

Carbon sequestration and its impact on agriculture

Abhinaba Samanta¹ and Ria Mukhopadhyay^{1*}

¹Department of Agriculture, Swami Vivekananda University,
Barrackpore, West Bengal

*Corresponding author email id: riam@svu.ac.in

Abstract:

Carbon sequestration, the process of capturing and storing atmospheric carbon dioxide (CO₂), has emerged as a critical strategy to mitigate climate change and its effects on agriculture. Soils, forests, and other ecosystems act as natural carbon sinks, holding vast potential for offsetting greenhouse gas emissions. In agriculture, carbon sequestration not only contributes to climate resilience but also enhances soil health, productivity, and sustainability.

Adopting practices like conservation tillage, agroforestry, cover cropping, and organic farming increases carbon storage in soils while improving water retention, nutrient cycling, and biodiversity. Additionally, integrating biochar and compost can further enhance soil organic carbon levels. These practices not only mitigate the negative effects of climate change, such as droughts and extreme weather events but also provide co-benefits like improved crop yields and reduced reliance on chemical inputs.

However, challenges remain, including the long-term stability of sequestered carbon, the economic feasibility for farmers, and the need for supportive policies. Advanced technologies, such as precision agriculture and remote sensing, can aid in monitoring carbon sequestration and ensuring sustainable implementation.

This paper explores the potential of carbon sequestration in transforming agriculture into a climate-positive industry while emphasizing the need for interdisciplinary collaboration among scientists, policymakers, and farmers.

Keywords: carbon dioxide, sequestration

1. Introduction

Rising atmospheric CO₂ is driving climate change; agriculture both emits GHGs and holds potential as a carbon sink. Carbon sequestration – the removal and durable storage of CO₂ in plants, soils or geological formations – helps limit climate warming. Two broad forms exist: natural (biological/terrestrial) sequestration via ecosystems (forests, grasslands, soils, oceans) and **engineered (artificial/technological)** sequestration (carbon capture technologies and land-use changes (Hogan et al.2024). In agricultural contexts, practices like cover cropping, agroforestry and no-till can boost soil organic carbon (SOC), partially offsetting emissions. Agricultural carbon sinks were long overlooked in climate policy, but recent studies highlight their large mitigation potential, especially in the Global South. For example, improved carbon management on farmland could sequester *up to 2.8 gigatonnes CO₂-eq per year by 2050* globally, reducing mitigation costs and even raising GDP through agricultural revenues. To realize these benefits, we must understand the types of sequestration, context-specific practices (e.g. in India), co-benefits, and the constraints on scaling them. Agriculture occupies a larger portion of global land area (about 35%) than any other human activity. Because of its scale and intensity, agriculture emits a large quantity of greenhouse gases into the atmosphere (Hutchinson, Campbell, Desjardins., et al. 2007). In India, agricultural land constitutes approximately 51.09% of the total geographical area. This translates to roughly 178.53 million hectares, or about 1,785,279 square kilometers.

Types of Carbon sequestration

Biological (Terrestrial) Carbon Sequestration: This encompasses carbon stored in living systems – plants, forests, grasslands, and soils – and is largely part of the natural carbon cycle(Lelechenko et al, 2024). For example, forests and wetlands act as vast carbon reservoirs; trees absorb CO₂ via photosynthesis and lock it in wood and roots, while soil microbes incorporate plant residues into SOC (Lelechenko et al, 2024). Terrestrial sequestration typically means using

photosynthesis (land plants) to draw down CO₂, storing organic carbon in biomass and soil. This differs from geological methods that inject human-emitted CO₂ underground.

Geological Carbon Sequestration: Involves capturing CO₂ (often from industrial or power-plant emissions) and injecting it deep underground into rock formations or depleted reservoirs. CO₂ is pressurized and pumped into porous rock (saline aquifers, old oil wells, unmineable coal seams, basalt) where it is trapped by physical and chemical processes. This form is potentially permanent (thousands of years) but requires engineered infrastructure and monitoring to prevent leakage.

