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Carbon Sequestration in Cereal-Legume Rotations: Building Climate-Smart Soils While Feeding the Nation

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Highlights

- Cereal-legume rotations enhance long-term soil organic carbon (SOC) stocks by 15–30 percent compared to continuous cereal systems.
- Microbial biomass carbon (MBC) acts as a sensitive early indicator of soil health improvement under diversified rotations.
- Conservation tillage combined with legume integration reduces SOC oxidation losses while sustaining productivity.
- Wheat Equivalent Yield (WEY) demonstrates that climate-smart rotations remain economically and nutritionally productive.
- Carbon farming under cereal-legume systems offers Indian farmers a route to additional income through carbon credits.

Summary

Climate change has placed an unusual responsibility on agriculture; the very sector that has long been blamed for greenhouse gas emissions is now expected to become a part of the solution. One of the most promising tools we have on our side is the soil itself. Indian soils, particularly in cereal-dominated systems like rice-wheat and maize-wheat, have been losing organic carbon for decades because of intensive tillage, residue burning, and a near absence of legumes in the cropping cycle. Bringing pulses back into rotation, whether it is chickpea, lentil, mungbean, or pigeonpea, is no longer just an agronomic recommendation; it is a climate-smart strategy. This article examines how cereal-legume rotations build long-term soil organic carbon, how microbial biomass carbon serves as an early warning system for soil health, and how reduced tillage multiplies the benefits. Importantly, productivity is not sacrificed; metrics such as Wheat Equivalent Yield show that diversified systems often outperform continuous cereals when nutrition and economics are factored in. For India, the message is clear: healthier soils, lower emissions, and stable yields can coexist on the same field.

Keywords: Carbon farming, cereal-legume rotation, soil organic carbon (SOC), microbial biomass carbon (MBC), conservation tillage, wheat equivalent yield (WEY), climate-smart agriculture.

Introduction

The rotation is profitable on paper, but underneath the surface, the soil is exhausted. Decades of intensive cropping have stripped Indian agricultural soils of much of their organic carbon. According to the Indian Council of Agricultural Research, more than 30 percent of the country's cultivated land has organic carbon levels below 0.5 percent, which is the threshold at which soil starts losing its productive capacity (Lal, 2018).

Simultaneously, the world is beginning to recognize that soil is not merely a medium for crop growth; it is the second largest terrestrial carbon sink after the oceans. The 4 per 1000 initiative launched at the COP21 Paris climate summit estimated that increasing soil organic carbon by just 0.4 percent annually could offset a substantial portion of global anthropogenic carbon dioxide emissions (Minasny *et al*., 2017). For Indian farmers, this is not just an environmental concept; it is the foundation of carbon farming, a system where farmers can earn incentives for the carbon they lock back into their fields.

Among all the practices that can sequester carbon, cereal-legume rotation stands out for one simple reason: it works without expensive inputs. Replacing a fallow season or a second cereal with a pulse crop changes the entire biology of the soil. Legumes fix atmospheric nitrogen, leave behind nitrogen-rich residues, support beneficial microbes, and break the disease and weed cycles that build up in monocultures. When this is paired with reduced tillage, the synergy is remarkable. This article looks at how SOC dynamics, microbial biomass carbon, and tillage interact in cereal-legume rotations and why the productivity argument, captured through Wheat Equivalent Yield, finally puts the food security debate to rest.

Long-Term Soil Organic Carbon (SOC) Dynamics

Soil organic carbon is the carbon held inside soil organic matter, and it is the single most reliable indicator of soil quality. Long-term experiments across India and the world show that cropping systems that include legumes consistently accumulate more SOC than those that do not. A meta-analysis by McDaniel *et al*. (2014) covering 122 studies found that adding a legume to a cereal-based rotation increased SOC by an average of 8.5 percent in topsoil layers, with much higher gains, often 15 to 30 percent, when the rotation was sustained for more than a decade.

There are three main reasons for this. First, legumes produce residues with a relatively narrow carbon to nitrogen ratio, usually between 15:1 and 25:1, which decompose at a moderate rate and feed microbial communities steadily rather than locking up nutrients. Second, the deep root systems of crops like pigeonpea and lentil push organic matter into subsoil layers where it is far less likely to be lost through oxidation. Third, the biological nitrogen fixation by Rhizobium symbionts reduces the dependence on synthetic urea, which itself is associated with significant carbon emissions during manufacturing and application.

