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Soil carbon sequestration and regenerative agriculture: A pathway to climate-resilient farming

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Abstract

Climate change, land degradation, and increasing pressure on natural resources pose significant challenges to the sustainability and resilience of global agricultural systems. Soil carbon sequestration has emerged as a vital strategy for mitigating climate change while enhancing soil health and agricultural productivity. Regenerative agriculture, based on principles of soil restoration, biodiversity enhancement, and ecosystem regeneration, provides an effective framework for increasing soil organic carbon and building climate-resilient farming systems. This article examines the role of regenerative agricultural practices—such as conservation tillage, cover cropping, crop diversification, organic amendments, and integrated crop-livestock systems—in promoting soil carbon sequestration. The mechanisms through which enhanced soil carbon improves soil structure, water retention, nutrient cycling, and microbial activity are discussed, highlighting their contribution to increased resilience against climate-induced stresses. The article further explores the potential of regenerative agriculture to reduce greenhouse gas emissions, improve farm productivity, and strengthen food security. Policy support, farmer participation, and research-driven innovations are emphasized as essential enablers for scaling regenerative practices and achieving long-term sustainability and climate resilience in agricultural landscapes.

Keywords: Soil carbon sequestration, regenerative agriculture, climate resilience, soil health, sustainable farming

1. Introduction

Agriculture is both a major contributor to and a victim of global climate change, facing unprecedented challenges arising from rising temperatures, erratic rainfall patterns, frequent droughts and floods, and increasing soil degradation. These climate-induced stresses are intensifying pressure on farming systems worldwide, particularly in regions already constrained by limited natural resources and fragile ecosystems. Conventional agricultural practices, characterized by intensive tillage, monocropping, excessive reliance on synthetic inputs, and poor residue management, have significantly depleted soil organic carbon stocks and weakened soil structure. As a result, soils have become less resilient to climatic extremes, leading to declining productivity, reduced water-use efficiency, and increased vulnerability of farming systems. Addressing these interconnected challenges requires innovative approaches that not only sustain crop yields but also restore ecosystem functions and enhance climate resilience.

Soil carbon sequestration has gained global recognition as a critical climate mitigation and adaptation strategy within agricultural landscapes. Soils represent the largest terrestrial carbon reservoir, holding more carbon than the atmosphere and vegetation combined. Even modest increases in soil organic carbon can have profound impacts on atmospheric carbon dioxide concentrations while simultaneously improving soil fertility, water retention, and biological activity. By capturing atmospheric carbon dioxide through plant photosynthesis and storing it in stable soil organic matter fractions, agricultural soils can serve as effective carbon sinks. However, the potential of soils to sequester carbon has been substantially reduced by decades of extractive farming practices, emphasizing the urgent need for management systems that rebuild soil carbon stocks in a sustainable and scalable manner.

Regenerative agriculture has emerged as a promising paradigm capable of reversing soil degradation while enhancing carbon sequestration and climate resilience. Rooted in ecological

principles, regenerative agriculture seeks to regenerate soil health, increase biodiversity, and strengthen ecosystem services rather than merely sustaining current levels of productivity. Practices such as reduced or zero tillage, continuous soil cover through cover crops, diversified crop rotations, organic amendments, agroforestry, and integrated crop-livestock systems play a central role in restoring soil structure and promoting biological activity. These practices enhance carbon inputs to the soil, reduce carbon losses, and stimulate microbial processes that stabilize organic carbon in soil aggregates. By improving soil porosity and water-holding capacity, regenerative systems enable crops to better withstand droughts, floods, and temperature extremes, thereby increasing overall system resilience.

Beyond environmental benefits, soil carbon sequestration under regenerative agriculture offers substantial agronomic and socio-economic advantages. Increased soil organic carbon enhances nutrient cycling and availability, reduces dependency on external inputs, and improves crop productivity and profitability over time. Healthier soils support diverse microbial communities that contribute to disease suppression and nutrient transformation, further strengthening crop performance. Moreover, regenerative agriculture aligns closely with global food security objectives by promoting stable yields, reducing production risks, and supporting long-term land productivity. As climate change continues to threaten global food systems, integrating soil carbon sequestration strategies into mainstream agricultural practices becomes increasingly essential.

