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Carbon Sequestration in Agricultural Soils: Opportunities and Challenges

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ABSTRACT

Agricultural soils represent a critical component of the global carbon cycle, serving as both sources and sinks of atmospheric carbon dioxide (CO_2). With the global soil organic carbon (SOC) pool estimated at approximately 1,500 petagrams of carbon (Pg C) in the top one meter, agricultural soils hold immense potential for climate change mitigation through enhanced carbon sequestration. This review paper examines the mechanisms, opportunities, and challenges associated with carbon sequestration in agricultural soils. Key practices including conservation tillage, cover cropping, agroforestry, biochar application, crop rotation, and organic amendments are discussed in terms of their effectiveness in enhancing SOC storage. The global sequestration potential of croplands is estimated between 0.90 and 1.85 Pg C per year through improved management practices. However, significant challenges persist, including the impermanence of stored carbon, difficulties in measurement, reporting, and verification (MRV), high implementation costs, farmer adoption barriers, and policy gaps. This review synthesizes current scientific evidence and highlights that an integrated approach combining technological innovation, supportive policies, carbon market development, and farmer education is essential to realize the full potential of soil carbon sequestration as a viable climate change mitigation strategy.

Keywords: *Carbon Sequestration; Soil Organic Carbon; Agricultural Soils; Climate Change Mitigation; Sustainable Agriculture.*

INTRODUCTION

Climate change represents one of the most pressing challenges confronting humanity in the twenty-first century. The Intergovernmental Panel on Climate Change (IPCC) has unequivocally established that reducing global greenhouse gas (GHG) emissions to net zero is imperative to halt global warming (IPCC, 2021).

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Among the various mitigation strategies, soil carbon sequestration has emerged as one of the most effective and scalable natural climate solutions. Agricultural soils, which cover approximately 50% of the potentially vegetated land surface globally, occupy a unique position in the carbon cycle—they can function as either net sources or net sinks of carbon depending upon management practices, biomass input levels, and climatic conditions (Sanderman et al., 2017). The global soil carbon pool to one-meter depth is estimated at approximately 2,500 Pg C, of which about 1,500 Pg C is soil organic carbon. This pool is roughly 3.2 times the size of the atmospheric carbon pool and four times that of the biotic pool (Batjes, 2016). Since the dawn of agriculture, cultivated soils have lost an estimated 50 to 70% of their original SOC stocks, contributing approximately 78 ± 12 Pg C to the atmosphere (Sanderman et al., 2017). This historical depletion, however, also represents an opportunity—by reversing these trends through improved agricultural management, soils can act as significant carbon sinks, capturing and storing atmospheric CO_2 (Lal, 2004).

The concept of carbon sequestration in agricultural soils involves the capture of atmospheric CO_2 through photosynthesis and its subsequent storage as soil organic matter (SOM). When carbon inputs to soils from plant residues, root exudates, and organic amendments exceed carbon losses from decomposition, erosion, and leaching, a net accumulation of SOC occurs (Minasny et al., 2017). Agricultural soils can potentially sequester 0.8 to 1.2 gigatons of CO_2 per year, which offers significant co-benefits including improved soil fertility, enhanced water retention, and greater ecosystem resilience (Shahzad et al., 2022).

This review paper aims to comprehensively examine the current state of knowledge regarding carbon sequestration in agricultural soils. It discusses the underlying mechanisms of soil carbon storage, evaluates the major agricultural practices that enhance sequestration, identifies the key opportunities and challenges, and provides recommendations for future research and policy directions.