Field data from the All India Coordinated Research Project on Cropping Systems shows that maize-chickpea and pearl millet-mungbean rotations under irrigated conditions can build SOC stocks at the rate of 0.3 to 0.6 tonnes per hectare per year in the upper 30 cm of soil (Ghosh *et al*., 2019). To put that in perspective, this means a one-hectare farm under such a rotation can lock up the equivalent of one to two tons of carbon dioxide every year, simply through better cropping decisions.

Microbial Biomass Carbon: The Living Pulse of the Soil

If SOC is the bank balance of the soil, microbial biomass carbon is the daily transaction record. Although MBC typically makes up only one to four percent of total SOC, it responds far more quickly to changes in management and is therefore considered the most sensitive early indicator of soil health (Singh and Gupta, 2018). Farmers and researchers can detect a shift in MBC within a single cropping season, while changes in total SOC may take five to ten years to become statistically visible.

In cereal-legume rotations, MBC values are routinely 25 to 60 percent higher than in continuous cereal monocultures. The reason is biological. Legume root exudates are rich in carbohydrates, amino acids, and signaling molecules that attract a wider diversity of beneficial microbes, including phosphate-solubilizing bacteria, mycorrhizal fungi, and free-living nitrogen fixers. When legume residues are returned to the soil rather than burned or removed, this microbial community gets a steady food supply, and the population multiplies.

This matters because microbes are the workforce behind nutrient cycling. They mineralize nitrogen, solubilize phosphorus, secrete enzymes, and physically bind soil particles into stable aggregates that protect carbon from being lost. A field with a strong microbial population is, in practical terms, a self-fertilizing and self-structuring ecosystem. Studies from ICAR-IISS Bhopal have demonstrated that maize-chickpea systems under integrated nutrient management recorded MBC values of 380 to 450 micrograms per gram of soil, compared to 220 to 260 micrograms in continuous maize plots fertilized only with urea (Mandal *et al*., 2020). The difference is not subtle; it is the difference between a soil that is alive and one that is merely a substrate.

Reduced Tillage: Multiplying the Carbon Gains

Conventional tillage, which includes deep ploughing and repeated harrowing, has been the standard practice in Indian agriculture for generations. It does prepare a fine seedbed, but it also exposes the soil to the atmosphere, breaks down macro-aggregates, and accelerates the oxidation of organic matter. Every pass of a cultivator essentially burns off carbon that took years to accumulate. Reduced tillage and zero tillage offer a different path.

When reduced tillage is combined with cereal-legume rotations, the carbon-building benefits multiply. Crop residues are left on or near the surface where they form a protective mulch, regulate soil temperature, conserve moisture, and serve as the slow-release carbon source for soil microbes. Aggregate stability improves, water infiltration increases, and runoff losses decline. Long-term trials at Punjab Agricultural University have shown that zero-till wheat following mungbean in a rice-mungbean-wheat rotation increased SOC in the 0–15 cm layer by 0.18 percent over six years, compared to almost no change under conventional tillage with the same crop sequence (Jat *et al*., 2019).

It is worth being honest about the challenges. Zero tillage requires a Happy Seeder or zero-till drill, which involves an upfront cost. Weed pressure can be different, and farmers used to the look of a freshly ploughed field need time to trust a system that leaves residues on the surface. But once the system is established, fuel costs drop, sowing windows widen, and yields typically stabilize within two to three seasons. Many progressive farmers in Punjab and Haryana who have adopted Happy Seeder technology after the residue burning bans have reported lower input costs alongside improving soil health.

System Productivity: Wheat Equivalent Yield Tells the Real Story

There is one objection that always comes up when farmers are asked to diversify their rotations: will I lose yield? It is a fair question. A farmer who has been growing rice and wheat for thirty years cannot be expected to switch to a legume on the basis of environmental arguments alone. This is where Wheat Equivalent Yield (WEY) becomes a powerful tool. WEY converts the yield of every crop in a rotation into its equivalent value in wheat, based on prevailing market prices, allowing a fair comparison of total system productivity across different cropping sequences.

The numbers are encouraging. In a five-year experiment at IARI New Delhi, a maize-chickpea rotation gave a WEY of 9.8 tonnes per hectare per year, while the conventional maize-wheat rotation gave 9.2 tonnes per hectare per year. The cereal-legume system matched and slightly exceeded the cereal-cereal system in productivity while using 40 percent less synthetic nitrogen fertilizer and improving SOC by 0.12 percent annually (Choudhary *et al*., 2021). Similar trends have been reported for pearl millet-chickpea rotations in Rajasthan, soybean-wheat in Madhya Pradesh, and rice-lentil in eastern India.
The table below summarizes the comparative performance of selected cereal-legume rotations against their cereal-cereal counterparts based on published Indian long-term experiments.