Despite its potential, the adoption of regenerative agriculture remains limited due to barriers such as knowledge gaps, short-term economic considerations, policy constraints, and lack of measurable incentives for carbon sequestration. Bridging these gaps requires coordinated efforts involving scientific research, policy frameworks, farmer engagement, and technological innovation. Carbon markets, incentive-based schemes, and site-specific management recommendations can play a vital role in encouraging widespread adoption. In this context, the present article explores the role of soil carbon sequestration within regenerative agriculture as a pathway to climate-resilient farming, highlighting key practices, underlying mechanisms, benefits, and future prospects for sustainable agricultural development.

2. Soil Carbon Sequestration: Processes, Potential, and Climate Significance

Soil carbon sequestration refers to the process of capturing atmospheric carbon dioxide through plant photosynthesis and storing it in the soil in the form of soil organic carbon (SOC). This process occurs when carbon fixed by plants is transferred to the soil through root exudates, crop residues, leaf litter, and organic amendments, where it becomes incorporated into soil organic matter. Soil organic carbon exists in various pools, ranging from labile fractions that are rapidly decomposed by microorganisms to more stable fractions that can remain in the soil for decades or even centuries. The stabilization of carbon is strongly influenced by soil texture, mineral composition, aggregation, microbial activity, and land management practices. Practices that enhance carbon inputs while minimizing losses through oxidation and erosion are therefore central to effective soil carbon sequestration.

The sequestration potential of agricultural soils is substantial, particularly in degraded or carbon-depleted systems. Intensive

tillage, residue removal, monocropping, and excessive use of synthetic fertilizers have historically accelerated the decomposition of organic matter and increased carbon emissions from soils. In contrast, improved soil management practices can reverse these trends by increasing carbon inputs and promoting physical and biochemical stabilization mechanisms. Reduced tillage limits soil disturbance and slows organic matter oxidation, while crop residues and cover crops provide continuous carbon inputs. Soil aggregation plays a crucial role by physically protecting organic carbon within microaggregates, making it less accessible to microbial decomposition. Additionally, interactions between organic compounds and soil minerals, especially in clay-rich soils, contribute to long-term carbon stabilization.

From a climate change perspective, soil carbon sequestration represents a dual-benefit strategy by mitigating greenhouse gas emissions while enhancing climate adaptation. Increasing SOC levels improves soil structure, porosity, and water-holding capacity, enabling soils to better retain moisture during droughts and drain excess water during heavy rainfall events. These properties enhance crop resilience to climate extremes, reducing yield variability under stress conditions. Moreover, soils rich in organic carbon support diverse and active microbial communities that improve nutrient cycling and reduce nitrous oxide emissions by enhancing nitrogen-use efficiency. Thus, soil carbon sequestration not only contributes to climate mitigation but also strengthens the adaptive capacity of agricultural systems.

Despite its recognized benefits, the rate and permanence of soil carbon sequestration are influenced by environmental conditions and management consistency. Carbon gains can be reversed if regenerative practices are discontinued, emphasizing the need for long-term commitment and supportive policy frameworks. Advances in soil carbon measurement, modeling, and monitoring technologies are improving the ability to quantify sequestration outcomes, which is critical for integrating soil carbon into climate-smart agriculture programs and carbon credit mechanisms. Harnessing the full potential of soil carbon sequestration requires a systems-based approach that integrates ecological principles with site-specific management strategies.

3. Regenerative Agriculture: Principles and Practices for Carbon-Rich Soils

Regenerative agriculture is an ecologically grounded farming approach that aims to restore and enhance soil health, biodiversity, and ecosystem functionality while maintaining profitable agricultural production. Unlike conventional or even sustainability-focused systems that often prioritize yield maintenance, regenerative agriculture emphasizes rebuilding natural capital, particularly soil organic matter and biological diversity. Central to this approach is the recognition that healthy soils are living systems whose physical, chemical, and biological components interact to regulate productivity and resilience. By fostering these interactions, regenerative agriculture creates conditions conducive to increased soil carbon sequestration and long-term climate resilience.

