (Crews *et.al.,* 2018). Studies have shown that conventional ploughing leads to a 20–60% decline in SOC over a few decades. Shallow-rooted annual crops and the removal of crop residues reduce carbon inputs to the soil. Fertiliser-induced microbial priming often accelerates organic matter breakdown rather than enhancing sequestration. Continuous cropping without organic amendments leads to carbon mining, where carbon export exceeds replenishment. The Green Revolution's input-intensive model has resulted in declining SOC levels in major food-producing belts, undermining long-term soil health. The depletion of SOC severely impairs soil function. Reduced carbon levels lead to decreased microbial activity, compromised soil aggregation, and lower water holding capacity (Gupta *et.al.,* 2015). Soils with low SOC are more prone to compaction, crusting, and erosion, decreasing root penetration and nutrient uptake. Yield stability is affected, particularly under rainfed conditions. From a climate perspective, carbon-depleted soils become net emitters of greenhouse gases. Historic agricultural land conversion has released over 78 Gt of carbon into the atmosphere. Restoring 1 ton of carbon per hectare per year in degraded soils could offset 3.5 billion tons of CO_2 globally, highlighting the mitigation potential of soil-centric approaches. Thus, carbon degradation not only jeopardises food security but also exacerbates climate instability.

3. PRINCIPLES OF REGENERATIVE AGRICULTURE

Regenerative agriculture is grounded in the philosophy of healing the land through biologically driven processes that restore the natural functions of agroecosystems (Babaniyi *et.al.,* 2024). Its foundational goals include rebuilding soil organic matter, enhancing biodiversity, restoring water cycles, increasing nutrient use efficiency, and improving farmer resilience. Unlike extractive farming models that deplete ecological capital, regenerative approaches aim to create a net positive impact on the environment. Key principles include minimising soil disturbance, maximising soil cover through cover crops or mulches, promoting crop diversity, integrating livestock for nutrient recycling, and fostering symbiotic microbial communities. These practices prioritise soil health as the central axis of sustainability and productivity, aligning agriculture with natural regenerative cycles. Conventional agriculture is typically characterised by intensive tillage, heavy synthetic input use, monocultures, and mechanised operations aimed at maximising short-term yields (Durham *et.al.,* 2021). This model often leads to degradation of soil organic carbon, water pollution, and biodiversity loss. Conservation agriculture, by contrast, includes principles like minimal tillage, permanent soil cover, and crop rotation to maintain productivity while reducing environmental harm. While it offers significant improvements over conventional practices, conservation agriculture often stops short of actively rebuilding soil function or biodiversity. Regenerative agriculture encompasses conservation agriculture's core tenets but goes beyond by seeking to regenerate rather than merely sustain. For example, while conservation systems may reduce soil loss, regenerative systems aim to increase soil carbon stocks annually by 0.2–0.5 Mg C ha^{-1} yr^{-1} (Jordon *et.al.,* 2022). This makes regenerative agriculture not only a sustainable but also a restorative strategy with a broader environmental and social agenda.

Ecological intensification seeks to enhance agricultural productivity by optimising ecosystem functions rather than increasing external inputs (Bommarco *et al.,* 2013). Regenerative agriculture fits this paradigm by leveraging natural processes such as nutrient cycling, biological pest control, and symbiotic nitrogen fixation to increase output without compromising ecological integrity. For example, legume-based rotations improve nitrogen availability, while multi-species cover crops reduce erosion and increase biomass input, thus enhancing carbon sequestration. Regenerative systems are inherently more resilient to climate variability due to improved water retention, reduced temperature fluctuations in the root zone, and enhanced biological buffering capacity. A meta-analysis highlighted that healthy soils with high organic matter content can absorb 20–50% more rainfall, reducing runoff and drought stress. Practices like agroforestry, managed grazing, and organic amendments build adaptive capacity by fostering soil–plant–microbe interactions critical for stress tolerance and nutrient efficiency. By realigning agriculture with ecological thresholds, regenerative farming offers a climate-adaptive pathway that improves livelihoods while restoring ecosystem functions (Fuchs *et al.,* 2025).