Technological (Artificial) Carbon Sequestration: Refers to engineered methods to remove CO₂ from the atmosphere or emissions stream. Examples include direct air capture (DAC) (machines that chemically scrub CO₂ from ambient air and store it geologically), bioenergy with carbon capture and storage (BECCS) (growing biomass for energy and capturing the CO₂ produced), biochar (pyrolyzing biomass to stable charcoal added to soils), and other novel processes (e.g. electrochemical methods, engineered minerals) (Lelechenko et al, 2024). Technological methods are distinct from biological/land methods; they require high energy and investment but can potentially achieve “negative emissions” even from hard-to-abate sectors (Lelechenko et al. 2024).

Natural vs. Artificial Sequestration: Natural sequestration relies on ecosystems and the carbon cycle: e.g., forest regrowth, soil organic matter accumulation, and ocean uptake. Artificial (engineered) sequestration uses human-designed interventions: CO₂ capture systems, land use changes, or chemical enhancements (Lelechenko et al, 2024). Natural sinks are often cost-free but reversible (vulnerable to disturbance); artificial methods can be made permanent but are currently costly. In practice, many mitigation strategies combine both: e.g., agroforestry (natural vegetation) implemented as a deliberate climate measure (Nath et al. 2021), or biochar application (a technological product) to agricultural soil.

Carbon Sequestration in Agriculture: Importance and Practices in India

Agriculture is responsible for ~ 12 GtCO₂e/yr of global emissions, yet it also harbors large soil carbon reserves. India, with its vast farming population, stands to gain multiple benefits from soil and biomass carbon enhancement. Expanding carbon sinks in agriculture can help India meet its climate goals. For instance, modeling suggests that modest expansions of agroforestry on croplands could significantly offset India's projected emissions by 2050 (Nath et al. 2021). India's Nationally Determined Contributions (NDCs) call for additional carbon sinks from afforestation; incorporating agricultural practices like agroforestry directly supports these targets. Recognizing this, India launched a National Agroforestry Policy (2014) to boost tree cover in farming landscapes, aiming to meet timber, food, and fuel needs while creating carbon sinks. Large rural programs like MGNREGS (rural employment/land development) have built carbon sinks through soil and water conservation activities: one study estimated MGNREGS sequestered 102 MtCO₂ in 2017–18, rising to 249 MtCO₂ by 2030 (Murthy et al. 2021). Thus, agricultural carbon sequestration is increasingly seen as a climate–development strategy in India

Effective Agricultural Practices (India): Numerous farming practices can sequester carbon:

Conservation Agriculture (CA): No-till or reduced tillage, along with crop residue retention and crop rotation, preserve and build SOC (Kaur et al. 2023). Trials in the Indo-Gangetic Plains show that CA (zero-till, permanent beds) significantly increases soil carbon over time and also raises crop yields (Mishra et al., 2018). By minimizing soil disturbance and keeping organic matter on the field, CA is a key practice for Indian farmers.

Agroforestry: Integrating trees with crops (or livestock) vastly increases carbon stocks in biomass and soil. For example, agrosilvopastoral systems (crops+trees+livestock) in India's humid zones can capture far more carbon than conventional cropping (Nath, A.J. et al. 2021). Experts estimate that

expanding agroforestry area by just 5% every five years could offset India's projected 2050 emissions (Nath et al. 2021). In practice, alley cropping, farm shelterbelts, and multi-story cropping (e.g., coconut+pepper+banana) all sequester carbon while providing fruits, fodder and fuel.

Cover Crops and Crop Rotations: Sowing legumes or grasses in fallow periods adds root biomass and protects soil, boosting SOC. Rotations including pulses (mungbean, cowpea) increase below-ground carbon inputs and soil nitrogen. On Indian farms, adding cover legumes has improved yields and soil C in long-term trials (Hooper et al., 2005; Parihar et al., 2018).

Crop Residue Management: Avoiding burning and instead incorporating or mulching crop residues is crucial. Burning of rice/stubble is common in North India and leads to immediate carbon loss; conversely, retaining residues recycles carbon and nutrients. Along with improved nutrient management (balanced fertilization and organic amendments), this maintains SOC.

