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Carbon Farming for a Greener Tomorrow: Enhancing Soil Organic Matter, Crop Residue Management and Regenerative Agriculture for Climate Mitigation

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INTRODUCTION

Agriculture is closely connected with climate change because farming systems both contribute to greenhouse gas emissions and have considerable potential to remove atmospheric carbon dioxide through plants and soils. Intensive cultivation, excessive soil disturbance, burning of crop residues, declining soil organic matter, inefficient fertilizer use and land degradation can reduce soil carbon stocks and increase greenhouse gas emissions. At the same time, agricultural soils represent one of the largest manageable carbon reservoirs available for climate mitigation. Carbon farming has therefore emerged as an important approach for transforming agricultural soils from sources of carbon loss into more effective carbon sinks. Carbon farming refers to the deliberate management of agricultural land to increase carbon storage in soil and vegetation while maintaining food production and improving resource use efficiency. The approach includes practices such as residue retention, cover cropping, crop diversification, conservation tillage, organic amendments, agroforestry, improved nutrient management and restoration of degraded soils. Recent reviews indicate that carbon farming practices can increase soil organic carbon, although the magnitude of the response varies with climate, soil type, crop system, management duration and the combination of practices used.

Soil organic matter is central to carbon farming because it improves several physical, chemical and biological properties of soil. Increasing organic matter can improve aggregation, water holding capacity, nutrient cycling, microbial activity and resistance to erosion. Carbon rich soils can also support greater resilience against drought and other climatic stresses. However, soil carbon sequestration is not unlimited. Carbon accumulation depends on the amount and quality of carbon entering the soil, decomposition processes, environmental conditions and the capacity of soil minerals and aggregates to stabilize organic carbon.

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Crop residues provide an important source of carbon and nutrients for maintaining soil organic matter. Instead of burning or removing residues, farmers can retain, mulch, compost or appropriately incorporate them into cropping systems. Cover crops provide another important pathway by increasing biomass production during periods when fields would otherwise remain bare. A global meta analysis found that cover crops can increase soil carbon sequestration, demonstrating their potential as a climate mitigation practice.

Regenerative agriculture extends these concepts by viewing the farm as an interconnected biological system. Rather than relying on a single practice, regenerative approaches generally combine reduced soil disturbance, continuous soil cover, crop diversification, organic matter addition, integration of biological processes and efficient nutrient management. Recent evidence from India indicates that regenerative practices including organic amendments, conservation tillage, residue retention and improved fertilizer management can contribute to increases in soil organic carbon, particularly when practices are maintained for several years.

Concept of Carbon Farming

Carbon farming is a management approach designed to increase the quantity of carbon captured by agricultural ecosystems and the proportion retained in relatively stable soil carbon pools. Plants capture atmospheric carbon dioxide through photosynthesis and convert it into organic compounds. A portion of this carbon is transferred to the soil through roots, root exudates, fallen leaves and crop residues. Soil organisms subsequently transform this material into different forms of soil organic matter. The carbon farming cycle can therefore be viewed as a continuous pathway involving atmospheric carbon dioxide capture, crop biomass production, residue return, microbial transformation, soil carbon stabilization and long term storage. Management practices influence every stage of this pathway.

Carbon farming should not be considered simply as the addition of carbon containing materials to soil. Effective carbon management requires consideration of both carbon gains and potential greenhouse gas emissions. For example, organic amendments may increase soil carbon but can also influence methane and nitrous oxide emissions under particular conditions. Therefore, the climate benefit of a carbon farming system should ideally be evaluated using a whole system greenhouse gas perspective rather than soil carbon measurements alone. Research from Southeast Asian cropping systems has highlighted this important issue, particularly for manure, compost and other organic inputs.

Soil Organic Matter as the Foundation of Carbon Farming

Soil organic matter consists of plant and animal residues at different stages of decomposition, microbial biomass and relatively stable organic compounds associated with soil minerals and aggregates. It plays an essential role in maintaining soil productivity. Increasing soil organic matter can improve soil structure by promoting aggregate formation. Well aggregated soils generally have better pore distribution and improved infiltration. Organic matter also contributes to water retention, which becomes particularly important under irregular rainfall and drought conditions. Furthermore, organic matter provides energy and nutrients for microorganisms that drive decomposition and nutrient cycling. From a climate perspective, soil organic matter represents an important pool of terrestrial carbon. The objective of carbon farming is not merely to increase total carbon temporarily but to encourage the formation and stabilization of carbon pools that can remain in soil for longer periods.