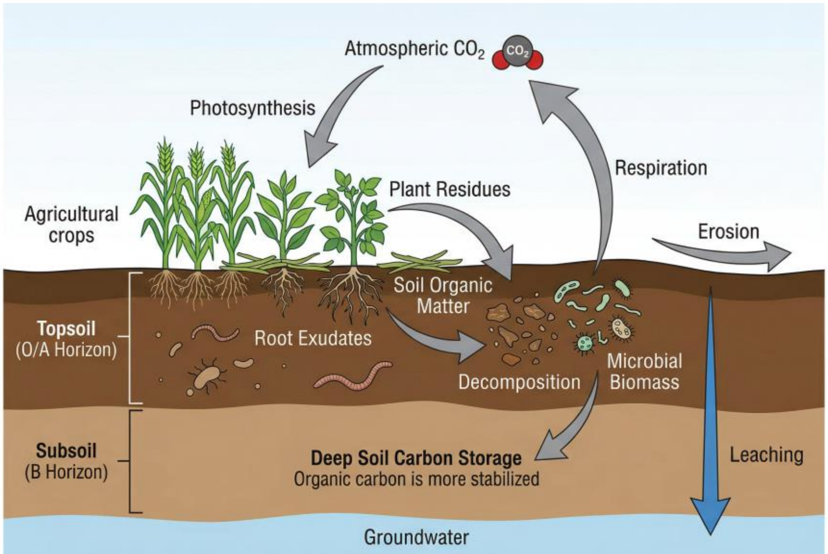

Figure1. The Soil Carbon Cycle in Agricultural Systems

2. Mechanisms of Soil Carbon Sequestration

Understanding the mechanisms through which carbon is stored in soils is fundamental to developing effective sequestration strategies. Soil carbon sequestration occurs through a complex interplay of physical, chemical, and biological processes that govern the transformation of plant-derived carbon into stable soil organic matter (Six et al., 2002).

2.1 Physical Protection

Physical protection of soil organic carbon occurs through occlusion within soil aggregates. Soil aggregation physically shields organic carbon from microbial decomposition by limiting the accessibility of decomposer organisms and extracellular enzymes to organic substrates (Six et al., 2002). Macro-aggregates (>250 µm) and micro-aggregates (53–250 µm) play distinct roles in carbon stabilization. Micro-aggregates, in particular, provide long-term protection due to their greater resistance to disruption. Soil structure and aggregation are hugely important to soil carbon storage and also contribute to water holding capacity and overall soil quality (Verbruggen et al., 2013).

2.2 Chemical Stabilization

Chemical stabilization involves the binding of organic carbon to mineral surfaces through adsorption onto clay particles and metal oxides. Soils with high clay content, particularly those rich in iron and aluminum oxides, have greater capacity to store carbon as mineral-associated organic matter (MAOM). This form of soil carbon is highly resistant to decomposition and can persist in soils for centuries to millennia (Lehmann & Kleber, 2015). The formation of organo-mineral complexes represents one of the most stable forms of carbon storage in terrestrial ecosystems.

2.3 Biological Processes

Biological processes, particularly microbial transformation, play a central role in soil carbon cycling. Soil microorganisms decompose plant residues and root exudates, converting them into microbial biomass and metabolic byproducts that contribute to the formation of stable humic substances (Kallenbach et al., 2016). Mycorrhizal fungi are especially important as they contribute significant amounts of carbon to the soil through their hyphal networks and play a critical role in redistributing carbon into protected soil pools. Sites with a large, diverse, and active soil microbial community have greater potential for long-term soil carbon storage (Frey, 2019).

3. Agricultural Practices for Enhanced Carbon Sequestration

Several agricultural management practices have been identified as effective strategies for enhancing soil carbon sequestration. The effectiveness of these practices varies depending on soil type, climate, crop systems, and management intensity.

