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From Carbon Loss to Carbon Gain: Enhancing Soil Organic Carbon, Cover Cropping and Climate-Smart Agronomy for Sustainable Agriculture

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INTRODUCTION

Agriculture is increasingly challenged by soil degradation, declining soil fertility, climate variability, water scarcity and the need to produce more food from limited land resources. One of the most important indicators connecting soil health, agricultural productivity and climate change is soil organic carbon. Soil organic carbon represents the carbon stored in soil organic matter and is closely associated with nutrient cycling, soil structure, water retention, microbial activity and long-term productivity. When agricultural soils lose organic carbon through intensive cultivation, erosion, residue removal and excessive soil disturbance, their capacity to support productive and resilient cropping systems can decline. Historically, the conversion of natural ecosystems into agricultural land has resulted in substantial changes in soil carbon stocks. Intensive tillage exposes protected organic matter to oxygen and microbial decomposition, while removal or burning of crop residues reduces the amount of carbon returned to the soil. Repeated monocropping and insufficient organic inputs can further accelerate carbon depletion. Climate change can intensify these processes through higher temperatures, irregular rainfall, drought and extreme weather events. Therefore, rebuilding soil organic carbon is not only a soil fertility strategy but also an important component of climate change mitigation and adaptation.

Climate-smart agriculture provides a framework for addressing these challenges by combining practices that improve productivity, strengthen resilience to climate variability and reduce greenhouse gas emissions where possible. Conservation tillage, crop residue retention, cover cropping, diversified crop rotations, organic amendments, integrated nutrient management, agroforestry and efficient water management can all contribute to improving soil carbon dynamics.

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A meta analysis of climate-smart practices found that conservation tillage, cover crops and organic carbon inputs can substantially improve soil carbon stocks, although the magnitude of response varies with climate, soil properties and management conditions.

The transition from carbon loss to carbon gain therefore requires an integrated approach. Rather than relying on one practice, farmers need to manage carbon inputs, decomposition, soil disturbance, erosion and nutrient availability together. Among the available approaches, cover cropping is particularly important because it adds carbon to the soil while protecting the soil surface during periods when conventional cropping systems would otherwise leave it exposed.

Soil Organic Carbon as the Foundation of Sustainable Agriculture

Soil organic carbon is a major component of soil organic matter and acts as an important reservoir of nutrients and energy for soil organisms. Carbon enters agricultural soils primarily through plant roots, root exudates, crop residues, fallen leaves, manure and other organic materials. Microorganisms transform these materials into different forms of organic carbon, some of which remain relatively active while other fractions become physically or chemically protected within soil aggregates and mineral associations. The quantity and quality of soil organic carbon influence many soil properties. Higher organic carbon generally contributes to better aggregation, improved infiltration, greater water-holding capacity and greater biological activity. Organic carbon also contributes to the gradual release of nutrients and provides energy for microorganisms involved in nutrient cycling.

Soil organic carbon can be broadly considered through different pools. Particulate organic carbon is relatively responsive to recent carbon inputs and can provide an early indication of changes in soil management. Mineral associated organic carbon is generally more persistent because organic compounds become associated with mineral surfaces. Microbial biomass carbon represents an active biological component of the soil carbon system. Recent research demonstrates that agricultural management can influence these different carbon pools differently. A global meta-analysis found that cover crops increased several soil carbon fractions, including particulate organic carbon, mineral associated organic carbon and microbial biomass carbon.

From Carbon Loss to Carbon Gain

Carbon loss from agricultural soils is commonly associated with intensive tillage, erosion, residue removal, inadequate organic inputs, continuous cultivation and inappropriate land management. When crop residues are removed from fields, a major pathway of carbon return is lost. Similarly, excessive soil disturbance can accelerate decomposition of organic matter and expose protected carbon to microbial activity. Carbon gain requires increasing the quantity and efficiency of carbon entering the soil while reducing unnecessary carbon losses. Maintaining living roots for longer periods is particularly important because roots continuously interact with microorganisms and contribute carbon below the soil surface. Cover crops can extend the period during which agricultural land has active vegetation and therefore increase carbon inputs between main crops.