Carbon stabilization occurs through several mechanisms. Organic compounds can become physically protected inside soil aggregates or chemically associated with minerals. Microbial processing can also transform plant residues into compounds that become stabilized within the soil matrix. Consequently, management practices that continuously supply organic inputs while reducing soil disturbance can contribute to the

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development of more stable carbon pools. However, carbon sequestration varies among soils and environments. Clay content, mineralogy, temperature, moisture, crop productivity and management history influence the capacity of soil to retain additional carbon. Carbon farming strategies should therefore be adapted to local soil and climatic conditions rather than applying the same prescription everywhere.

Crop Residue Management for Carbon Sequestration

Crop residues include stalks, leaves, roots, husks, straw, pods and other plant materials remaining after harvest. These materials contain carbon and nutrients that can contribute to soil organic matter formation. Traditional residue burning rapidly converts much of this biomass carbon into atmospheric gases and removes potentially useful nutrients from the field. Residue retention provides a relatively simple pathway for returning carbon to agricultural soil. Surface residues protect soil from raindrop impact and wind erosion, reduce direct evaporation and moderate soil temperature. As residues decompose, they release nutrients and contribute organic compounds to the soil.

Residue management should nevertheless be based on local conditions. Excessive residue accumulation can interfere with planting operations, temporarily immobilize nitrogen during decomposition and provide habitat for some pests or pathogens under certain cropping systems. Appropriate residue chopping, distribution, partial incorporation or surface mulching can help balance these considerations. Residue incorporation can increase soil carbon inputs, but surface retention may provide additional benefits related to erosion control and moisture conservation. The most suitable approach depends on soil type, climate, machinery availability, residue quality and cropping system. Recent carbon farming research indicates that crop residue maintenance contributes positively to soil organic carbon, although its average effect is generally smaller than some combinations involving organic amendments or cover crops. A European review reported positive soil carbon responses from crop residue maintenance, improved rotations, reduced soil disturbance and cover crops.

Cover Crops and Continuous Soil Cover

Cover crops are grown primarily to protect and improve the soil rather than for direct harvest. Legumes, grasses and mixtures of cover crops can provide additional biomass and extend the period during which living roots remain active in the soil. Cover crops contribute carbon through aboveground biomass, root biomass and root exudates. Living roots stimulate microbial activity and can increase the flow of carbon into the soil. Cover crops also reduce erosion, improve soil structure and help protect soil from extreme temperatures.

A major advantage of cover crops is their ability to increase carbon inputs during periods when conventional cropping systems may leave the soil bare. A meta-analysis of cover cropping studies estimated an average annual soil carbon increase of approximately 0.32 Mg C per hectare per year during the first several decades, although the actual response varies among systems. More recent research has demonstrated that cover crops can influence different soil carbon pools differently. Global evidence indicates increases in particulate organic carbon and microbial biomass carbon, while changes in mineral associated organic carbon may develop more slowly. The choice of cover crop should therefore consider rainfall availability, soil type, crop rotation, nutrient requirements and termination method. Legumes can contribute biologically fixed nitrogen, whereas grasses often produce substantial carbon rich biomass. Mixtures may combine several ecosystem functions.

Conservation Tillage and Reduced Soil Disturbance

Frequent intensive tillage can disrupt soil aggregates, expose protected organic matter to microbial decomposition and increase the risk of erosion. Conservation tillage and reduced soil disturbance aim to maintain soil structure and reduce unnecessary disruption. Reduced

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tillage can work effectively when combined with residue retention and diversified rotations. The objective is not simply to reduce the number of tillage operations but to develop a production system that maintains soil cover, minimizes erosion and supports biological activity. Carbon responses to reduced tillage can vary substantially with soil depth and environmental conditions. Surface soil may show greater carbon concentration under reduced disturbance while deeper soil responses can differ. Consequently, carbon assessment should consider soil depth and changes in total carbon stocks rather than relying only on carbon concentration in shallow soil samples.

