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Carbon Farming for Sustainable Agriculture

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ABSTRACT

Nowadays, intensive agricultural practices often lead to indiscriminate use of inputs, degradation of natural resources, increased emission of greenhouse gases, however, at the same time it helps to achieve the food security. To sustain the food security and desired productivity in future, there is need of sustainable management of natural resources which protects, enhances, or maintains the soil health and quality. Soil organic carbon is the key component as it governs nearly all properties of soil and its proper management make soil sustainable. Carbon farming offers a promising pathway to enhance the soil organic carbon by adopting different soil and crop management practices. Effective approaches include conservation agriculture, use of organic inputs, biochar application, adoption of suitable agroforestry system etc. Despite the wide scope for implementing carbon farming techniques, several challenges persist, including limited awareness, complex mechanisms involved, and inadequate understanding of their comparative benefits. Nevertheless, carbon farming remains essential for the future of agriculture, particularly in the context of climate change.

Keywords : Soil organic carbon, Conservation agriculture, Tillage, Organic farming, Biochar.

Introduction

Agriculture faces numerous challenges now-a-days, including significant negative impacts due to climate change through greenhouse gas emissions (GHGs) and the depletion of soil health and quality. Although conventional intensive agricultural practices help to achieve higher productivity and food security but often lead to indiscriminate use of farm inputs, higher GHG emissions, and degradation of natural resources (Kumara *et al.*, 2023). Further, intensive farming practices and the unscientific cultivation of lands resulted in the depletion of soil organic carbon (SOC) and other essential nutrients (Lal, 2016; Feng *et al.,* 2018). Consequently, it deteriorates soil health and makes it infertile and unsuitable for further cultivation. It is well known that soil organic carbon is the central element of soil fertility and productivity as it governs almost all properties of soil being physical, chemical and biological. Therefore, it is essential to enhance soil organic matter or carbon content in agricultural lands to enrich soil fertility and productivity while

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mitigating greenhouse gas emissions. Carbon farming is one of the ways to enrich soil organic carbon. Carbon farming refers to the adoption of agricultural practices and land-use systems that increase net carbon sequestration in soils and vegetation while reducing greenhouse gas (GHG) emissions from farming activities (Lal, 2019; Paustian *et al.,* 2016). It aligns with the broader framework of *climate-smart agriculture* and contributes simultaneously to climate-change mitigation, adaptation, and sustainable production. The concept integrates ecological, agronomic, and economic dimensions to create a carbon-positive farming landscape.

Need of Carbon Farming

Agricultural soils constitute one of the largest terrestrial carbon reservoirs, with the top ~30 cm of soil globally holding more carbon than the atmosphere or all vegetation combined (Sharma *et al.*, 2021; Petropoulos *et al.,* 2025). Over recent decades, however, conventional and intensive farming practices have increasingly degraded the soils through the depletion of soil organic carbon and essential nutrients, leading to declines in soil health, productivity and resilience. For instance, the removal of crop residues, intensive tillage practices, monocropping, excessive agrochemical use and cultivation of degraded lands predominantly drive SOC losses and nutrient depletion (Lal, 2016). In this context, carbon farming emerges as a strategic imperative for multiple reasons.

i) Climate change mitigation: As soils lose carbon, carbon di-oxide CO_2 is released to the atmosphere, contributing to enhance greenhouse gas (GHG) concentrations. Shifting to practices that build SOC and reduce GHG emissions can help to meet climate change mitigation targets (Sharma *et al.,* 2021).

ii) Soil health and productivity: Increased SOC improves soil structure, water retention, nutrient-holding capacity, microbial activity, soil fertility, biodiversity, and ecosystem services (Vistarte *et al.*, 2024). It is well proved that, in degraded agricultural lands, boosting SOC is fundamental to restoring productivity and sustaining food security.

iii) Resilience to climatic stresses: As climate change intensifying weather extremes such as droughts, floods etc., soils rich in organic carbon are more resilient in buffering water retention, reducing erosion and maintaining crop stability under stress. Carbon farming thereby contributes to adaptation as well as mitigation.

iv) Restoration of degraded lands: Worldwide, vast agricultural landscapes are degraded because of low SOC, depleted nutrient pools, compacted or eroded soils etc. Carbon farming practices (e.g., cover crops, minimal tillage, agroforestry, organic amendments) support the rehabilitation of such lands and the rebuilding of nutrient stocks (Petropoulos *et al.,* 2025).

v) Multiple-benefit co-services: Beyond carbon sequestration, carbon farming can deliver co-benefits such as reduced fertilizer dependence, improved biodiversity, enhanced ecosystem services, and potentially generating income via carbon markets (Sharma *et al.,* 2021).

