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Carbon farming and ecosystem services in eastern India

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Carbon farming provides an integrated approach to improve carbon sequestration and retention, and to reduce emissions through targeted management of agricultural systems including conservation agriculture, zero tillage direct-seeded rice, residue retention, crop diversification, agroforestry, integrated farming systems and improved nutrient-water management. These practices provide a wide suite of ecosystem services beyond carbon credits including provisioning, regulating, supporting and cultural services. Total ecosystem service valuation provides a more comprehensive assessment of their benefits. This valuation, natural-capital accounting and benefit-cost assessment all can help provide the evidentiary base for decisions about carbon-farming and credits.

Keywords: Carbon credit, Conservation agriculture, Direct seeded rice, Sustainable development goals

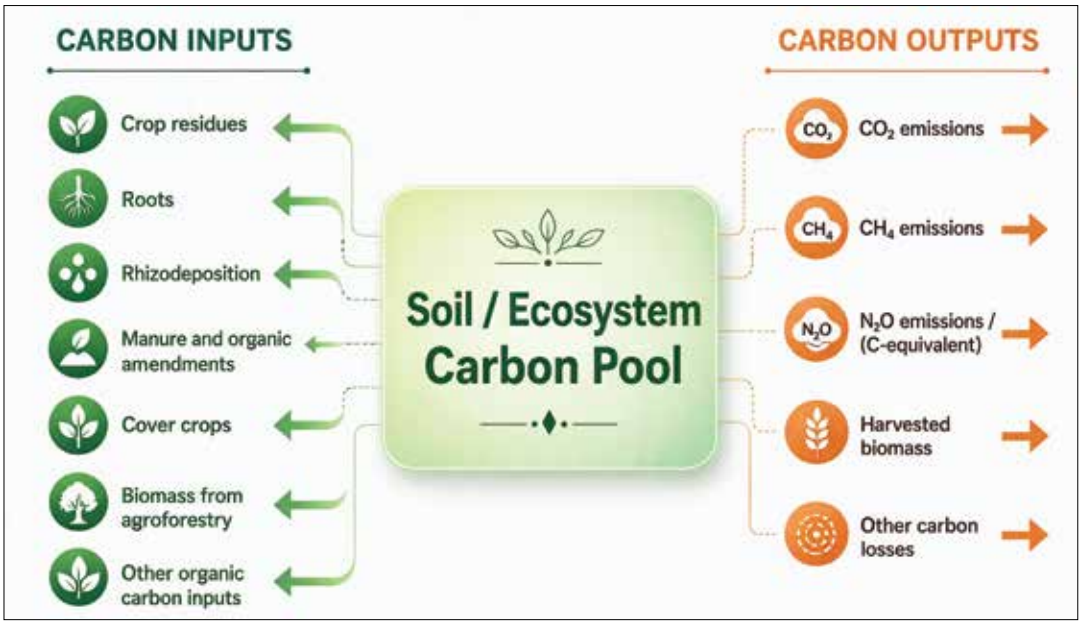
INDIAN agriculture is currently transitioning into a phase in which the expansion of food production must be accompanied by the restoration of soil health, the conservation of water and biodiversity, the reduction of greenhouse gas (GHG) emissions, and the enhancement of the economic resilience of farmers. Carbon farming promotes agricultural practices that increase carbon retention in soil and biomass while reducing GHG emissions, providing an integrated strategy to achieving these goals. However, the value of carbon farming extends beyond carbon sequestration and carbon credits. Agricultural landscapes provide a wide range of ecosystem services, including food production, nutrient cycling, soil formation, water management, carbon dynamics, climate mitigation, insect control, air filtration, and cultural benefits. Many of these services are economically invisible in traditional agriculture accounting. Indian agriculture faces numerous and linked issues. Increasing strain on land and water resources, poor soil quality, inefficient fertiliser and irrigation use, residue burning, heavy tillage, and climate variability all have the potential to undermine production systems' long-term resilience. Rice-based systems are especially essential since they take up a huge fraction of agricultural land in the Indo-Gangetic Plains and need significant water, energy, and labour inputs.

Carbon farming: Concept and relevance to Indian agriculture

Carbon farming affords the opportunity to address several of these issues concurrently. It is widely described as the intentional management of agricultural systems to promote carbon sequestration and retention and/or minimise GHG emissions while maintaining or improving agricultural productivity. Conservation agriculture, zero tillage, direct-seeded rice (DSR), residue retention, diverse crop rotations, cover crops, agroforestry, integrated farming systems, enhanced nutrient management, and efficient irrigation can all help achieve this goal. Thus, carbon farming is a new technique for converting agricultural land from a source of GHG emissions to a more carbon-efficient system while potentially earning additional economic gains through carbon credits. Carbon farming refers to management approaches that influence carbon flows in the atmosphere, plants, soil, and agricultural products.