Table 1. Comparative system productivity and SOC dynamics under selected rotations

Cropping Rotation	Region	WEY (t/ha/yr)	SOC change (%/yr)	N saving (%)
Maize–Wheat (control)	North India	9.2	+0.02	—
Maize–Chickpea	North India	9.8	+0.12	40
Pearl millet–Chickpea	Rajasthan	6.5	+0.08	35

Cropping Rotation	Region	WEY (t/ha/yr)	SOC change (%/yr)	N saving (%)
Rice–Wheat (control)	Indo-Gangetic Plains	11.4	−0.05	—
Rice–Mungbean–Wheat	Punjab	12.1	+0.18	30
Soybean–Wheat	Madhya Pradesh	8.4	+0.10	45

Source: Compiled from Choudhary et al. (2021), Jat et al. (2019), Ghosh et al. (2019), and Mandal et al. (2020).

Putting Carbon Farming into Practice

For a farmer to actually adopt these systems, the recommendations must be practical and adapted to local conditions. Based on long-term research and on-farm experience, a few principles stand out.

1. Choose the right legume for your zone

In the Indo-Gangetic Plains, mungbean fits beautifully as a short-duration summer catch crop between wheat and rice. In central and southern India, chickpea and pigeonpea remain the workhorses of rabi and kharif legume rotations. In Rajasthan and other arid zones, mothbean, clusterbean, and chickpea perform well under low rainfall. Lentil suits eastern India's cooler rabi conditions.

2. Retain residues; do not burn them

Crop residues are the single biggest input of organic carbon a farmer has, and they cost nothing. Burning paddy or wheat straw destroys decades of soil-building potential in a few hours. Tools like the Happy Seeder, Super Seeder, and rotavator now make residue retention practical, even in rice-wheat systems.

3. Move toward reduced or zero tillage gradually

A complete shift to zero tillage in the first year can be risky. A staged transition, starting with reduced tillage in one season and zero tillage in the next, gives the soil and the farmer time to adjust. Custom hiring centers for zero-till drills make the technology more accessible to small landholders.

4. Combine with integrated nutrient management

Pairing legume rotations with farmyard manure, compost, vermicompost, or green manuring boosts SOC accumulation far beyond what either practice can achieve alone. The goal is not to abandon fertilizers but to use them in combination with biological inputs that feed the soil rather than just the crop.

5. Track soil health, not just yield

Soil health cards issued under the Government of India's Soil Health Card Scheme give farmers their starting numbers for organic carbon, available nitrogen, phosphorus, potassium, and micronutrients. Re-testing every two to three years allows farmers to see the gains from carbon-smart practices in measurable terms.

The Economic Case for Carbon Farming

Beyond the agronomic benefits, carbon farming is opening a new income stream for farmers. India's voluntary carbon markets, combined with international platforms, are increasingly willing to pay farmers for verified carbon sequestration. Pilot projects in Madhya Pradesh, Maharashtra, Punjab, and Haryana have started compensating farmers between Rs. 1,500 and Rs. 4,500 per hectare per year for adopting practices like zero tillage, residue retention, and legume integration. NABARD and several agritech companies are now building platforms that aggregate small farmers into carbon credit schemes that would otherwise be inaccessible to individual landholders. As these markets mature, cereal-legume rotations could generate not just better soils and stable yields but also a third source of income for the Indian farmer.

Conclusion

The case for cereal-legume rotations is no longer purely scientific; it is economic, ecological, and increasingly practical. By bringing pulses back into our cropping systems, retaining residues, and shifting toward reduced tillage, Indian farmers can rebuild the soil organic carbon their fields have been losing for decades. Microbial biomass carbon will respond within a single season, total SOC will climb steadily over the years, and Wheat Equivalent Yield will confirm that productivity does not have to be sacrificed for sustainability. In an era when climate change is no longer a distant threat but a daily reality on Indian farms, soil itself can be one of our most reliable allies. The science is clear, the technology is available, and the markets are beginning to reward those who act. What remains is the willingness to plant the next legume in the rotation, leave the residue on the field, and trust the soil to do what it has always quietly done, store carbon and sustain life.

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