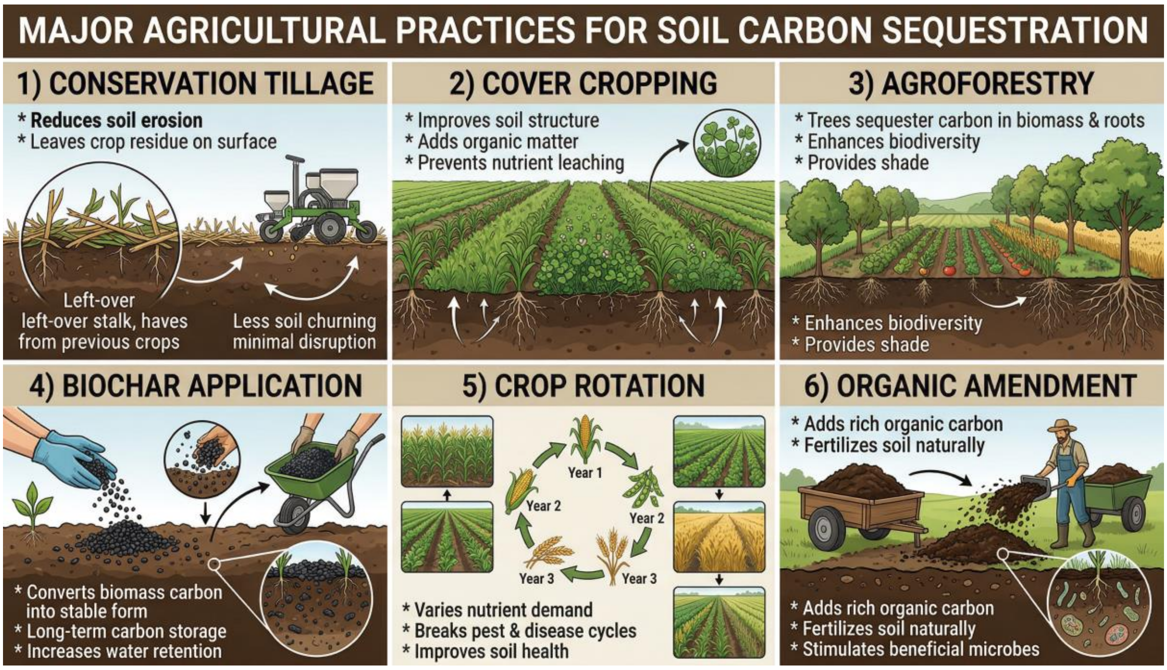

Figure2. Major Agricultural Practices for Soil Carbon Sequestration

3.1 Conservation Tillage

Conservation tillage, including no-till and reduced tillage systems, represents one of the most widely adopted practices for soil carbon sequestration. Transitioning from conventional tillage to no-till reduces the loss of soil carbon through multiple mechanisms: tillage enhances microbial activity due to aeration and disrupts soil aggregates which protect SOC from decomposition (Ogle et al., 2012). No-till farming promotes the formation of stable soil aggregates that physically protect organic carbon from microbial decomposition and improves soil porosity and water infiltration, creating a more favorable environment for carbon accrual (West & Post, 2002). The USDA Natural Resource Conservation Service reports expected carbon sequestration rates of approximately 0.31 MT/acre/year for no-till and 0.20 MT/acre/year for reduced tillage across most regions in the United States (USDA NRCS, 2021). Long-term studies confirm that most agricultural regions experience measurable increases in SOC when switching from conventional tillage to no-till systems (Powlson et al., 2014).

3.2 Cover Cropping

Cover crops increase soil organic carbon through multiple pathways: they add biomass carbon inputs through photosynthetically fixed carbon, improve protection for SOC through enhanced soil aggregation, and decrease carbon loss through reduced soil erosion (Poeplau & Don, 2015). Leguminous cover crops provide the additional benefit of biological nitrogen fixation, enriching the soil and reducing the need for synthetic fertilizers. Cover crop roots enhance soil aggregation and physically protect organic carbon, while above-ground biomass acts as a protective layer preventing carbon loss through erosion and runoff (Blanco-Canqui et al., 2015). Research has demonstrated cover crop carbon sequestration potential ranging from 0.04 to 0.4 MT/acre/year depending on biomass amount, years in cover crops, and initial soil carbon levels (Ruiz & Blanco-Canqui, 2017).