4. KEY REGENERATIVE PRACTICES FOR SOIL CARBON ENHANCEMENT

A. Conservation Tillage and Zero Tillage

Conservation tillage and zero tillage minimize mechanical disturbance, preserving soil structure and reducing oxidation of organic matter (Table 1) (Boincean *et al.,* 2019). Zero tillage leaves at least 30% of the soil surface covered with crop residues, limiting erosion and promoting organic carbon retention in the topsoil. Studies report that zero tillage systems can increase SOC content by 0.15–0.30 Mg C ha^{-1} yr^{-1} over conventional tillage. Soil microbial communities benefit from retained residues, which serve as continuous organic inputs. Minimal disturbance under zero tillage enhances the stability of soil aggregates and supports beneficial microbes (Lupwayi *et al.,* 2001). Aggregates physically protect organic carbon from decomposition by isolating it from microbial access. Microbial biomass carbon has been observed to increase by 20–30% under long-term zero-tillage systems compared to conventional systems. Improved aggregation also increases water infiltration and reduces runoff, enabling deeper root penetration and enhancing below-ground carbon inputs.

B. Cover Cropping and Green Manuring

Cover crops such as legumes, grasses, and brassicas provide living roots that deposit carbon via exudates and biomass (Wendling *et al.,* 2016). They contribute significantly to belowground carbon pools. Hairy vetch and rye, for example, can add 1.5 to 4.5 Mg of biomass per hectare, contributing substantial organic matter to the soil. Root exudates also stimulate microbial activity and promote carbon stabilization through microbial necromass. The effectiveness of cover crops depends on seasonal compatibility, biomass productivity, and termination methods (Wortman *et al.,* 2012). Diverse mixtures with legumes (e.g., clover), cereals (e.g., rye), and crucifers (e.g., radish) enhance the functional diversity of soil microbial communities. Multi-species cover crops have been shown to sequester more carbon than monocultures, with increases of 0.2–0.4 Mg C ha^{-1} yr^{-1}.

C. Organic Amendments (Compost, Farmyard Manure, Biochar)

The application of compost, farmyard manure (FYM), and biochar enhances SOC levels by

Table 1. Soil Organic Carbon Dynamics under Regenerative Agricultural Practices (Source: Boincean et al., 2019, Wendling et al., 2016)

Regenerative Practice	Mechanism Influencing SOC	Impact on SOC Dynamics	Examples/Case Studies
Conservation Tillage / No-till	Minimizes soil disturbance, reduces erosion, enhances residue retention	Improves SOC sequestration in topsoil, increases microbial activity	Long-term no-till in US Great Plains showed 20–25% SOC increase
Cover Cropping	Adds organic inputs, enhances root biomass, improves soil aggregation	Increases labile C pools and SOC stabilization	Rye and clover cover crops enhanced SOC in temperate soils
Crop Rotation & Diversification	Introduces varied residue quality, supports microbial diversity	Enhances SOC storage through diversified inputs	Maize-soybean-wheat rotations increase SOC compared to monocultures
Agroforestry Systems	Tree-crop integration increases litterfall, root turnover, and microclimate regulation	Enhances SOC in deeper soil layers, improves long-term carbon storage	Silvopastoral systems in Latin America showed higher SOC
Organic Amendments (Compost, Manure, Biochar)	Supplies stable organic matter, improves nutrient cycling	Significant increase in SOC stability and humus formation	Biochar application increased SOC by 15–30% in tropical soils
Grazing Management (Rotational/Adaptive)	Balances plant regrowth and residue return, prevents overgrazing	Improves root biomass input, enhances SOC in grasslands	Adaptive multi-paddock grazing in US rangelands enhanced SOC
Integrated Nutrient Management	Combines organic and inorganic sources, optimizes microbial processes	Improves SOC stabilization and reduces C losses	Long-term INM in rice-wheat systems increased SOC pools
Water Conservation Practices (Mulching, Rainwater Harvesting)	Enhances soil moisture, reduces erosion, supports biomass growth	Promotes higher residue decomposition and SOC accumulation	Mulching increased SOC in semi-arid regions