Crop residue retention is another important component of carbon gain. Residues provide organic material that can be decomposed gradually and incorporated into soil organic matter. However, residue management must be adapted to local conditions because residues also have value as livestock feed, fuel and raw material. Sustainable management therefore requires balancing soil carbon benefits with farmers' other needs. Reduced soil disturbance can further support carbon retention by protecting soil aggregates and reducing the physical disruption of soil organic matter. Climate-smart agriculture is most effective when residue retention, cover cropping, appropriate tillage and diversified rotations are combined rather than implemented independently. Evidence from tropical and subtropical regions indicates that combinations of conservation practices can produce positive effects on soil carbon stocks, although outcomes depend strongly on local soil and climatic conditions.

Cover Cropping as a Carbon Building Strategy

Cover crops are crops grown primarily to protect and improve the soil rather than for direct harvest as the principal commercial product. They may be grown between two main crops or during periods when agricultural fields would otherwise remain bare. Common cover crops include legumes such as clover, vetch and field pea, cereals such as rye and oats and broadleaf species such as radish and mustard. The carbon benefits of cover crops arise through several mechanisms. First, cover crops increase aboveground biomass production and return organic residues to the soil. Second, their root systems contribute carbon directly below the soil surface. Third, living roots support microbial communities and contribute to the formation and stabilization of soil organic matter. Fourth, vegetation protects the soil surface from erosion, reducing the physical removal of carbon rich topsoil.

A meta analysis of global cropland systems found that cover cropping increased near surface soil organic carbon by an average of approximately 15.5 percent. The response was influenced by soil texture, climate, initial carbon concentration, duration of cover crop use and cover crop composition. Cover crop mixtures also produced greater increases than some single species systems in the analyzed studies. Earlier research also demonstrated that cover cropping can gradually increase soil carbon stocks over time. Poeplau and Don reported an average annual soil carbon increase of approximately 0.32 Mg carbon per hectare per year during the observed period following introduction of cover crops. Their analysis emphasized that carbon accumulation does not continue indefinitely and eventually approaches a new equilibrium.

The selection of cover crops should therefore be based on local climate, soil type, cropping calendar, water availability and economic objectives. Legumes can contribute biologically fixed nitrogen, while grasses often produce substantial biomass and fibrous root systems. Mixtures can provide complementary characteristics and may improve resource use and soil protection.

Role of Cover Crop Diversity

Cover crop diversity is important because different plant species contribute different types and quantities of biomass to the soil. Grasses generally provide high amounts of carbon rich residues, while legumes can provide nitrogen rich biomass. Broadleaf species can contribute different root architectures and may improve soil physical conditions. Mixtures can also increase the diversity of root exudates and support a broader range of microorganisms. However, diversity should not be adopted simply as a general rule. The best combination depends on local production systems. A cover crop that consumes excessive soil moisture in a water limited environment could create competition with the subsequent crop. Therefore, carbon gain must always be considered together with water availability and crop productivity. Recent evidence shows that cover crops influence both relatively active and more persistent soil carbon pools. Fohrafellner and colleagues found increases in particulate organic carbon, microbial biomass carbon and mineral associated organic carbon under cover cropping, although the magnitude of response varied according to soil and management conditions.

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Conservation Tillage and Soil Carbon Protection

Tillage is an important determinant of soil carbon dynamics. Intensive tillage physically disrupts soil aggregates and can increase the exposure of protected organic matter to decomposition. Repeated disturbance can also increase soil erosion and reduce surface residue protection. Reduced tillage and no tillage aim to minimize soil disturbance while maintaining crop production. These practices can increase surface residue retention, reduce erosion and improve soil structure. However, the effect of reduced tillage on total soil carbon can depend on sampling depth, soil texture, climate and residue management. Therefore, apparent increases in surface carbon should be interpreted carefully and should not automatically be considered equivalent to whole profile carbon sequestration. A meta analysis focused on tropical and subtropical regions reported positive effects of conservation tillage on soil organic carbon stocks and highlighted that the combination of conservation tillage with other practices can strengthen carbon benefits.