Organic Soil Amendments: Use of farmyard manure, compost, and biochar (charcoal from agricultural waste) enriches SOC and fertility. Biochar, in particular, is being studied in India as a way to lock stable carbon in soils (Rogelj, J. et al., 2018). Manure recycling also contributes a significant carbon sink in cropland.

Permanent Grasses and Pasture Improvement: In rangelands and orchard lands, maintaining vegetative cover year-round stores carbon. Sowing deep-rooted perennial grasses or improving grazing lands (by legume understory or rotational grazing) has been shown globally to sequester carbon (Rogelj, J. et al., 2018). In India, enriching common grazing lands or village pastures could similarly raise carbon stocks and fodder. (Nath et al. 2021)

Afforestation on Degraded Land: Planting trees on fallow or degraded fields (e.g. watershed plantations) builds biomass carbon. Even if not on prime cropland, such afforestation (e.g. under MGNREGS "drought proofing") provides carbon sinks and restores soil health. Over 2019–2025, India's MGNREGS

drought-proofing (tree planting) is projected to create an additional 281–561 MtCO₂ sink (Murthy et al. 2021).

These practices not only sequester carbon but also improve soil water retention, fertility, and farm incomes, creating co-benefits for farmers (Kaur et al. 2023)(Murthy et al. 2021). In the next section we detail the multiple co-benefits observed from agricultural carbon sequestration.

Co-benefits of Carbon Sequestration in Agriculture

Enhancing carbon in agricultural systems yields multiple side benefits beyond climate mitigation:

Improved Crop Yields and Food Security: Rising SOC generally improves soil fertility, water holding capacity and nutrient availability, directly boosting yields. For example, a world-wide analysis found that each 1 Mg/ha increase in SOC can increase cereal yields by tens of kg/ha (20–70 kg/ha wheat, 10–50 kg/ha rice, etc.), potentially adding tens of millions of tonnes of grain. Indian studies similarly report higher yields under no-till and residue management (Mishra et al., 2018). Thus, soil carbon gains support food production and incomes.

Soil Health and Fertility: Higher SOC improves soil structure and aggregation, reducing erosion and compaction. Improved soil moisture retention helps crops resist drought. Experts note that healthy soils enriched with organic carbon act like a sponge and “fertilizer”, reducing the need for synthetic inputs. Indeed, agroforestry and cover cropping enhance soil nutrients (via leaf litter and nitrogen fixation) and biological activity (Ravindranath, Murthy et al. 2021) (Ganeshamurthy and Srinivasarao, 2009; Hazra et al., 2018).

Livelihood and Economic Benefits: Carbon projects can provide income to farmers. Global modeling suggests that sequestration on cropland could generate up to \$375 billion in payments for carbon credits by mid-century (Frank, et al. 2024). In India, voluntary carbon markets are emerging for practices like agroforestry and rice-residue management (Chaudhary et al., 2020). Moreover, many carbon-enhancing practices (e.g. mulching, composting) often improve yields and reduce input costs, so farmers gain indirectly.

Ecosystem Services: Agroforestry and cover crops increase biodiversity (more habitat for birds, insects, microbes) and can reduce pest pressures. Vegetative cover prevents soil erosion and nutrient runoff, benefiting water bodies. Studies highlight that agroforestry provides habitat connectivity and reduces land degradation (Nath et al. 2021). In India's ecologically fragile areas, tree-based systems also support water infiltration and preserve topsoil.

Climate Resilience: Carbon-rich soils moderate temperature extremes and buffer against heavy rains or droughts. Vegetation (trees and perennial grasses) provides shade and windbreaks. Collectively, these co-benefits mean that carbon sequestration in agriculture often aligns with sustainable development goals, improving farm resilience and community well-being.

In summary, carbon-sequestering practices are often “no-regrets” from a farm perspective: they enhance productivity, soils, and livelihoods while also capturing CO₂ (Nath et al. 2021).