3.3 Agroforestry

Agroforestry, the integration of trees and shrubs into agricultural landscapes, represents a highly effective strategy for carbon sequestration. Trees sequester carbon in both above-ground biomass and below-ground root systems, while simultaneously enhancing SOC storage through increased litter inputs and root turnover (Zomer et al., 2016). Agroforestry systems can sequester significantly more carbon compared to conventional agricultural systems due to the complementary nature of tree and crop carbon inputs. The practice also enhances biodiversity, provides shade for livestock, reduces wind erosion, and creates diversified income streams for farmers (Nair et al., 2009).

3.4 Biochar Application

Biochar, a carbon-rich material produced through the pyrolysis of organic biomass, has emerged as a promising tool for long-term soil carbon sequestration. Unlike most forms of organic carbon that decompose relatively rapidly, biochar’s highly aromatic structure resists microbial decomposition, enabling it to persist in soils for centuries to millennia (Lehmann et al., 2011). Biochar application offers multiple co-benefits including improved nutrient retention, enhanced water holding capacity, increased cation exchange capacity, and support for microbial diversity (Do Nascimento et al., 2023). Studies have demonstrated that biochar can stabilize approximately 50% of the carbon in biomass, significantly outperforming direct land application or burning of crop residues. A biochar study on cadmium remediation demonstrated 33.73 t CO_2 eq/ha of carbon sequestration, illustrating the dual environmental benefits of this approach (Lehmann & Joseph, 2015).