Key principles of regenerative agriculture include minimizing soil disturbance, maintaining continuous soil cover, increasing plant diversity, keeping living roots in the soil for as long as possible, and integrating livestock where appropriate. Reduced or no-tillage practices help preserve soil structure and protect organic carbon from rapid oxidation. Continuous soil cover

through crop residues, mulches, or cover crops reduces erosion, moderates soil temperature, and enhances microbial activity. Diverse crop rotations and intercropping systems increase the quantity and diversity of organic inputs, stimulating soil microbial communities and improving nutrient cycling. The presence of living roots throughout the year supports rhizosphere processes that enhance carbon input and microbial-mediated stabilization of organic matter.

The integration of organic amendments such as compost, farmyard manure, green manures, and biochar further enhances regenerative outcomes by directly increasing soil carbon stocks and improving soil fertility. Agroforestry and perennial cropping systems contribute additional carbon through woody biomass and deep root systems, which deposit carbon at greater soil depths where it is more stable. Integrated crop-livestock systems recycle nutrients efficiently and promote carbon accumulation through manure inputs and improved pasture management. Collectively, these practices create synergistic effects that enhance soil carbon sequestration while improving water-use efficiency, nutrient availability, and crop productivity.

Beyond biophysical benefits, regenerative agriculture offers socio-economic advantages that support farmer livelihoods and food security. Improved soil health reduces reliance on external inputs such as synthetic fertilizers and pesticides, lowering production costs and environmental risks. Enhanced resilience to climate stress reduces yield fluctuations and production risks, contributing to stable farm incomes. Moreover, regenerative systems align with emerging policy and market incentives focused on ecosystem services, including carbon sequestration and biodiversity conservation. However, widespread adoption requires access to knowledge, extension services, financial support during transition periods, and policy frameworks that reward long-term environmental stewardship.

In the context of climate-resilient farming, regenerative agriculture provides a practical and scalable pathway to restoring soil carbon while sustaining agricultural productivity. By aligning agricultural practices with natural processes, regenerative systems enhance the capacity of soils to function as carbon sinks and buffers against climate extremes. When supported by research, policy incentives, and farmer-centered approaches, regenerative agriculture has the potential to transform conventional farming systems into resilient, carbon-rich agroecosystems capable of meeting future food security and climate challenges.

4. Role of Soil Microbial Communities in Carbon Sequestration and Regenerative Systems

Soil microbial communities play a central role in regulating soil carbon dynamics and determining the success of regenerative agriculture systems. Microorganisms, including bacteria, fungi, actinomycetes, and archaea, are responsible for the decomposition, transformation, and stabilization of organic carbon inputs in soil. Through processes such as mineralization, humification, and aggregation, microbes convert plant-derived carbon into microbial biomass and stable soil organic matter fractions. Fungal networks, particularly arbuscular mycorrhizal fungi, contribute significantly to carbon sequestration by transferring carbon from plant roots into soil aggregates and producing recalcitrant compounds such as glomalin, which enhance soil structure and long-term carbon stabilization. The diversity and functional composition of microbial communities influence whether carbon is rapidly respired back to the atmosphere or retained in stable soil pools.

Regenerative agricultural practices strongly influence microbial activity and diversity by creating favorable soil conditions. Reduced tillage preserves microbial habitats and fungal hyphal networks, while continuous organic inputs from cover crops, residues, and organic amendments provide substrates that sustain microbial metabolism. Diverse crop rotations and intercropping systems enhance microbial functional diversity by supplying a wide range of root exudates that stimulate different microbial groups. These biologically active soils exhibit higher carbon-use efficiency, meaning a greater proportion of carbon inputs are converted into stable organic matter rather than lost as carbon dioxide. In addition, enhanced microbial interactions improve nutrient cycling, reduce nutrient losses, and support plant health, creating a positive feedback loop between soil biology and carbon sequestration.

Microbial-mediated carbon stabilization is further enhanced through physical protection mechanisms such as aggregate formation and biochemical processes involving microbial by-products. Microbial necromass, which consists of dead microbial cells and residues, is now recognized as a major contributor to stable soil organic carbon. These residues bind with soil minerals and become occluded within aggregates, contributing to long-term carbon storage. Understanding and managing soil microbial communities through regenerative practices is therefore essential for maximizing soil carbon sequestration and building climate-resilient agricultural systems.