Mitigation Techniques via Carbon Sequestration

To harness carbon sequestration, a suite of mitigation techniques is employed:

Afforestation and Reforestation: Planting trees on non-forest land (afforestation) or replanting deforested areas (reforestation) creates large biomass carbon sinks. Although not strictly an “agricultural” practice, programs that convert marginal croplands or degraded lands into forests (e.g. shelterbelt plantations) provide carbon and ecosystem co-benefits. (However, care is needed: planted forests must be maintained for decades to be effective, as younger stands can be vulnerable to fire or harvest.

Agroforestry and Silvopasture: Integrating trees with crops/livestock sequester carbon in multiple pools. Silvopasture systems (trees in pasture) are included here. Techniques include alley cropping, windbreaks, fodder banks, and improved grazing. As noted, India's agroforestry has huge potential)(Nath,A.J. et al. 2021).

Conservation Tillage and Residue Management: No-till and strip-till systems leave crop residues on the surface, protecting soil carbon. Retaining or incorporating residues (rather than burning) increases SOC over time. Conservation agriculture is widely promoted in India for this reason (Mishra et al., 2018).

Cover Cropping and Crop Rotations: Growing legumes or grasses in the off-season adds organic matter to soil. Rotations with deep-rooted or high-residue crops (e.g. legumes, oilseeds, fodder cereals) improve carbon inputs. For example, adding mungbean or cowpea to rotations significantly raises SOC (Mishra et al., 2018).

Organic Amendments: Application of manure, compost or biochar (pyrolyzed organic waste) builds stable carbon in soil. Biochar is especially potent: studies show biochar can sequester carbon on decadal timescales while improving soil fertility (Frank, S., et al. 2024).

Grassland and Pasture Management: Improving grazing lands (reseed with mixed grasses, manage stocking rates) increases soil carbon. Maintaining perennial cover on grasslands stores more carbon than converting them to crops.

Blue Carbon (Wetland Restoration): Though less directly agricultural, restoring rice terraces, mangroves, and freshwater wetlands in farming landscapes can lock carbon in soils and biomass. (Coastal mangroves and paddy fields hold substantial “blue carbon”.)

Technology-Based CCS on Farms: Techniques like direct air capture (DAC) or industrial CO₂ capture are generally not farm-level practices but could complement decarbonization. For example, using crop residue bioenergy with CCS (BECCS) would remove CO₂. These are emerging and currently expensive.

Together, these mitigation techniques aim to increase carbon inputs or decrease carbon losses in soils and vegetation. By combining multiple practices (e.g. agroforestry + conservation tillage + residue retention), agricultural landscapes can become net carbon sinks while also improving productivity.

Factors Affecting Carbon Sequestration

Several factors influence how much carbon can be sequestered and how stable it is:

Land Management: Tillage intensity is critical. Frequent plowing accelerates soil organic matter breakdown and CO₂ release; conversely, no-till promotes accumulation (KAUR, R. et al. 2023) (Dey et al., 2020). Crop choice and residue handling also matter: high-biomass or deep-rooted crops contribute more carbon than shallow-rooted ones (Ganeshamurthy and Srinivasarao, 2009; Hazra et al., 2018).. Overgrazing or residue burning reduces SOC significantly. In India, decades of intensive cultivation have already depleted 30–75% of original SOC in arable soils, meaning management changes can potentially rebuild that loss.

Soil Properties: Soil texture and mineralogy affect carbon storage. Fine-textured (clay-rich) soils bind organic molecules more tightly, slowing decomposition (Mahbobeh, Hossein et al., 2019). Soils with higher cation exchange capacity also protect organic matter. Conversely, coarse sandy soils have lower carbon-holding capacity. Soil pH and fertility influence microbial activity: nutrient limitations or acidic conditions can limit biomass production or decomposition.

Climate and Environment: Temperature and moisture regimes drive decomposition rates and plant growth. Cooler, wetter climates tend to preserve SOC longer, whereas hot arid conditions promote rapid mineralization of organic matter. In India's tropical climate, high temperatures can limit stable carbon buildup unless organic inputs are large and continuous. Extreme events (drought, floods, storms) can also disrupt carbon stores.