Given these drivers, the adoption of carbon farming is increasingly and being promoted at policy and farm-levels. Yet its implementation demands appropriate practices, reliable measurement protocols, incentives, training, and integration into farming systems and value chains.

Principal of Carbon Farming

The fundamental principle of carbon farming is to shift agricultural practices and landscapes from being net sources of carbon to net sinks. This may be achieved by promoting photosynthetic carbon capture and minimizing carbon losses through oxidation, erosion, or decomposition (Smith *et al.,* 2020). Soils, which store about two to three times more carbon than the atmosphere, represent the most stable and significant sink for terrestrial carbon (Lal, 2004).

Carbon sequestration in agriculture occurs through three main pathways- Soil organic carbon accumulation via plant root residues, microbial biomass, and organic inputs; biomass sequestration in agroforestry and perennial systems; stabilized carbon in the form of biochar and long-lived organic compounds (Woolf *et al.,* 2010). Each pathway functions differently in terms of permanence, saturation, and monitoring feasibility. Integrating these pathways ensures long-term carbon storage stability. Credible carbon farming requires adherence to principles of additionality (benefits beyond business-as-usual), permanence (long-term retention), leakage prevention (avoiding displacement of emissions), and measurability/verifiability (Paustian *et al.,* 2019).

Carbon Management through Carbon Farming Practices

By integrating suitable and mutually compatible climate-smart management practices, enables us to sequester atmospheric carbon into soils and vegetation. These practices not only improve long-term productivity and resilience but also offer potential incentives through carbon credits and ecosystem services. There are several agricultural management practices towards a successful carbon farming, however, following are key strategies for carbon management through carbon farming practices.

Soil Management Practices

1. Conservation tillage or no-till: Minimizes soil disturbance, reducing SOC oxidation and erosion.
2. Cover cropping and crop rotations: Maintain continuous soil cover and diverse root biomass inputs, reduce soil erosion.
3. Organic amendments: Application of compost, manure, and crop residues to restore depleted SOC.
4. Biochar addition: Introduces highly stable and recalcitrant carbon with several other soil benefits.

Vegetation and Land-uses Management

1. Agroforestry: Integrating trees with crops or livestock increases above- and below-ground biomass carbon and diversifies income.
2. Afforestation and reforestation: Long-term carbon storage through tree plantations or natural regeneration on degraded land.

3. Grassland restoration and improved grazing: Enhances root biomass, SOC accumulation, and methane mitigation from enteric fermentation.

Soil-centric practices such as conservation tillage or no-till, cover cropping, and the use of organic amendments play a pivotal role in enhancing and stabilizing soil organic carbon (SOC). Conservation tillage minimizes soil disturbance, reducing carbon oxidation and erosion losses, while cover crops and diverse crop rotations maintain continuous soil cover and contribute to root-derived carbon inputs. The incorporation of organic amendments—such as compost, manure, and retained crop residues—restores depleted SOC and improves soil aggregation and nutrient cycling. Additionally, biochar application introduces highly stable forms of carbon that persist in soil for decades to centuries, while simultaneously improving nutrient retention, water-holding capacity, and microbial habitat quality. Collectively, these soil-centric interventions form the foundation of carbon farming strategies, offering synergistic benefits for soil fertility, resilience, and long-term carbon sequestration in sustainable agricultural systems (Paustian *et al.*, 2019; Lal, 2020; Smith *et al.,* 2020).

Vegetation and land-use–based management systems offer substantial potential for long-term carbon sequestration through enhanced biomass production and improved soil organic carbon (SOC) dynamics. Agroforestry, which integrates trees with crops or livestock, contributes to both above- and below-ground carbon storage while diversifying on-farm income and improving microclimatic conditions. Afforestation and reforestation initiatives further enhance carbon sequestration by establishing perennial vegetation on degraded or marginal lands, thereby increasing biomass accumulation and promoting soil carbon recovery over decadal timescales. Likewise, grassland restoration and improved grazing management strengthen root biomass production, stimulate soil aggregation, and contribute to methane mitigation through optimized forage quality and reduced enteric emissions. Together, these vegetation-centred systems serve as vital components of carbon farming strategies, simultaneously improving ecosystem resilience, biodiversity, and livelihood sustainability (Griscom *et al.,* 2017; Lal, 2020; Bossio *et al.,* 2020).