Table 1: Major Regenerative Agricultural Practices and Their Role in Soil Carbon Sequestration

Regenerative Practice	Description	Effect on Soil Carbon
Conservation tillage	Reduced or zero soil disturbance	Minimizes carbon loss and improves carbon stabilization
Cover cropping	Growing crops during fallow periods	Increases carbon inputs through biomass addition
Crop diversification	Inclusion of multiple crop species/rotations	Enhances below-ground carbon allocation
Organic amendments	Application of compost, manure, crop residues	Directly increases soil organic carbon
Agroforestry	Integration of trees with crops	Long-term carbon storage in biomass and soil
Integrated crop-livestock systems	Managed grazing with cropping	Enhances nutrient cycling and carbon inputs

Table 2: Mechanisms of Soil Carbon Sequestration under Regenerative Agriculture

Mechanism	Process Involved	Impact on Soil Health
Aggregate formation	Binding of soil particles by organic matter and microbes	Improves soil structure and carbon protection
Microbial carbon stabilization	Conversion of plant residues into stable microbial by-products	Enhances long-term carbon storage
Reduced oxidation	Limited exposure of soil carbon to oxygen	Slows decomposition rates
Root-derived carbon inputs	Carbon deposition from root exudates	Improves rhizosphere carbon pools
Mineral-associated organic matter	Carbon binding to clay and silt particles	Increases carbon persistence

Table 3: Benefits of Increased Soil Organic Carbon for Climate Resilience

Soil Function	Benefit	Climate Adaptation Outcome
Water-holding capacity	Improved moisture retention	Greater drought tolerance
Soil structure	Reduced compaction and erosion	Improved resistance to floods
Nutrient availability	Enhanced nutrient cycling	Reduced dependency on fertilizers
Microbial diversity	Increased biological activity	Improved stress tolerance
Root penetration	Better root growth	Higher yield stability

Table 4: Contribution of Soil Carbon Sequestration to Climate Change Mitigation

Aspect	Role of Soil Carbon
Carbon sink	Captures atmospheric CO ₂
Greenhouse gas reduction	Lowers net emissions from agriculture
Energy efficiency	Reduces synthetic input demand
Ecosystem services	Supports biodiversity and soil life
Long-term sustainability	Enhances system resilience

Table 5: Barriers and Enablers for Adoption of Regenerative Agriculture

Category	Key Factors
Barriers	Limited awareness, short-term yield concerns, lack of incentives
Technical gaps	Inadequate region-specific recommendations
Economic constraints	Initial transition costs
Enablers	Policy support, extension services, carbon markets
Knowledge systems	Farmer training and participatory research

Table 6: Linkages Between Regenerative Agriculture and Food Security

Dimension of Food Security	Contribution of Regenerative Agriculture
Availability	Sustained crop yields
Accessibility	Reduced input costs
Stability	Resilience to climate shocks
Utilization	Improved nutritional quality
Sustainability	Long-term land productivity

5. Soil Carbon Sequestration, Water Use Efficiency, and Climate Resilience

Soil carbon sequestration is closely linked with improved soil physical properties that enhance water-use efficiency and climate resilience in agricultural systems. Soils with higher organic carbon content exhibit better aggregation, increased porosity, and improved infiltration rates, allowing them to capture and retain more water during rainfall events. This enhanced water-holding capacity is particularly critical under climate change scenarios characterized by erratic rainfall, prolonged droughts, and intense precipitation events. Carbon-rich soils act as natural buffers, reducing surface runoff and erosion while making water more available to crops during periods of moisture stress. As a result, crops grown in high-carbon soils experience reduced yield variability and improved performance under adverse climatic conditions. Regenerative agricultural practices contribute significantly to strengthening the soil-water-carbon nexus. Practices such as cover cropping and residue retention protect the soil surface from evaporation and temperature extremes, while deep-rooted plants enhance soil structure and promote water movement into deeper layers. Increased organic matter also improves soil cation exchange capacity, enhancing nutrient retention and reducing leaching losses under heavy rainfall. In water-limited environments, improved soil moisture retention reduces irrigation requirements, contributing to resource conservation

and sustainable water management. These benefits are especially important in semi-arid and rainfed agricultural regions where water scarcity is a major constraint to productivity. Climate resilience is further enhanced by the ability of carbon-rich soils to support robust root systems and beneficial microbial populations that help plants withstand stress. Improved soil biological activity enhances nutrient availability and root-microbe interactions, increasing plant tolerance to drought, heat, and salinity. By stabilizing yields and reducing dependency on external inputs, soil carbon sequestration strengthens both ecological and economic resilience at the farm level. Thus, enhancing soil carbon stocks through regenerative practices represents a key adaptation strategy for sustaining agricultural productivity under increasingly unpredictable climatic conditions.