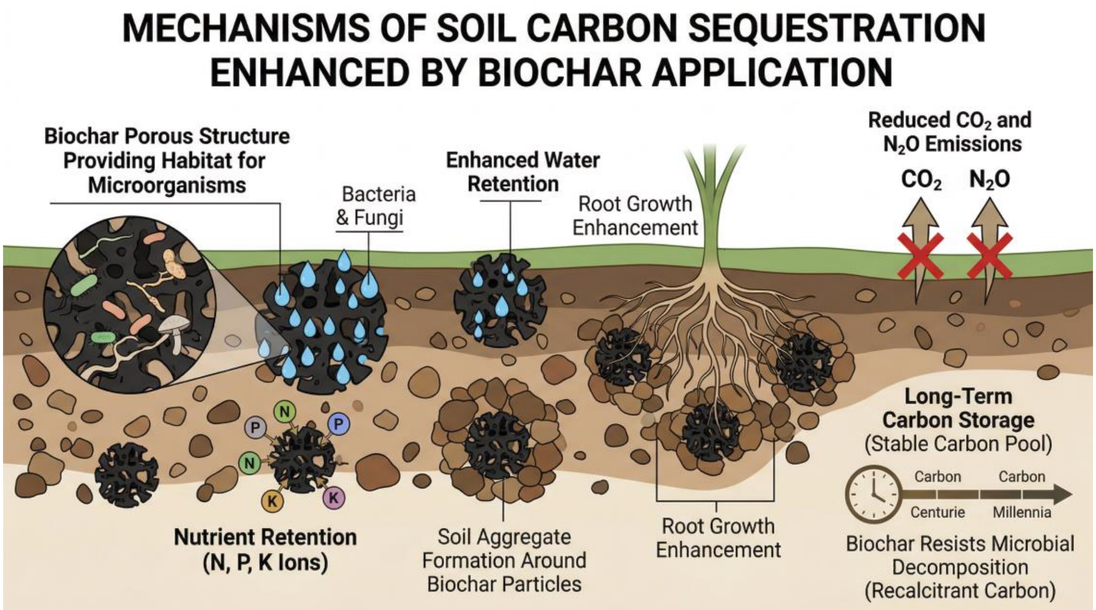

Figure3. Mechanisms of Soil Carbon Sequestration Enhanced by Biochar Application

3.5 Crop Rotation and Diversification

Implementing diverse crop rotations enhances soil carbon sequestration by varying root architecture, biomass inputs, and nutrient cycling patterns throughout the growing season. Rotating between high-residue crops such as corn and wheat with leguminous crops optimizes both carbon and nitrogen inputs to the soil (Lal, 2004). Diverse rotations improve soil biodiversity, break pest and disease cycles, and contribute to greater soil organic matter accumulation over time. The integration of perennial crops and deep-rooted species in rotation systems further enhances below-ground carbon inputs, as deeper roots deposit organic carbon at greater soil depths where decomposition rates are slower (Paustian et al., 2016).

3.6 Organic Amendments

The application of organic amendments including compost, farmyard manure, and crop residues directly adds organic carbon to soils and stimulates biological activity that promotes SOC stabilization. Organic amendments improve soil structure, enhance microbial biomass, and increase the formation of stable organo-mineral complexes (Nelson & Sommers, 1996). Integrated nutrient management that combines organic amendments with judicious use of mineral fertilizers optimizes both crop productivity and soil carbon storage. These practices also reduce dependence on synthetic chemical inputs, contributing to overall agricultural sustainability (Schlesinger & Amundson, 2019).

Table1. Estimated Carbon Sequestration Rates of Various Agricultural Practices

Agricultural Practice	Sequestration Rate	Key Reference
No-till Farming	0.31 MT/acre/year	USDA NRCS (2021)
Reduced Tillage	0.20 MT/acre/year	USDA NRCS (2021)
Cover Crops	0.04–0.4 MT/acre/year	Blanco-Canqui et al. (2015)
Agroforestry	0.5–3.5 t C/ha/year	Nair et al. (2009)
Biochar Application	1.0–1.8 t C/ha/year	Lehmann et al. (2011)
Organic Amendments	0.3–0.6 t C/ha/year	Schlesinger & Amundson (2019)

4. Opportunities

4.1 Climate Change Mitigation

Soil carbon sequestration offers a powerful natural solution for climate change mitigation. Recent estimates suggest that by 2050, agricultural soils could remove up to five gigatons of CO_2 annually from the atmosphere (Fuss et al., 2018). A geospatial analysis by Zomer et al. (2017) estimated that croplands worldwide could sequester between 0.90 and 1.85 Pg C/year through improved management, representing 26–53% of the aspirational target of the '4 per 1000 Initiative' for food security and climate. The sequestration potential varies by region, with North America, South Asia, and Europe showing the highest total potential for soil carbon storage on croplands.

4.2 Enhanced Soil Health and Agricultural Productivity

Carbon sequestration directly improves soil physical, chemical, and biological properties. Organic carbon-rich soils exhibit enhanced soil structure, improved porosity, greater water retention capacity, and increased nutrient availability (Shahane & Shivay, 2021). These improvements translate to higher crop yields, reduced irrigation requirements, and enhanced resilience to drought and flooding events. The economic benefits for farmers extend beyond productivity gains to include reduced input costs through decreased dependence on synthetic fertilizers and improved water use efficiency (Bot & Benites, 2005).

4.3 Carbon Markets and Economic Incentives

The emergence of voluntary carbon markets has created new economic opportunities for farmers who adopt carbon-sequestering practices. Programs such as those developed by Indigo Carbon, Nori, and the Ecosystem Services Market Consortium work with farmers to implement practices that sequester carbon, provide measurement and verification of carbon offsets, and sell those offsets to buyers interested in compensating for their carbon emissions (Ritter & Treakle, 2020). These market mechanisms offer supplemental revenue streams that can incentivize the widespread adoption of sustainable agricultural practices. Additionally, government programs and payment-for-ecosystem-services schemes are increasingly supporting farmers in their transition to carbon-sequestering management systems (Paustian et al., 2016).