Conservation Agricultural Practices

Conservation agriculture (CA), which combines minimal soil disturbance, permanent soil cover and diversified crop rotations, is widely promoted for enhancing soil organic carbon (SOC) and improving soil health. Meta-analyses consistently show higher SOC under CA than under conventional tillage, though the extent and depth of enrichment vary with management intensity and site conditions (Francaviglia *et al.*, 2023; Li *et al.*, 2020; Beillouin *et al.*, 2023). The greatest gains occur when reduced or zero tillage is combined with residue retention or cover cropping, while tillage reduction alone yields limited carbon accrual. In most cases, SOC increases are first observed in surface layers (0–10 cm) and extend deeper only with long-term adoption or added organic inputs (Lessmann *et al.,* 2021; Teng *et al.,* 2024).

SOC response to CA depends on climate, soil type, cropping intensity, and initial carbon status. Semi-arid and sub-humid regions or carbon-depleted soils generally show greater improvements than high-rainfall or residue-limited systems (Lessmann *et al.,* 2021; Li *et al.,* 2020). Long-term implementation and soil management (>10 years) is typically required for measurable and stable SOC increases (Francaviglia *et al.*, 2023).

Mechanistically, CA enhances SOC by reducing soil disturbance, thereby slowing organic matter oxidation and improving aggregate stability. Residue retention provides continuous carbon inputs and supports microbial processes that stabilize carbon within soil aggregates (Beillouin *et al.,* 2023; Teng *et al.,* 2024). Complementary practices such as applying organic amendments, integrating agroforestry, or adopting crop–livestock systems can further strengthen SOC sequestration (Francaviglia *et al.*, 2023; Teng *et al.*, 2024).

From carbon farming perspective, CA offers practical opportunities to enhance soil health and contribute to climate change mitigation within existing farming systems. However, translating SOC gains into verifiable carbon credits requires robust monitoring, reporting, and verification (MRV) frameworks that consider baseline variability, sampling depth, and carbon permanence (Beillouin *et al.,* 2023). Therefore, CA should be viewed as part of an integrated regenerative approach—combined with residue retention, cover crops, and organic amendments—rather than a stand-alone carbon sequestration strategy for sustainable agriculture.

Organic Farming Practices

Unlike conventional systems that depend heavily on synthetic fertilizers and pesticides, organic systems emphasize the use of organic amendments/ inputs (farmyard manure, compost, and green manures etc.), diversified crop rotations, Cover crops etc. These practices collectively improve soil structure, enhance microbial activity, and increase carbon inputs to the soil, resulting in measurable SOC gains over time. Crystal-Ornelas *et al.* (2021) reported that best-management practices within organic systems—such as organic amendments, conservation tillage, and cover cropping—significantly increased SOC stocks, with organic amendments alone accounting for nearly a 24% increase in depth-weighted SOC. Similarly, Zhao *et al.* (2024), in a global meta-analysis comparing organic and conventional systems, found that organic farming significantly enhanced SOC storage, particularly when sampling depths exceeded 15 cm. These increases are attributed to both higher organic matter inputs and improved carbon stabilization mechanisms.

Organic amendments provide direct carbon inputs and improve the soil's cation exchange capacity, while residues and cover crops protect the soil surface, reduce erosion, and foster soil aggregation. Enhanced microbial biomass and enzyme activity under organic systems promote humification and the formation of stable carbon pools. Meena *et al.* (2022) observed that long-term organic management combining farmyard manure, crop residue retention, and biofertilizers in Indo-Gangetic rice–wheat systems increased

SOC by 78–123% compared to unfertilized controls. Such long-term trials highlight the cumulative effect of sustained organic inputs on building soil carbon stocks in tropical and subtropical regions.

The magnitude of SOC improvement under organic farming, however, depends on several interacting factors—soil type, climate, management duration, and input quality. Coarse-textured and degraded soils or regions with initially low SOC show greater relative gains, while carbon saturation in fine-textured soils may limit long-term sequestration potential (Zhao *et al.*, 2024). Furthermore, organic systems typically exhibit gradual carbon enrichment, often requiring more than a decade to manifest significant changes. This slow but steady increase aligns well with carbon farming objectives focused on permanence rather than short-term accumulation. However, the scalability of SOC sequestration through organic farming depends on sustainable organic input availability, efficient nutrient management, and integrating organic farming with complementary regenerative practices—such as residue retention, reduced tillage, and agroforestry—can enhance its contribution to both soil carbon sequestration and long-term agricultural sustainability.