supplying stable organic substrates. These materials decompose at different rates; FYM provides labile carbon, while compost and biochar contribute more stable fractions. FYM can increase SOC by 0.12–0.25 Mg C ha^{-1} yr^{-1} depending on application rate and climatic conditions. Biochar, a product of pyrolysed biomass, offers long-term stability due to its aromatic carbon structure (Leng *et al.,* 2019). It means the residence time in soil exceeds 100 years. A meta-analysis indicated that biochar-amended soils showed a 10–50% increase in total SOC. Compost and FYM also contribute to microbial biomass and humic substance formation, essential for carbon sequestration and nutrient retention.

D. Crop Rotation and Polyculture Systems

Rotating crops with varying root architectures and growth periods enhances carbon allocation both vertically and horizontally in soil. Deep-rooted crops like pigeon pea and maize contribute to deeper carbon deposition, while shallow-rooted legumes enrich the topsoil. Crop rotations have been shown to increase SOC by 5–15% over continuous monocropping. Polyculture systems support functional biodiversity, enhancing rhizosphere processes, microbial activity, and nutrient turnover (Altieri *et al.,* 2017). Intercropping cereals with legumes, such as maize-cowpea or sorghum-pigeon pea, improves nitrogen fixation and microbial carbon use efficiency, resulting in more stable soil organic matter pools. Such systems improve synchrony between carbon input and microbial assimilation.

E. Agroforestry and Silvopastoral Systems

Agroforestry integrates perennial trees with crops or livestock, enhancing carbon sequestration through continuous litter fall, root biomass, and reduced disturbance (Lorenz *et al.,* 2014). Trees such as *Azadirachta indica* and *Gliricidia sepium* sequester 1–3 Mg C ha^{-1} yr^{-1} depending on species and density. These systems also support nutrient cycling through leaf litter decomposition and root-microbe interactions. Tree-based systems contribute organic inputs via aboveground litter and belowground rhizodeposition. Perennial roots exude carbon throughout the year, stabilising microbial biomass and forming stable aggregates. These contributions enhance the passive pool of SOC, critical for long-term carbon retention.

F. Managed Grazing and Pasture Regeneration

Properly managed grazing stimulates root growth and photosynthetic activity in grasslands, enhancing soil carbon inputs (Chen *et al.,* 2015). Adaptive grazing strategies such as rotational grazing allow recovery periods for vegetation, improving biomass accumulation and root turnover. Grasslands under rotational grazing can sequester 0.3–1.2 Mg C ha^{-1} yr^{-1}. The intensity and timing of grazing influence both carbon input and retention. Overgrazing leads to soil compaction and reduced photosynthetic capacity, whereas moderate grazing enhances microbial activity and root carbon allocation. Integrating legumes in pasture systems improves forage quality and contributes nitrogen-rich organic matter that supports microbial-mediated carbon stabilisation.