Vegetation Type: Forests and perennial vegetation generally sequester more carbon than annual crops, due to larger biomass and litterfall. The species composition matters too: fast-growing trees capture carbon quickly but may turnover faster, while long-lived species store carbon longer. Mixed systems (diverse species) often outperform monocultures in sustained sequestration.

Disturbances and Land Use Change: Wildfires, pests, or disease outbreaks can release stored carbon back to the atmosphere. Land-use change (e.g. converting forest to cropland) is a major factor: it can instantly lose decades of soil carbon. Ensuring permanence of sequestration is a challenge; for instance, afforested land must be protected for generations, or the carbon will be released when trees die or burn.

Socio-economic and Policy Factors: Adoption of sequestration practices depends on farmers' access to credit, knowledge, and incentives. Policies (carbon markets, subsidies) can drive or hinder uptake. Inadequate measurement and verification capabilities also limit implementation; without robust monitoring, the carbon benefits may be uncertain. Thus, non-biophysical factors indirectly affect sequestration potential.

Overall, carbon sequestration is maximized under suitable climate–soil conditions and sustainable land management. Site-specific assessments are needed: for example, interventions on degraded soils often yield larger carbon gains than on already-rich soils. Understanding these factors helps target the most effective practices in each region.

Advantages and Limitations of Carbon Sequestration

Advantages:

Climate Mitigation: The primary benefit is reducing net CO₂ emissions. Agricultural sequestration can provide a large, cost-effective sink: studies suggest expanded farm carbon sinks could supply up to ~40% of AFOLU (agriculture, forestry & land use) mitigation needed for 1.5 °C targets by 2050 (Frank et al. 2024). Enhancing soil carbon works “with nature” to offset emissions that are otherwise hard to cut.

Co-benefits for Agriculture: As detailed above, increased soil carbon yields higher productivity and resilience. This “double dividend” helps convince policymakers and farmers, since mitigation is bundled with development gains (Nath., et al. 2021)

Economic Incentives: Carbon markets and payments can make sequestration economically attractive. Global analyses project multi-billion-dollar opportunities for farmers (e.g.

up to \$375 billion by 2050 under \$160/tCO₂) (Frank, S., et al. 2024). Income from carbon credits or cost savings on inputs (due to better soils) improves farm economics.

Biodiversity and Ecosystem Services: Sequestration practices often enhance biodiversity (e.g. mixed cropping, hedgerows) and ecosystem function (water retention, nutrient cycling). Improved soil health and forested areas also clean water and air. These ecosystem services, while not always quantifiable in carbon markets, have high societal value

Adaptation and Sustainability: Richer soils and vegetation cover help farms adapt to climate stress (drought, flood). By restoring degraded lands, sequestration measures secure long-term agricultural sustainability. For example, revitalizing overgrazed rangelands can restore productivity.

Limitations:

Permanence and Reversibility: Sequestered carbon can be re-emitted. In biological systems, carbon is not locked indefinitely – drought, fire, or change in management can reverse gains. For instance, an unmaintained plantation may burn down or be cut down, releasing its carbon. Geological storage, while more stable, carries a risk of leakage if not properly managed. Thus, sequestration requires long-term stewardship and monitoring.

High Costs and Technical Barriers: Some technologies (DAC, CCS infrastructure, biochar production) are expensive and energy-intensive. For example, direct air capture costs ~\$500–800 per ton of CO₂, making it unprofitable without high carbon prices or subsidies. Many farmers also lack the capital or knowledge to adopt advanced practices without support.

Land and Water Competition: Expanding afforestation or bioenergy crops can compete with food production or water use. If not carefully managed, “carbon farming” could inadvertently pressure land and water resources. Agroforestry mitigates this by combining uses, but large-scale tree planting still requires trade-offs (e.g. potential reduction in cereal area).

Measurement and Verification Challenges: Accurately quantifying soil carbon changes is technically difficult

and time-consuming (requires long-term trials and measurements) (Benbi and Senapati, 2010; Parihar et al., 2018). Carbon credit programs depend on verifiable data; without reliable methods, farmers may not be rewarded for sequestration.