Crop Residue Management for Carbon Conservation

Crop residues are one of the most accessible sources of organic carbon in agricultural systems. Straw, leaves, stalks, roots and other crop residues can return substantial quantities of carbon to the soil. Retaining residues on the field protects the surface from erosion, reduces evaporation and contributes organic material for microbial decomposition. However, residue retention must be carefully managed. Excessive residue accumulation can interfere with seed placement, increase pest or disease risks in certain systems and delay soil warming. In some farming communities, residues are also required for livestock feeding. Therefore, a practical residue management strategy should consider the entire farm system. Residue management becomes more effective when combined with cover crops and appropriate nutrient management. Maintaining both crop residues and living roots creates a continuous carbon input pathway rather than relying only on residues after harvest.

Organic Amendments and Carbon Gain

Organic amendments such as farmyard manure, compost and other locally available organic materials can increase carbon inputs to agricultural soils. They can also improve nutrient availability, microbial activity and soil physical properties. However, carbon management should consider the complete greenhouse gas balance. Organic amendments may increase soil carbon but can also influence methane and nitrous oxide emissions depending on material type, moisture conditions and application method. Consequently, the objective should be net climate benefit rather than simply increasing the measured quantity of soil carbon. Carbon farming frameworks emphasize the importance of combining soil carbon storage with broader greenhouse gas management and agricultural productivity. Carbon farming can therefore be considered a circular approach in which crop biomass is converted into useful soil organic matter while improving soil health and agricultural resilience.

Crop Rotation and Carbon Stabilization

Crop rotation is another important climate-smart agronomic practice. Continuous cultivation of a single crop can simplify nutrient cycling and may contribute to biological and physical degradation of soil. Rotations involving cereals, legumes, oilseeds and other crops can diversify root systems, biomass inputs and nutrient demand. Rotations containing legumes can be particularly useful because biological nitrogen fixation reduces dependence on external nitrogen inputs in suitable systems. Improved nitrogen availability can also influence crop biomass production and therefore carbon inputs to the soil. Diversified rotations can be strengthened

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further through cover crops. For example, a cereal based system can include a legume cover crop after harvest, while a row crop system can use a mixture of grass and legume species. The objective is to increase the period of living soil cover and improve the continuity of carbon inputs.

Climate-Smart Agronomy for Soil Carbon Enhancement

Climate-smart agronomy integrates productivity, adaptation and mitigation objectives. For soil carbon management, this means selecting practices that simultaneously protect soil resources, maintain crop production and reduce vulnerability to climate stress. Important components include conservation tillage, residue retention, cover cropping, crop rotation, balanced fertilization, efficient irrigation, organic amendments, agroforestry and erosion control. Their effectiveness depends on local conditions and therefore should be adapted rather than applied as universal prescriptions. Research in tropical and subtropical regions shows that conservation tillage, cover crops and carbon rich amendments can improve soil carbon stocks, while the strongest outcomes may occur when several practices are combined. The same research also emphasizes that climate, soil characteristics and duration of management influence the response.

Table 1. Major climate-smart practices for converting agricultural soils from carbon loss to carbon gain

Practice	Main carbon mechanism	Additional soil benefit	Important management consideration
Cover cropping	Adds aboveground and belowground biomass	Reduces erosion and improves biological activity	Select species according to climate, water availability and crop calendar
Crop residue retention	Returns carbon rich plant material to soil	Protects soil surface and improves moisture conservation	Balance residue retention with livestock and farm requirements
Reduced tillage	Decreases disturbance and protects soil aggregates	Reduces erosion and improves soil structure	Performance depends on soil type, climate and residue availability
Crop rotation	Diversifies carbon inputs and root systems	Improves nutrient cycling and breaks pest cycles	Include complementary crops suited to local conditions
Legume integration	Increases biomass and biological nitrogen fixation	Improves nitrogen availability	Manage competition for water and nutrients
Organic amendments	Directly adds organic carbon to soil	Improves nutrient supply and microbial activity	Consider nutrient balance and possible greenhouse gas emissions
Agroforestry	Adds long lived woody biomass and root carbon	Enhances biodiversity and microclimate	Requires suitable tree species and appropriate spatial design
Efficient irrigation	Supports biomass production while reducing water losses	Improves water use efficiency	Avoid excessive irrigation that can increase emissions or nutrient loss
Integrated nutrient management	Supports crop biomass and carbon input	Improves nutrient use efficiency	Match nutrient supply with crop demand
Erosion control	Prevents loss of carbon rich topsoil	Protects soil fertility and productivity	Combine vegetation, residue cover and suitable land management