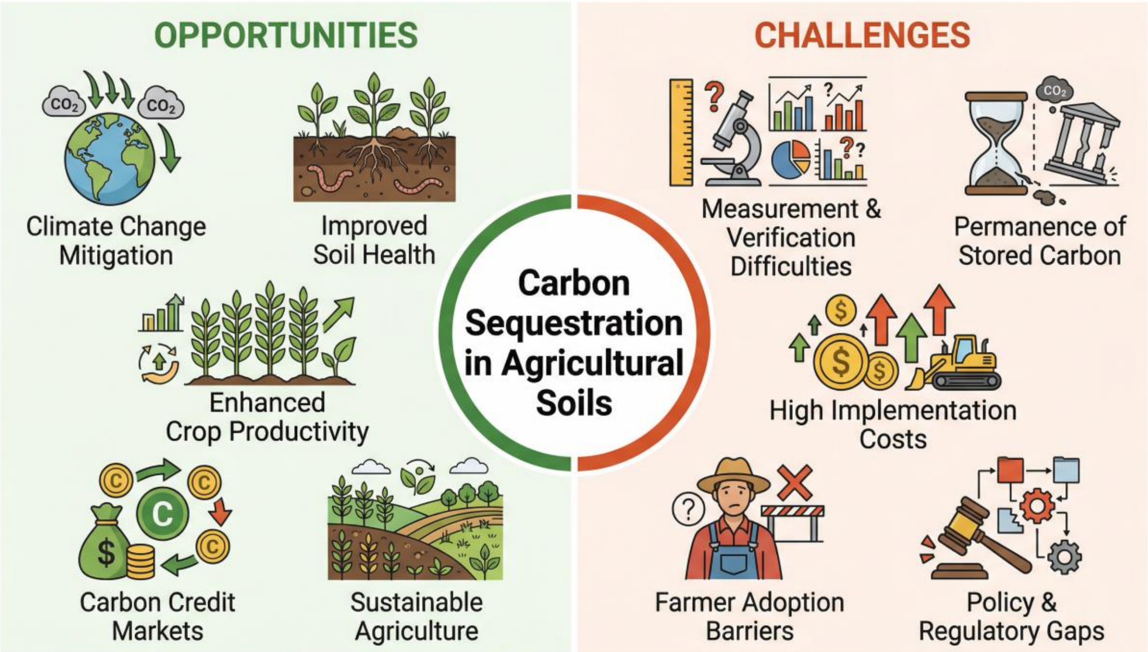

Figure4. Opportunities and Challenges of Carbon Sequestration in Agricultural Soils

5. Challenges

5.1 Permanence and Reversibility

One of the most significant challenges associated with soil carbon sequestration is the issue of permanence. Unlike geological carbon storage, soil carbon is inherently impermanent—carbon may be rapidly released back to the atmosphere if the practices used to sequester it are discontinued (Thamo & Pannell, 2016). A return to conventional tillage following no-till, for example, can reverse decades of accumulated carbon gains within a few years. Furthermore, soil carbon sequestration follows a saturation curve, increasing at a decreasing rate, with finite storage potential that can only be exploited once. This characteristic poses significant challenges for both carbon market design and long-term climate mitigation planning.

5.2 Measurement, Reporting, and Verification (MRV)

Accurate measurement of soil carbon changes remains technically challenging and economically costly. Given that soils already contain large background stocks of carbon, detecting small incremental changes requires high-precision sampling and analytical methods (Smith et al., 2020). Direct soil sampling and laboratory analysis through dry combustion provides the most accurate measurements but is expensive and time-consuming. Advanced methods including Eddy Covariance flux towers and near-infrared spectroscopy (NIRS) are being developed to provide more cost-effective monitoring solutions (Van Wesemael et al., 2023). However, high transaction costs make it infeasible to sample every field in carbon programs, necessitating heavy reliance on biogeochemical modeling to predict soil carbon sequestration, which introduces additional uncertainty.