Regenerative Agriculture and Soil Restoration

Regenerative agriculture focuses on rebuilding ecological functions within agricultural landscapes. It is generally associated with practices such as continuous soil cover, reduced soil disturbance, diversified crop rotations, cover crops, residue retention, organic amendments, integrated livestock systems and agroforestry. The central principle is to increase biological activity and improve the ability of agricultural ecosystems to regenerate soil resources. Healthy soils can support improved nutrient cycling, water infiltration, root growth and biological diversity.

Recent research shows that regenerative agriculture practices can increase soil organic carbon, but results are not uniform. A 2025 meta analysis of 147 studies from India found that different regenerative practices produced different levels of soil carbon response, with organic amendments, biochar and green manure among the stronger contributors, while conservation tillage and crop residue retention produced moderate but consistent benefits. The study also indicated that carbon gains were more pronounced over periods longer than five years. This long term perspective is important. Soil carbon accumulation is generally a gradual process, and short term changes may not accurately represent long term sequestration. Farmers therefore need management strategies that remain economically practical and biologically effective over many years.

Table 1. Major Carbon Farming Practices and Their Contributions

Carbon farming practice	Major contribution to soil and climate management	Important considerations
Crop residue retention	Returns carbon to soil, protects soil surface and reduces erosion	Excess residues may interfere with planting or temporarily immobilize nutrients
Cover cropping	Adds aboveground and belowground biomass and protects soil during fallow periods	Requires appropriate species selection and water management
Reduced tillage	Limits soil disturbance and helps maintain soil structure	Performance depends on residue management, soil type and weed control
Crop diversification	Increases biological diversity and distributes carbon inputs through different root systems	Requires suitable crop combinations and market planning
Organic amendments	Adds carbon and nutrients and can improve soil biological activity	Quality, application rate and greenhouse gas emissions must be considered
Green manuring	Adds fresh organic biomass and can improve nutrient cycling	Requires adequate moisture and suitable incorporation or termination timing
Agroforestry	Combines crop production with long term biomass and carbon storage	Requires appropriate tree species, spacing and management
Improved nutrient management	Supports crop biomass production while reducing unnecessary nutrient losses	Fertilizer decisions should be based on soil testing and crop requirements

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Figure 1: Integrated regenerative agriculture system for increasing soil organic carbon through diverse crops and cover crops, crop residue retention reduced tillage, organic amendments, agroforestry and microbial activity.

Organic Amendments and Green Manuring

Organic amendments such as farmyard manure, compost and other stabilized organic materials can increase carbon inputs and improve soil fertility. Their effectiveness depends on the quality, maturity, carbon to nitrogen ratio, application rate and frequency. Green manuring is another useful carbon farming strategy. Crops such as legumes can be grown specifically for incorporation into the soil. Green manure contributes easily decomposable organic matter and can improve nutrient cycling. Leguminous green manure can additionally contribute nitrogen through biological nitrogen fixation. However, organic carbon inputs should be managed carefully. Transporting large quantities of organic material over long distances can increase costs and associated emissions. Therefore, locally available biomass resources are often more practical.

Crop Rotation and Diversification

Continuous monocropping can simplify production but may reduce biological diversity and create repeated pressure on soil resources. Crop rotation introduces variation in root architecture, residue quality, nutrient demand and microbial interactions. Diversified rotations can increase the quantity and diversity of carbon entering soil. Deep rooted crops may contribute carbon to deeper soil layers, while shallow rooted crops can provide different forms of residue and microbial stimulation. Including legumes in rotations can improve nitrogen availability and reduce dependence on external nitrogen inputs. However, rotation design should be adapted to local climate, market opportunities and farm resources.

Agroforestry as a Carbon Farming Strategy

Agroforestry combines trees with crops, livestock or both. Trees capture carbon in

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woody biomass and roots while also contributing organic material to soil through litter and root turnover. Agroforestry can provide multiple ecosystem services, including erosion control, microclimate regulation, biodiversity conservation and additional products such as fruit, fodder, fuelwood or timber. Deep tree roots may access resources from soil layers that are less exploited by annual crops. The design of agroforestry systems must account for competition between trees and crops for water, nutrients and sunlight. Appropriate species selection and spacing are therefore essential.