5. SOIL CARBON SEQUESTRATION MECHANISMS UNDER REGENERATIVE SYSTEMS

Soil aggregation plays a pivotal role in stabilising organic carbon by creating microenvironments that limit microbial access and decomposition (Gupta *et al.,* 2015). Macroaggregates (>250 µm) and microaggregates (53–250 µm) are formed through root exudates, fungal hyphae, and polysaccharides secreted by microbes. These structures entrap organic particles, physically isolating them from enzymatic breakdown. Regenerative practices such as reduced tillage, cover cropping, and organic amendments significantly enhance aggregate formation. Plant roots and hyphal networks are central to the formation of stable aggregates that encapsulate particulate organic matter (POM). Studies have shown that soils under no-tillage and continuous residue cover can increase aggregate-associated carbon by 15–40% compared to conventionally tilled soils. Such physical entrapment is critical for long-term carbon persistence in soil matrices, making it one of the most effective mechanisms for carbon sequestration (Dynarski *et al.,* 2020). Soil minerals, particularly clays and metal oxides, interact with organic molecules to form organo-mineral complexes that resist microbial degradation. Fine-textured soils containing kaolinite, montmorillonite, and Fe/Al oxides exhibit high potential for chemically stabilising carbon through adsorption and ligand exchange. These associations shield organic matter from enzymatic action, prolonging its residence time from decades to centuries. Regenerative inputs such as compost and biochar enhance the availability of reactive sites for carbon binding (Beesley *et al.,* 2011). Mineral-associated organic matter (MAOM) can constitute up to 60–80% of total SOC in temperate and tropical soils. This mechanism is particularly important in humid environments, where rapid decomposition would otherwise lead to substantial carbon loss. Empirical studies indicate that mineral-associated carbon stabilisation is more efficient in soils with high cation exchange capacity and surface area, both of which are improved by long-term regenerative land management. Microbial processing is a dynamic pathway where soil organisms decompose plant and root-derived residues, converting labile carbon into microbial biomass and necromass (Bailey *et al.,* 2019). This microbial necromass becomes stabilised through its incorporation into aggregates and interactions with minerals. Microorganisms also produce extracellular polymeric substances (EPS) that contribute to aggregate stability and carbon encapsulation. Regenerative systems that supply continuous organic inputs from cover crops, green manure, and root exudates support diverse and abundant microbial populations. Microbial-derived carbon forms a substantial portion of persistent SOM due to its selective stabilisation by soil particles. Such systems foster copiotrophic microbial taxa organisms efficient at assimilating carbon, which are essential for converting fresh inputs into stable organic forms. Additionally, fungi play a key role in promoting carbon stabilisation via hyphal networks that enhance aggregate formation and reduce decomposition rates. Systems that promote soil biodiversity not only enhance nutrient cycling but also increase microbial carbon use efficiency (CUE), which directly contributes to the buildup of stable carbon pools (Adingo *et al.,* 2021).

6. MEASUREMENT, MONITORING, AND MODELLING OF SOIL CARBON

Quantitative assessment of soil carbon is essential for understanding sequestration potential and evaluating the impact of regenerative practices (Villat *et al.,* 2024). Dry combustion and wet oxidation are the two principal direct methods employed for estimating soil organic carbon (SOC). Dry combustion, often using automated elemental analysers such as the LECO CN analyser, measures carbon content by oxidising the sample at high temperatures (900–1000°C) in the presence of oxygen. This method provides accurate total carbon measurements and is considered the gold standard due to its precision and repeatability. Wet oxidation, such as the Walkley–Black method, uses potassium dichromate and sulfuric acid to oxidise organic matter, and the amount of unreacted dichromate is titrated to determine SOC content. While more cost-effective, it typically underestimates total carbon by 20–30% compared to dry combustion. To enhance accuracy, correction factors or modified digestion protocols are employed. Direct methods are indispensable in long-term field experiments and carbon accounting studies. Technological advancements in remote sensing (RS) and geographic information systems (GIS) have enabled spatial and temporal mapping of SOC at regional to global scales (Croft *et al.,* 2012). Sensors on platforms such as Landsat, Sentinel-2, and MODIS capture vegetation indices (e.g., NDVI, SAVI) and surface reflectance data that correlate with biomass productivity and, indirectly, with carbon input potential. Integration of field-sampled SOC data with spectral reflectance allows for calibration models using machine learning techniques like random forests and support vector machines. GIS platforms facilitate the visualisation and interpolation of SOC distribution based on topography, land use, and management variables. Researchers have used digital soil mapping approaches such as SoilGrids and ISRIC's WoSIS to generate global SOC estimates with spatial resolutions of 250–1000 meters. These tools are particularly useful for decision-making and targeting regenerative interventions at vulnerable or high-potential sites.