Agroforestry Systems

Agroforestry is among the most effective land-use systems for enhancing soil organic carbon (SOC) and mitigating climate change. The combination of woody perennials and annual crops increases biomass inputs, improves soil structure, and enhances below-ground carbon storage through extensive root systems and litter deposition. Numerous studies have reported that agroforestry systems maintain higher SOC levels than adjacent monocropping systems due to continuous organic inputs and reduced erosion and disturbance (Nair *et al.,* 2010; Lorenz and Lal, 2014).

Meta-analytical evidence indicates that agroforestry can increase SOC stocks by 20–30% compared to conventional agriculture, with greater benefits in humid and sub-humid regions and on degraded or marginal lands (Zomer *et al.*, 2016; Kim *et al.*, 2016). The SOC gains are concentrated in the upper 30 cm of soil but can extend deeper through fine-root turnover and rhizodeposition. Systems such as alley cropping and silvi-pasture are particularly effective, as they combine continuous litter fall with limited soil disturbance.

However, the magnitude of carbon sequestration depends on nature of tree species, density, management intensity, and local climatic conditions. Integration of legumes or deep-rooted species further enhances carbon stabilization by improving nitrogen availability and sub-soil carbon storage. From carbon-farming standpoint, agroforestry represents a long-term, resilient carbon sink that delivers both mitigation and adaptation benefits. Its inclusion in agricultural landscapes complements conservation and organic farming approaches, contributing significantly to climate-smart and sustainable agriculture.

Limitations and Challenges in Carbon Farming

The scope and intension of carbon farming practices seem very promising but there are few limitations and challenges. There are short-term yield reductions during transition to low-input or conservation systems; reversibility of carbon storage due to land-use changes or natural disturbances; risk of carbon leakage if intensified production elsewhere offsets gains; chance of SOC saturation — once soils reach equilibrium, sequestration slows (Six *et al.*, 2002).

Despite its potential, carbon farming initiatives face numerous challenges in its implementation. These programs often require complex policy frameworks and administrative procedures that discourage farmer participation due to design intricacies, conflicting policy–farmer objectives, and limited institutional support. Adoption is further influenced by individual landholder interests, farm characteristics, and managerial capacity (Liu *et al.,* 2018).

A major obstacle remains the lack of awareness and understanding among farmers regarding the concept, benefits, and requirements of carbon farming (Ingram *et al.,* 2016). Political instability and uncertainty regarding environmental outcomes also hinder large-scale adoption (Funk *et al.*, 2014). The absence of standardized methodologies, high transaction and certification costs, and limited access to credit make participation in carbon farming initiatives difficult (Macintosh and Waugh, 2012). Other constraints include unstable carbon prices, unclear economic benefits, and challenges in monitoring, verification, and carbon credit trading (Renwick *et al.,* 2002; Narassimhan *et al.,* 2018). Farmers often perceive carbon farming as conflicting with traditional objectives or as favouring those with a history of poor land management, leading to resentment and low participation (Ingram *et al.,* 2016; Tesfahunegn, 2019). Hence, while financial incentives are essential, they alone are insufficient to overcome these multidimensional barriers. A combination of policy simplification, technical capacity building, and transparent benefit-sharing mechanisms is necessary for successful carbon farming adoption.

Scope in Changing Climate

Carbon farming encompasses a wide range of land management interventions, manipulation in biological systems, and innovative technologies. The scope varies with respect to agro-ecological zone, land tenure, and market context. Unlike single-objective carbon offset projects, carbon farming integrates soil health, water conservation, biodiversity enhancement, and farm income stability (IPCC, 2022). It supports multiple Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). Robust Measurement, Reporting, and Verification (MRV) is essential for validating carbon credits and scaling carbon farming.

Conclusion

Carbon farming represents a transformative approach to sustainable agriculture, linking farm productivity with global climate goals. Its principles rest on optimizing carbon capture and minimizing GHG emissions through soil, vegetation, and livestock management. The scope extends from traditional conservation agriculture to emerging engineered solutions. With appropriate MRV, supportive policy, and equitable incentives, carbon farming can provide a scientifically robust and socially just pathway toward carbon-neutral food systems.

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