6. Policy, Technology, and Socioeconomic Dimensions of Regenerative Carbon Farming

The widespread adoption of soil carbon sequestration and regenerative agriculture practices depends heavily on supportive policy frameworks, technological innovations, and socioeconomic considerations. While the environmental benefits of regenerative farming are well established, farmers often face barriers such as initial yield fluctuations, limited access to knowledge, and financial constraints during the transition period. Policy interventions that provide incentives, technical support, and risk mitigation mechanisms are essential to encourage farmers to adopt and sustain regenerative practices. Carbon credit schemes, payments for ecosystem services, and climate-smart agriculture programs can play a critical role in rewarding farmers for carbon sequestration and other environmental benefits. Technological advancements are enhancing the feasibility and scalability of soil carbon sequestration initiatives. Innovations in soil carbon measurement, remote sensing, digital agriculture, and modeling tools have improved the ability to monitor carbon stocks and assess the impact of management practices. Precision agriculture technologies enable site-specific nutrient and water management, optimizing resource use while minimizing emissions. Decision-support tools and climate forecasting systems help farmers make informed management choices that align productivity goals with environmental sustainability. These technologies bridge the gap between ecological principles and practical farm-level implementation. Socioeconomic factors, including farmer awareness, education, and institutional support, are equally important for successful implementation. Participatory approaches that involve farmers in knowledge generation and decision-making foster greater ownership and long-term commitment to regenerative practices. Strengthening extension services, promoting farmer-to-farmer learning, and integrating indigenous knowledge systems can enhance adoption rates. At the global level, aligning regenerative agriculture with food security, climate adaptation, and sustainable development goals ensures that soil carbon sequestration is not viewed as a standalone solution but as part of a holistic strategy for resilient and sustainable farming

systems.

7. Challenges and Limitations of Soil Carbon Sequestration and Regenerative Agriculture

Despite the growing recognition of soil carbon sequestration and regenerative agriculture as viable solutions to climate change and agricultural sustainability, several challenges limit their widespread adoption and effectiveness. One of the major constraints is the variability in soil carbon sequestration potential across different agro-ecological regions, soil types, and climatic conditions. Factors such as soil texture, mineralogy, baseline organic carbon levels, and rainfall patterns strongly influence the rate and extent of carbon accumulation. In some environments, particularly in already carbon-rich soils or highly degraded lands, the capacity for additional carbon sequestration may be limited or require extended time periods before measurable benefits are realized. This temporal lag can discourage farmers who often expect short-term economic returns from changes in management practices.

Another significant challenge lies in the accurate measurement, reporting, and verification of soil carbon stocks. Soil carbon dynamics are complex and spatially heterogeneous, making it difficult to quantify changes reliably at farm and landscape scales. Traditional soil sampling methods are labor-intensive, costly, and time-consuming, while newer digital and remote sensing approaches still face limitations in precision and standardization. Uncertainties in carbon accounting pose challenges for the development of credible carbon markets and payment mechanisms. Moreover, the permanence of sequestered carbon remains a concern, as changes in land use, tillage practices, or extreme climate events can lead to rapid carbon losses, undermining long-term mitigation benefits.

Socioeconomic and institutional barriers further constrain adoption of regenerative practices. Smallholder and resource-poor farmers may lack access to capital, technical knowledge, and supportive infrastructure required for transitioning to regenerative systems. In many regions, agricultural policies and subsidy structures continue to favor conventional, input-intensive farming practices, inadvertently discouraging sustainable alternatives. Additionally, limited awareness, risk aversion, and uncertainty regarding yield stability during transition periods often slow adoption. Addressing these challenges requires coordinated efforts across research, policy, and extension systems to create enabling environments that support regenerative agriculture at scale.