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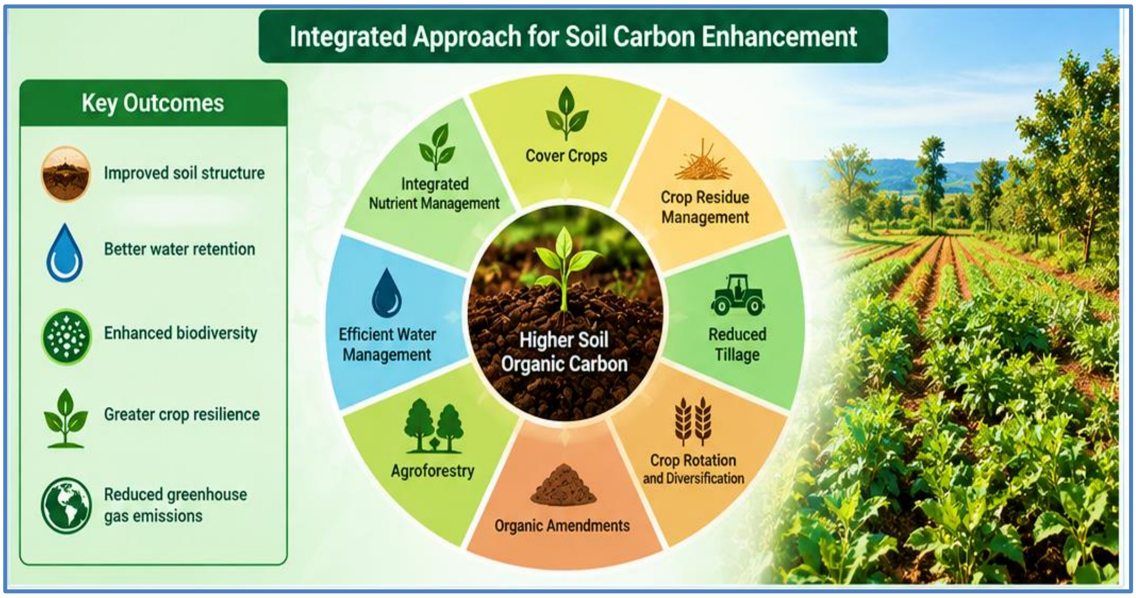

Figure 1: Integrated practices for enhancing soil organic carbon and building climate resilience in agricultural systems.

Agroforestry and Long-Term Carbon Storage

Agroforestry integrates trees with crops or livestock and can create additional pathways for carbon storage. Trees capture atmospheric carbon through photosynthesis and store it in trunks, branches, leaves and roots. Some of this carbon eventually enters the soil through root turnover and litter deposition. Agroforestry can also reduce erosion, improve microclimate and provide additional products such as fruits, fodder, fuelwood and timber. However, competition between trees and crops for light, water and nutrients must be carefully managed. Appropriate species selection and spatial arrangement are therefore essential. Climate-smart systems that integrate agroforestry with cover crops and residue management can create multiple carbon pools and increase ecological resilience. Evidence from conservation agriculture research indicates that combinations of complementary practices generally provide stronger soil carbon benefits than isolated interventions.

Soil Carbon and Climate Change Mitigation

Increasing soil organic carbon can contribute to climate change mitigation by transferring a portion of atmospheric carbon dioxide into soil organic matter. However, soil carbon sequestration should not be considered a permanent or unlimited carbon sink. Soils have finite carbon storage capacity and the rate of additional carbon accumulation generally declines as soils approach a new equilibrium. Therefore, carbon farming should be viewed as one component of a broader climate strategy. Reducing fossil fuel use, improving nitrogen use efficiency, reducing methane emissions and protecting existing carbon stocks are also important. Bai and colleagues demonstrated that climate-smart agricultural practices can increase soil carbon sequestration, but the magnitude varies among management systems and environmental conditions. Petersson and colleagues similarly found positive soil organic carbon responses across several carbon farming practices, including cover crops, organic amendments, improved rotations, residue maintenance and reduced soil disturbance.