Process-based models simulate soil carbon dynamics over time under varying land-use and management scenarios (Zhang *et al.,* 2023). The Century model simulates carbon, nitrogen, phosphorus, and sulfur flows in grassland, forest, and crop ecosystems based on inputs such as climate, soil texture, and management practices. It partitions SOC into active, slow, and passive pools and has been validated in numerous agroecological settings. The RothC (Rothamsted Carbon) model is designed to simulate SOC turnover in non-waterlogged topsoils. It divides SOC into decomposable plant material, resistant plant material, microbial biomass, humified organic matter, and inert organic matter. RothC is user-friendly and extensively used to estimate SOC change under organic amendments and tillage regimes. COMET-Farm, a model developed by USDA-NRCS, provides an online decision support tool that allows farmers and land managers to estimate greenhouse gas emissions and SOC changes under different regenerative practices (Paustian *et al.,* 2020). It integrates IPCC Tier 2 methodologies and empirical datasets, making it suitable for carbon accounting under voluntary carbon markets. Soil carbon monitoring must account for variability over both time and space. Temporal dynamics are influenced by climatic events, seasonal biomass inputs, and microbial activity, necessitating periodic measurement across cropping cycles. Long-term monitoring (≥5 years) is essential to capture the cumulative effects of regenerative practices. Spatial heterogeneity arises from variations in soil texture, topography, land use, and historical management. Stratified random sampling and geostatistical methods such as kriging and co-kriging are often employed to address this variability. The IPCC recommends a minimum bulk density and SOC sampling depth of 0–30 cm for reporting carbon stock changes in agricultural systems. Combining high-resolution temporal and spatial data enhances the reliability of carbon models and supports site-specific policy development and carbon credit schemes (Guan *et al.,* 2023).

7. CO-BENEFITS OF REGENERATIVE PRACTICES

Regenerative agricultural practices significantly improve soil structure, porosity, and organic matter content, leading to increased water infiltration and retention. Soils with higher organic carbon can hold more moisture due to the sponge-like properties of humic substances. Each 1% increase in soil organic matter can improve water holding capacity by approximately 20,000 to 27,000 litres per hectare. Zero tillage, cover cropping, and compost amendments enhance aggregate stability, reduce runoff, and promote percolation. For example, a study demonstrated that no-till and cover cropping systems in the Midwest United States reduced water runoff by 30–50% and increased soil water retention by up to 21%. Enhanced water infiltration mitigates both drought stress and erosion, making cropping systems more robust under variable precipitation regimes (Brempong *et al.,* 2023). Diversified regenerative systems support a rich variety of organisms above and below ground. Practices like intercropping, agroforestry, and maintaining hedgerows and flowering strips provide food, habitat, and nesting sites for pollinators and beneficial insects. Soil biodiversity also improves through increased microbial biomass, fungal diversity, and arthropod activity. Organic and diversified systems support 30% more species richness and 50% higher abundance of pollinators compared to conventional monocultures. Mycorrhizal fungi and rhizobacteria flourish in biologically active soils, enhancing nutrient uptake and plant health. Regenerative approaches, by eliminating synthetic inputs and enhancing ecological niches, promote stable predator-prey relationships and natural pest control (Pickett *et al.,* 1998)

Enhanced organic matter content and microbial activity under regenerative systems accelerate decomposition and nutrient mineralisation processes. Legume integration and compost application increase nitrogen availability through biological nitrogen fixation and organic amendments. Mycorrhizal associations expand the root absorptive surface, improving uptake of phosphorus, zinc, and other micronutrients. The Soil Health Institute reported that regenerative farms exhibit up to 78% higher soil enzymatic activity, a key indicator of nutrient transformation efficiency (Xu *et al.,* 2022). Additionally, cover crops scavenge residual nutrients and reduce leaching losses. A study showed that legume-based cover cropping systems returned up to 120 kg N ha^{-1} annually, reducing dependency on synthetic fertilisers. Over time, improved nutrient cycling reduces input costs, enhances crop nutrient density, and sustains productivity. Regenerative agriculture contributes to livelihood security by improving farm profitability, risk diversification, and adaptive capacity. Reduced dependence on costly agrochemicals and external inputs lowers production costs. Integration of livestock, trees, and multiple crop species generates diversified income streams. Regenerative practices improve soil buffering capacity, enabling crops to better withstand droughts, floods, and temperature extremes. A study across 30 farms in the U.S. Corn Belt reported that regenerative farms were 78% more profitable than conventional ones, despite lower input use. Additionally, the ability of such systems to sequester carbon and improve soil moisture supports climate mitigation and adaptation. Enhanced ecological function and community engagement foster long-term food and income security, especially for smallholder and rainfed farming systems vulnerable to climate variability (Kerr *et al.,* 2019).