The goal of carbon farming is not only to increase carbon in the soil. A farming system with a high carbon input can still have a negative carbon balance if carbon losses are substantial. This disparity is vividly established by a study of various rice establishment systems in the eastern Indo-Gangetic Plains. Carbon input for random puddled transplanted rice (RPTR) was 7.91 t C/ha/yr, the highest among examined systems. However, carbon output was at 18.6 t C/ha/yr. Zero tillage-DSR had a carbon intake of 6.35 t C/ha/yr, but only produced 6.0–6.2 t C/ha/yr.

High carbon input ≠ high carbon sequestration. Instead, carbon farming should focus on: Carbon input



Inflow and outflow of carbon in agricultural landscape

+ reduced carbon loss + reduced GHG emissions + increased stable soil carbon.

Major carbon-farming opportunities in India

***Conservation agriculture*:** Zero or minimum tillage, residue retention and crop diversification can reduce soil disturbance and improve soil structure. These practices can also reduce diesel consumption associated with repeated tillage operations.

***Direct-seeded rice*:** DSR eliminates or reduces puddling and transplanting operations. When combined with zero tillage (ZT), it provides an important opportunity for reducing resource requirements while improving several ecosystem functions. In the experimental comparison, both conventional-till DSR (CT-DSR) and ZT-DSR showed positive carbon-flow values, unlike the puddled transplanted rice systems.

***Residue management*:** Crop residues represent an important carbon resource. Retaining or appropriately recycling residues can return carbon and nutrients to soil, although management must be adapted to local weed, pest, nutrient and machinery conditions.

***Diversified cropping systems*:** Crop rotations, pulses and cover crops can increase below-ground carbon inputs and improve nutrient cycling.

***Agroforestry*:** Trees incorporated into agricultural landscapes can increase above-ground and below-ground carbon stocks while producing timber, fruit, fodder and other products.

***Integrated farming systems*:** Crop–livestock–tree and other integrated systems can increase internal recycling of biomass and nutrients and reduce dependence on external inputs.

***Improved nutrient and water management*:** Nitrogen-use efficiency, improved irrigation scheduling, alternate wetting and drying where suitable, and precision nutrient management can reduce GHG emissions and improve resource-use efficiency.

Ecosystem services: The broader value of carbon farming

The ecosystem service perspective is essential because carbon farming influences multiple ecological processes simultaneously. For agricultural systems, ecosystem services can be broadly organised into provisioning, regulating and supporting and cultural services.

Ecosystem services framework

A study was carried out for rice crops implementing seven establishing methods using a bottom-up methodology, in which ecosystem services were quantified experimentally and then transformed into monetary values. The assessment covered food, byproducts, pest control, soil formation, biological nitrogen fixation, nutrient mineralisation, hydrological flow, soil fertility, carbon flow, temperature regulation, air purification, and cultural services. This method is especially important to carbon farming because the



Field view of conservation agriculture practices



Field view of diversified cropping system under micro irrigation system at ICAR RCER, Patna



Ecosystem services framework

carbon benefit is simply one aspect of a much bigger ecological portfolio.

Provisioning value for food and by-products was ₹1.09–1.18 lakh/ha/yr for grain and ₹13,300–14,600/ha/yr for straw (2020 prices). Soil development was strongest under ZT-DSR (~370 earthworms/ha) and ZT-MTR (~363/ha), providing the highest economic return among systems. Nutrient mineralisation reached its optimum in ZT-DSR (1,887 kg N/ha/yr), while RPTR was around 66% lower, reducing the need for exogenous fertilizer. After accounting for residues, rhizodeposition, and GHG emissions (CH_4 + N_2O as CO_2-eq), carbon flow switched from negative under RPTR (approx -₹13,800/ha/yr) to positive under ZT-DSR. Temperature regulation (20 hot days >35 °C via evaporative cooling) and air purification (O_2 from photosynthesis) provided significant non-market benefits (about 36% and 29–30% of total ES value). The average ecosystem service value across systems was around ₹6.73 lakh/ha/yr (2020). Zero-till DSR represented a 9.3% benefit. These results demonstrate that conservation rice systems provide significant regulatory benefits in addition to farm-gate revenues. The study found temperature regulation of 36.2%, air purification 29.5%, food 18.3%, nutrient mineralisation 12.6%. Together these four services contributed 96.6% of total ecosystem service value. At the broader classification level:

- Provisioning services = 79.4%
- Regulation and maintenance = 20.3%
- Cultural services = 0.3%

Carbon credits and ecosystem service payments

Carbon credits are a realistic approach to convert some of the climate benefit into direct financial returns for farmers. The fundamental premise is straightforward. Verified emission reduction (or sequestration) equals baseline GHG emissions minus projected GHG emissions (or + net carbon stored). One carbon credit can be generated for each tonne of CO_2-equivalent (t CO_2e) that is accurately measured, reported, and validated using approved technique. After project creation, monitoring, verification, and revenue-sharing expenditures, the net amount that reaches the farmer is usually smaller.