Carbon Farming and Climate Mitigation

Carbon farming contributes to climate mitigation primarily by increasing carbon storage and reducing emissions associated with inefficient agricultural management. Higher soil carbon stocks represent carbon transferred from the atmosphere into terrestrial ecosystems. However, soil carbon sequestration should not be viewed as a permanent substitute for reducing fossil fuel emissions. Soil carbon can be lost again if management changes, erosion occurs or stored carbon is mineralized. Carbon farming should therefore complement, rather than replace, broader greenhouse gas reduction strategies. A comprehensive carbon farming system should also consider nitrous oxide and methane emissions. Nitrogen management, water management, manure handling and residue decomposition can influence these gases. Therefore, the most climate beneficial system is one that improves soil carbon while maintaining or reducing total greenhouse gas emissions.

Economic and Environmental Benefits for Farmers

- Carbon farming can provide benefits beyond climate mitigation. Improved soil structure can reduce erosion and improve water infiltration. Greater organic matter can improve nutrient availability and water retention. These effects can contribute to greater crop resilience during climatic stress.
- Residue retention can reduce the need for residue disposal or burning. Cover crops can provide forage, biological nitrogen fixation or additional biomass. Diversified rotations can reduce production risks associated with dependence on a single crop.
- Nevertheless, carbon farming may involve initial costs. Cover crop seed, specialized machinery, residue management, organic amendments and changes in farm planning may require investment. Farmers therefore need locally appropriate economic incentives, technical guidance and market opportunities.
- Carbon markets may provide an additional incentive for farmers who increase verified soil carbon stocks. However, credible carbon programs require accurate measurement, reporting and verification. The permanence of carbon storage, additionality, baseline selection and monitoring costs must be carefully addressed.

Carbon Farming in Indian Agriculture

Carbon farming has particular relevance to India because the country contains diverse soils, climates and cropping systems, ranging from irrigated intensive agriculture to rainfed and resource constrained farming. Many Indian soils have experienced declining organic matter because of intensive cultivation, residue removal, erosion and inadequate organic inputs. Practices such as crop residue retention, green manuring, cover crops, conservation agriculture, integrated nutrient management, agroforestry and organic amendments can contribute to improving soil carbon. Recent Indian evidence demonstrates that regenerative agricultural practices can increase soil organic carbon, with stronger responses often occurring after several years of continued management. Carbon farming in India should therefore be based on region specific strategies. In irrigated systems, cover crops and diversified rotations may be practical. In rainfed areas, residue retention, moisture conservation and drought tolerant cover crops may be more appropriate. In degraded soils, organic amendments and integrated nutrient management can help rebuild soil function.

Future Prospects

- The future of carbon farming will increasingly depend on integrating soil science, agronomy, ecology, digital agriculture and climate science. Remote sensing, soil sensors, geographic information systems and digital farm records can support monitoring of crop biomass, residue cover and soil conditions.
- Improved soil carbon models can help estimate carbon changes across large agricultural areas. Artificial intelligence and machine learning may also contribute to identifying management practices that are most suitable for particular soil and climate conditions.
- Biological approaches will remain important. Greater understanding of plant root systems, microbial communities and soil carbon stabilization mechanisms can support the development of cropping systems capable of delivering greater and more persistent carbon inputs.
- Carbon farming should ultimately move toward integrated systems rather than isolated practices. Combining residue management with cover crops, diversified rotations, reduced soil disturbance, balanced nutrient management and organic inputs may provide greater benefits than relying on a single intervention.

CONCLUSION

Carbon farming provides a practical pathway for linking climate mitigation with soil health and sustainable crop production. Enhancing soil organic matter, retaining crop residues, using cover crops, reducing unnecessary soil disturbance, diversifying crop rotations and applying suitable organic amendments can increase carbon inputs and improve soil functioning. Evidence from recent global and Indian studies supports the potential of these practices, although their effectiveness varies according to soil, climate, crop system and management duration. The most effective carbon farming strategy is therefore not a single practice but a locally adapted combination of complementary management approaches. Farmers should focus on maintaining continuous carbon inputs, protecting soil from erosion, improving biological activity and minimizing avoidable greenhouse gas emissions. With appropriate scientific guidance, economic incentives, carbon monitoring and long term management, carbon farming can contribute to healthier soils, resilient agricultural systems and a greener tomorrow.

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