8. CONSTRAINTS AND TRADE-OFFS

The transition to regenerative agriculture often entails higher upfront investments compared to conventional systems. These costs arise from acquiring composting units, cover crop seeds, mulching materials, fencing for rotational grazing, or establishing agroforestry systems. For example, adopting conservation tillage and cover crops in maize–soybean systems can cost an additional $50–100 per hectare during the initial years. Labour requirements also increase due to practices like manual mulching, compost preparation, and diversified cropping schedules. Smallholders may face difficulties affording mechanisation suited to low-disturbance operations or lack access to institutional credit that supports regenerative transitions. These economic barriers can delay adoption unless offset by public incentives or long-term profitability guarantees. Many regenerative practices depend on external biomass sources such as crop residues, animal manure, compost, or green manure crops (Tindwa *et al.,* 2024). Availability is constrained in high-intensity or residue-scarce systems, particularly in dryland farming or regions with competing demands for fodder and fuelwood. For instance, studies in semi-arid Africa reported that less than 35% of households had sufficient livestock to generate FYM required for organic amendments. The production of quality compost also requires infrastructure, water, and training. Without reliable biomass, farmers struggle to implement cover cropping, mulching, or biochar use at scale, limiting soil carbon accumulation and regenerative potential.

Effective adoption of regenerative practices requires a deep understanding of site-specific ecology, soil biology, crop-livestock interactions, and adaptive management (Sher *et al.,* 2024). Knowledge-intensive practices such as crop rotation design, composting techniques, or integrated pest management are often underrepresented in extension curricula. Studies have shown that fewer than 40% of agricultural extension programs globally include modules on organic soil health management or climate-smart practices. Farmers may lack exposure to regenerative models or peer learning platforms, which hinders widespread behavioural change. Moreover, extension agents often lack training or resources to support ecological approaches, resulting in low adoption despite interest. Strengthening research–extension–farmer linkages and participatory trials is crucial for scaling regenerative systems (Staley *et al.,* 2024). During the transition phase, regenerative practices may not deliver immediate yield benefits, particularly in degraded soils or unfamiliar agroecologies (Ryan *et al.,* 2017). Yield reductions of 5–25% have been reported in early years due to factors like nutrient immobilisation, weed pressure, or poor biomass establishment. For example, switching to organic inputs without adequate nitrogen replacement may initially suppress cereal yields. Regenerative models such as agroforestry and polyculture systems often take multiple seasons to stabilise and express their full ecological benefits. This temporal lag creates disincentives, especially for smallholders dependent on consistent annual output. Market access, certification delays, and lack of carbon payment mechanisms further contribute to the opportunity cost associated with adoption. Balancing ecological restoration with economic viability requires adaptive financial models, such as ecosystem service payments, transitional subsidies, or carbon credits (Vanderklift *et al.,* 2019).

9. CONCLUSION

Regenerative agricultural practices offer a transformative pathway to restore soil carbon, enhance ecosystem functionality, and build climate resilience in agroecosystems. Through conservation tillage, cover cropping, organic amendments, crop diversification, agroforestry, and managed grazing, these practices promote physical, chemical, and biological mechanisms that stabilise soil organic carbon. Empirical evidence from long-term trials, meta-analyses, and regional case studies consistently shows that regenerative systems can sequester 0.2 to 1.5 Mg C ha^{-1} yr^{-1} while improving water retention, biodiversity, nutrient cycling, and farmer livelihoods. Despite initial costs, knowledge gaps, and short-term trade-offs, the long-term environmental and economic co-benefits outweigh the challenges. Integration of scientific knowledge with policy support, extension services, and market incentives is essential to scale regenerative models. Accelerating their adoption can significantly contribute to carbon neutrality goals, sustainable agriculture, and food security under increasingly variable climatic conditions.

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 no competing interests exist.

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