However, ecosystem service value should not be confused with carbon-credit revenue. Ecosystem service value covers numerous advantages, whereas a carbon credit is a defined and confirmed climate benefit based on a specific carbon-market methodology. This distinction is important for scientific and policy discussions.

Opportunities for small and marginal farmers

India's fragmented landholding structure makes individual participation in carbon markets difficult.



Flowchart of earning carbon credits



Aggregation is therefore essential. Farmer Producer Organisations (FPOs) may provide aggregation of small holdings, training, provide input and machinery access, soil testing, establishing a carbon baseline, record keeping, providing MRV support, collaborative carbon-credit marketing. This method can lower transaction costs and make carbon farming more affordable to smallholders.

Sustainable Development Goals and carbon farming

Carbon farming can support multiple Sustainable Development Goals (SDGs) at the same time.

SDG 2: Zero Hunger: Sustainable food production can be supported by increased soil fertility, nutrient cycling, water-use efficiency, and climate resilience.

SDG 6: Clean Water and Sanitation: Reducing agricultural water demand can be achieved through improved soil structure, infiltration, groundwater recharge, and effective irrigation.

SDG 8: Decent Work and Economic Growth: Ecosystem service payments and carbon markets can offer additional revenue streams.

SDG 12: Responsible Consumption and Production: More sustainable production results from the effective use of energy, water, fertilisers, and crop residues.

SDG 13: Climate Action: Increased soil and biomass carbon and decreased CH_4 and N_2O emissions directly contribute to climate mitigation.

SDG 15: Life on Land: The health of terrestrial ecosystems is supported by increased landscape diversity, decreased degradation, and improved soil biological activity.

SDG 17: Partnerships for the Goals: Farmers, FPOs, researchers, government agencies, carbon-market organisations, and financial institutions must collaborate to scale carbon farming.

Proposed carbon farming-ecosystem service index

A future research framework can integrate these indicators into a Carbon Farming–Ecosystem Service Index (CFESI):

$$CFESI = \sum_{i=1}^{n} (x_i \times w_i)$$

Where x_i = normalised value of the i^{th} ecosystem service indicator (scaled, for example, between 0 and 1); w_i = weight assigned to that indicator (with $\sum w_i = 1$); n = total number of selected ecosystem service indicators.

Research priorities for India

***Long-term field trials*:** Long-term monitoring of carbon accumulation and ecosystem service responses rather than merely short-term measures is needed.

Carbon budgets at farm and landscape scale: Carbon flows should be estimated over crop cycles and landscapes, rather than just individual plots.

Soil carbon + GHG monitoring integration: Soil organic carbon cannot achieve climate advantages alone. Quantification of CO_2, CH_4 and N_2O emissions is also needed.

Digital monitoring: Remote sensing, GIS, proximal soil sensing, artificial intelligence and machine learning can all contribute to reduce monitoring costs and improve spatial carbon estimation.

Bundled payments for ecosystem services: Farmers might be paid for a variety of demonstrated environmental benefits, not just carbon.

SUMMARY

Carbon farming provides a practical route for Indian agriculture to raise productivity while storing more carbon in soil and biomass and cutting greenhouse gas emissions. Its ultimate value, however, is found in all aspects of ecosystem services produced, which includes providing, regulating, supporting, and cultural functions. The quantification and economic valuation of these ecosystem services allow a more comprehensive assessment of the environmental and economic benefits of sustainable farming systems. In the Indo-Gangetic Plains, zero-till direct-seeded rice had the highest total ecosystem-service value accounting for roughly 9% more than conventional puddled transplanted rice. This demonstrates that carbon farming is more than just a source of carbon credits; it is a multifunctional, ecosystem-based strategy that simultaneously improves soil formation, nutrient cycling, hydrological function, climate regulation, air purification, and resource-use efficiency, benefits that are invisible in traditional farm accounting but are critical for the long-term resilience of smallholder systems in India.

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