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Economic and Agricultural Benefits

- Carbon building practices can provide benefits beyond climate mitigation. Improved soil structure can increase water infiltration and reduce runoff. Greater water holding capacity can help crops tolerate short periods of drought. Increased biological activity can support nutrient cycling and potentially improve nutrient use efficiency.
- Cover crops can also provide weed suppression, erosion control, nitrogen fixation and habitat for beneficial organisms. Crop residues can reduce soil temperature fluctuations and protect the soil surface. Reduced tillage can reduce fuel use and machinery operations in appropriate production systems.
- Nevertheless, adoption depends strongly on farm economics. Cover crops may require additional seed, planting operations and management. Reduced tillage may require new equipment or changes in weed management. Organic amendments can involve transportation costs. Consequently, climate-smart practices should be evaluated not only for carbon benefits but also for labour requirements, input costs, crop yields and long-term profitability.

Carbon Farming in Indian Agriculture

India has substantial potential for soil carbon improvement because many agricultural soils have experienced long periods of intensive cultivation, erosion and declining organic matter inputs. Small and fragmented farms, diverse climatic conditions and strong dependence on monsoon rainfall make location specific carbon management particularly important. Cover crops, crop residue retention, conservation tillage, integrated nutrient management, farmyard manure, compost, agroforestry and diversified cropping systems can contribute to carbon restoration. In rainfed regions, practices that increase water infiltration and reduce evaporation are especially valuable because soil carbon and soil moisture are closely connected. The tropical and subtropical meta analysis by Das, Chatterjee and Rajbanshi showed that conservation tillage, cover crops and organic carbon inputs can increase soil carbon stocks, but responses vary according to climate, soil characteristics and management duration. For Indian agriculture, carbon gain should therefore be integrated with existing principles of conservation agriculture, integrated farming systems, watershed management and climate-resilient agriculture.

Future Prospects

- The future of soil carbon management will increasingly depend on integrated and site specific approaches. Remote sensing, digital soil mapping, proximal soil sensors and machine learning can improve the spatial assessment of soil carbon. Long-term field experiments will remain essential for determining whether observed carbon gains are stable over time.
- Carbon accounting systems can also help farmers evaluate the climate benefits of management changes. However, carbon measurement and verification systems should be scientifically robust, transparent and economically accessible to farmers.
- Future research should focus on identifying combinations of practices that maximize carbon gain without reducing crop yield or increasing other greenhouse gas emissions. Greater attention is also required for tropical and subtropical agriculture because soil carbon responses can differ substantially from those observed in temperate regions.

- The integration of cover crops, residue retention, reduced tillage, diversified rotations, organic amendments and agroforestry offers a promising pathway. Rather than treating soil carbon as a separate environmental objective, it should become a central component of sustainable crop production.

CONCLUSION

The transition from carbon loss to carbon gain represents an important pathway toward sustainable and climate-resilient agriculture. Soil organic carbon is fundamental to soil fertility, water management, biological activity, structural stability and long term crop productivity. Cover crops can increase carbon inputs while protecting soil from erosion and supporting biological processes. Residue retention, reduced soil disturbance, diversified rotations, organic amendments and agroforestry can further strengthen carbon accumulation when appropriately combined. However, soil carbon sequestration is strongly influenced by climate, soil characteristics, management duration and farming conditions. Therefore, there is no universal carbon farming package suitable for every location. The most effective strategy is to combine locally appropriate climate-smart practices that increase carbon inputs, reduce carbon losses, protect existing soil carbon and maintain agricultural productivity. Moving from carbon loss to carbon gain should therefore be understood not simply as a climate mitigation strategy but as a broader pathway for restoring soil health, improving farm resilience and supporting sustainable food production. Building soil carbon today can help create more productive and climate-resilient agricultural systems for the future.

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