Institutional and Policy Hurdles: Carbon sequestration in agriculture is not always recognized or incentivized in policy frameworks. Historically, agriculture has been excluded from emissions trading schemes due to complexity. Without clear markets or regulations, adoption is slower.

Saturation Effects: Soils have a finite capacity to sequester. After a period (often decades), a soil may reach a new equilibrium of SOC, limiting further uptake unless disturbed. This means sequestration rates typically decline over time in a given field.

In practice, these limitations mean sequestration is a supplement, not a substitute, for emissions reductions. Technological capture and negative-emission strategies must accompany aggressive emission cuts in the energy and industry sectors. However, the net balance of carbon sequestration (benefits minus any re-emissions) is overwhelmingly positive when practices are well-designed and managed.

Conclusion

Carbon sequestration in agricultural systems offers a powerful dual benefit: mitigating climate change while improving agricultural sustainability. Biological sequestration (through healthy soils, forests and agroecosystems) and engineered methods (e.g. CCS, biochar) together form a portfolio of strategies. In India and worldwide, practices like conservation agriculture, agroforestry, and residue management have demonstrated real-world potential to capture carbon and improve yields (Mishra et al., 2018). National programs (e.g. MGNREGS) and policies are increasingly recognizing these co-benefits (Murthy et al. 2021)

Nevertheless, realizing the full promise of carbon farming requires overcoming challenges – ensuring permanence, financing, and scientific monitoring. It also demands

aligning farmer incentives with environmental goals. When thoughtfully implemented, however, carbon sequestration can be a win-win, it helps meet climate targets while boosting soil fertility, crop productivity, and livelihoods. Continued research, innovation and supportive policy will be key. Future agricultural development in India and beyond will likely hinge on integrating carbon-smart practices into routine farm management, turning farms into part of the climate solution.

References

Hogan, J. A. et al. (2024). Climate change determines the sign of productivity trends in US forests. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, 121(4). <https://doi.org/10.1073/pnas.2311132121>.

Kaur R, Kaur N, Kumar S, Dass A, and Singh T. (2023) Carbon Capture and Sequestration for Sustainable Land Use – A Review. *The Indian Journal of Agricultural Sciences* 93 (1): 11–18. <https://doi.org/10.56093/ijas.v93i1.12483>

Frank S, Augustynczyk LD, Havlík A, et al. (2024) Enhanced agricultural carbon sinks provide benefits for farmers and the climate. *Nat Food* 5:742–753 <https://doi.org/10.1038/s43016-024-01039-1>

Hutchinson JJ, Campbell CA, Desjardins RL (2007) Some perspectives on carbon sequestration in agriculture <https://doi.org/10.1016/j.agrformet.2006.03.030>.

Sunquist E. et al. (2024) Carbon Sequestration to Mitigate Climate Change. U.S. Geological Survey (USGS)

Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. *Journal of Cleaner Production*, 281:124831.

Ravindranath NH, Murthy IK (2021) Mitigation co-benefits of carbon sequestration from MGNREGS in India. *PLoS One*. 20:16(5):e0251825. doi: 10.1371/journal.pone.0251825.

Mishra AK, Hitoshi S, Sahay JH, Lal JM, Kumar J, Shinya F (2024) Conservation agriculture enhances crop productivity and soil carbon fractions in Indo-Gangetic Plains of India, *Frontiers in Sustainable Food Systems*,

Rogelj J. et al. (2018) Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332.

Mahbobeh I, Sadeghi H (2019) Effects of soil texture and nitrogen on ability of carbon sequestration in different organs of two *Tamarix* species as a good choice for carbon stock in dry lands, *Ecological Engineering*. <https://doi.org/10.1016/j.ecoleng.2019.08.007>

Awale R, Emeson MA, Machado S (2017). Soil organic carbon pools as early indicators for soil organic matter stock changes under different tillage practices in inland Pacific northwest. *Front. Ecol. Evol.* 5:96. doi: 10.3389/fevo.2017.00096

Lal R (2004) Soil carbon sequestration to mitigate climate change, *Geoderma*, Volume 1231–2, <https://doi.org/10.1016/j.geoderma.2004.01.032>.