8. Future Prospects and Research Needs for Regenerative Carbon Farming

The future of soil carbon sequestration and regenerative agriculture holds significant promise, particularly as global attention increasingly focuses on climate-smart and nature-based solutions. Advancements in soil science, microbiology, and agroecology are expanding our understanding of the mechanisms governing carbon stabilization and loss in agricultural soils. Future research should prioritize identifying region-specific regenerative practices that maximize carbon sequestration while maintaining or enhancing crop productivity. Long-term field experiments across diverse agro-climatic zones are essential to evaluate the sustainability, resilience, and economic viability of regenerative systems under changing climate conditions.

Emerging technologies offer new opportunities to enhance the effectiveness and scalability of regenerative carbon farming. Innovations in soil sensing, artificial intelligence, machine

learning, and digital agriculture can improve real-time monitoring of soil health indicators, including organic carbon dynamics. Improved modeling tools can help predict long-term carbon sequestration outcomes and guide adaptive management strategies. Additionally, integrating plant breeding programs with regenerative principles to develop crop varieties with deeper root systems, higher biomass production, and enhanced carbon allocation to soils can further strengthen sequestration potential. Research on plant-microbe interactions and microbial carbon-use efficiency also represents a critical frontier for enhancing soil carbon storage.

Interdisciplinary research linking biophysical, socioeconomic, and policy dimensions is essential to support the transition toward regenerative agriculture. Greater emphasis is needed on understanding farmer behavior, adoption pathways, and the role of incentives and institutional frameworks in scaling regenerative practices. Participatory research approaches that involve farmers, extension agents, and local communities can ensure that innovations are context-specific, practical, and socially acceptable. Aligning regenerative agriculture research with global sustainability agendas, including climate adaptation, biodiversity conservation, and food security, will further enhance its relevance and impact.

9. Implications for Food Security, Environmental Sustainability, and Climate Policy

Soil carbon sequestration through regenerative agriculture has far-reaching implications for food security, environmental sustainability, and climate policy. By improving soil fertility, structure, and biological activity, carbon-rich soils support stable and sustained crop yields, even under adverse climatic conditions. This yield stability is critical for ensuring food availability and reducing vulnerability to climate-induced production shocks, particularly in regions heavily dependent on rainfed agriculture. Enhanced soil health also contributes to improved nutritional quality of crops, supporting broader food and nutritional security goals.

From an environmental perspective, regenerative agriculture offers multiple co-benefits beyond carbon sequestration. Improved soil organic matter reduces erosion, enhances water quality by minimizing nutrient runoff, and supports biodiversity both above and below ground. Regenerative systems also reduce dependence on synthetic fertilizers and pesticides, thereby lowering greenhouse gas emissions and minimizing environmental pollution. These ecological benefits contribute to the restoration of degraded landscapes and the resilience of agroecosystems, aligning agricultural production with environmental conservation objectives.

At the policy level, integrating soil carbon sequestration into climate mitigation and adaptation strategies presents a cost-effective and scalable solution. Nationally Determined Contributions (NDCs) under international climate agreements can incorporate regenerative agriculture as a key component of land-based mitigation efforts. Policies that promote carbon farming, reward ecosystem services, and support climate-smart agricultural transitions can accelerate adoption at scale. By recognizing soil as a critical natural asset, policymakers can foster farming systems that simultaneously address climate change, resource conservation, and food security, ensuring a sustainable and resilient future for global agriculture.

9. Conclusion

Soil carbon sequestration through regenerative agriculture represents a powerful pathway toward climate-resilient farming

systems. By restoring soil health, enhancing biodiversity, and improving ecosystem functions, regenerative practices strengthen agricultural resilience to climate stress while contributing to climate change mitigation. The integration of soil carbon management with regenerative principles offers multiple benefits, including improved productivity, reduced environmental impacts, enhanced food security, and sustainable livelihoods. Scaling these approaches requires supportive policies, scientific innovation, and active farmer participation. Embracing regenerative agriculture is essential for building resilient, sustainable, and climate-smart agricultural systems for future generations.

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