5.3 Farmer Adoption Barriers

Despite the demonstrated benefits of carbon-sequestering practices, farmer adoption remains limited due to multiple barriers. These include unfamiliarity with new practices, concerns about implementation costs and potential yield penalties during transition periods, and uncertainty about long-term economic returns (Prokopy et al., 2019). Survey data indicates that farmers identify low compensation levels, excessive paperwork, and the 'black box' nature of carbon credit calculations as major deterrents to participation in carbon markets. Additionally, the focus on additionality in carbon programs—requiring farmers to implement new practices rather than rewarding those already using sustainable methods—creates significant equity concerns and can be a major source of farmer frustration (Ritter & Treakle, 2020).

5.4 Policy and Institutional Gaps

Effective scaling of soil carbon sequestration requires comprehensive policy frameworks that align agricultural, environmental, and climate objectives. Current policy landscapes in many countries lack coherent integration of carbon sequestration goals into agricultural support programs (Freibauer et al., 2004). Issues of land tenure, particularly in developing countries, create additional barriers as farmers without secure land rights have little incentive to invest in long-term soil improvement practices. Furthermore, inconsistent carbon accounting methodologies and the absence of standardized protocols for measuring and crediting soil carbon make it difficult to develop robust and credible carbon market mechanisms at scale (Lal et al., 2015).

5.5 Trade-offs and Environmental Risks

Storing additional organic carbon in soils can sometimes lead to unintended trade-offs, including increased nitrogen and phosphorus leaching that reduces water quality, or elevated emissions of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4). These effects have been documented particularly in organic soils during peatland rewetting and in mineral soils through the application of exogenous organic matter (Valkama et al., 2024). Understanding and managing these trade-offs is essential for ensuring that carbon sequestration efforts deliver net positive climate benefits without compromising other environmental objectives.

6. Future Research Directions

Future research should focus on several key areas to advance the science and practice of soil carbon sequestration. First, the development of cost-effective monitoring technologies, including remote sensing and machine learning approaches, is needed to improve MRV systems and reduce transaction costs in carbon programs. Second, long-term field experiments across diverse agro-climatic zones are essential for establishing reliable baseline data on sequestration rates and understanding the interactions between management practices, soil types, and climate conditions (Paustian et al., 2016). Third, research into optimizing biochar production methods for different soil types and developing integrated management strategies that combine multiple carbon-sequestering practices simultaneously will help maximize sequestration potential. Finally, socio-economic research on farmer decision-making processes, incentive design, and institutional arrangements is critical for developing effective programs that achieve broad participation and sustained adoption of carbon-sequestering practices.

CONCLUSION

Carbon sequestration in agricultural soils represents a significant opportunity for addressing climate change while simultaneously improving agricultural sustainability and productivity. The global soil carbon pool, estimated at approximately 1,500 Pg C of organic carbon, and the historical depletion of 50–70% of SOC in cultivated lands indicates substantial capacity for re-sequestration through improved management practices. Conservation tillage, cover cropping, agroforestry, biochar application, crop rotation, and organic amendments each contribute to enhanced soil carbon storage, with global cropland sequestration potential estimated at 0.90–1.85 Pg C per year.

However, realizing this potential requires overcoming significant challenges including the impermanence of stored carbon, the high costs and technical difficulties of measurement and verification, barriers to farmer adoption, and gaps in policy and institutional support. The development of robust carbon markets, supported by standardized MRV protocols and adequate farmer compensation, will be essential for scaling sequestration efforts.

Carbon sequestration is a win-win approach toward addressing climate change, maintaining agricultural productivity, and enhancing soil health (Raihan, 2023). An integrated strategy that combines technological advancement, favorable government incentives, well-informed farmer engagement, and continued scientific research can facilitate the large-scale adoption of carbon-sequestering practices. By embedding these practices within broader sustainable agricultural frameworks, the global community can leverage agricultural soils as a powerful tool in the fight against climate change while building more resilient and productive food systems for future generations.

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