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# Carbon Farming as a Tool for Climate Resilience in Smallholder Agriculture

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## ABSTRACT

Climate change presents significant challenges to smallholder farmers, whose livelihoods are deeply intertwined with weather patterns, soil health, and overall ecosystem stability. As extreme weather events become more frequent and unpredictable, smallholder agriculture faces increasing risks, including reduced crop yields, soil degradation, and heightened food insecurity. Carbon farming—an approach that integrates agricultural practices designed to sequester carbon dioxide ($CO_2$) in soil and vegetation—has emerged as a promising strategy to address these challenges. By improving soil organic matter, enhancing biodiversity, and promoting sustainable land use, carbon farming offers a holistic approach to climate resilience. This review explores the potential of carbon farming as a multifaceted solution for climate change mitigation and adaptation in smallholder systems. It draws upon theoretical and conceptual frameworks to assess the effectiveness of carbon farming practices, such as agroforestry, cover cropping, conservation tillage, and biochar application. Additionally, empirical studies demonstrate how these practices improve soil fertility, increase water retention, and reduce greenhouse gas emissions, contributing to both environmental sustainability and food security. However, several

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ARTICLE INFO

Received: 16 March 2024 | Revised: 6 April 2024 | Accepted: 16 April 2024 | Published Online: 5 June 2024

DOI: https://doi.org/10.55121/nc.v3i2.207

CITATION

Sadiq, S.M., Singh, I.P., Ahmad, M.M., et al., 2024. Carbon Farming as a Tool for Climate Resilience in Smallholder Agriculture. New Countryside. 3(2): 67–81. DOI: https://doi.org/10.55121/nc.v3i2.207

challenges hinder widespread adoption, including financial constraints, knowledge gaps, and policy limitations. Addressing these barriers requires targeted interventions, such as capacity-building programs, financial incentives, and supportive policy frameworks. Ultimately, this review underscores the dual benefits of carbon farming: mitigating climate change through carbon sequestration while enhancing smallholder farmers' adaptive capacities. By integrating carbon farming into agricultural systems, policymakers and stakeholders can foster long-term resilience, ensuring sustainable livelihoods for smallholders while contributing to broader climate goals.

***Keywords:*** Carbon Farming; Climate; GHG Emission; Resilience; Smallholder

# 1. Introduction

Smallholder agriculture underpins the livelihoods of millions globally, especially in the developing world, where it plays a critical role in providing food security, employment, and economic sustenance. According to the Food and Agriculture Organization [1], smallholders contribute up to 70% of the global food supply, making their resilience vital to global food systems. However, smallholder farmers are increasingly vulnerable to the multifaceted impacts of climate change. These impacts include erratic rainfall patterns, prolonged droughts, extreme weather events, rising temperatures, and declining soil fertility, which exacerbate food insecurity and economic instability.

The Intergovernmental Panel on Climate Change (IPCC, 2022) as reprted by [2] highlights that agriculture is responsible for approximately 23% of global greenhouse gas (GHG) emissions, primarily due to methane emissions from livestock, nitrous oxide from fertilizers, and carbon dioxide from deforestation and land-use changes. Paradoxically, agriculture also presents significant opportunities for climate mitigation through carbon sequestration and climate-smart practices, making it a potential ally in global efforts to combat climate change.

Carbon farming is gaining attention as an integrated approach that combines climate-smart agriculture with regenerative practices to promote sustainable land management. It involves practices such as agroforestry, cover cropping, reduced or no-tillage farming, compost application, crop rotation, and enhanced grazing management. These techniques offer a dual benefit by sequestering atmospheric carbon into soils and vegetation while simultaneously improving soil organic matter, water retention capacity, and biodiversity. This can lead to more resilient agroecosystems capable of withstanding climate shocks. Furthermore, carbon farming can enhance productivity, reduce dependency on synthetic inputs, and contribute to long-term soil fertility, making it economically and ecologically viable for smallholder systems.

Beyond the environmental benefits, carbon farming holds significant potential for socio-economic upliftment. For smallholder farmers, adopting carbon farming practices can unlock new revenue streams through carbon credit markets. These markets enable farmers to monetize the carbon sequestered in their soils, creating financial incentives for sustainable farming. However, barriers such as high upfront costs, limited access to technology and knowledge, inadequate institutional support, and unclear property rights often hinder widespread adoption.

This paper systematically reviews the application of carbon farming in smallholder systems, exploring its theoretical underpinnings, real-world evidence, and practical feasibility. By critically evaluating case studies and field evidence, it provides insights into the transformative potential of carbon farming as a tool for climate resilience and sustainable development. This review also identifies challenges and policy gaps, offering actionable recommendations to scale up carbon farming in smallholder agriculture worldwide.

# 2. Theoretical Framework

The theoretical foundation of carbon farming is deeply rooted in ecological resilience theory and the scientific understanding of carbon sequestration dynamics, integrating ecological, biochemical, and agronomic principles to address the challenges of climate change and agroecosystem sustainability.

## 2.1. Ecological Resilience Theory

Resilience theory, as proposed by [3], defines the capacity of an ecosystem to absorb disturbances while reorganizing and adapting to changes without collapsing into qualitatively different states. This theory is particularly relevant to smallholder agricultural systems, which face constant pressures from climatic variability, resource degradation, and socioeconomic challenges.

Carbon farming exemplifies ecological resilience through practices that enhance soil organic matter (SOM), improve biological diversity, and promote agroecosystem stability. For instance:

- **Soil Organic Matter (SOM)**: SOM acts as a buffer against environmental stresses such as drought, erosion, and nutrient loss. Increased SOM enhances water retention, provides essential nutrients, and improves soil structure, enabling crops to withstand climatic extremes.
- **Biodiversity**: Agroforestry, intercropping, and cover cropping enhance both above-ground and below-ground biodiversity. This diversity promotes beneficial soil microbes, pest suppression, and pollinator activity, further stabilizing yields under fluctuating environmental conditions.
- **System Adaptability**: Resilience in carbon farming also extends to its ability to reduce dependency on synthetic inputs and foster adaptive capacity. By relying on nature-based solutions, such systems are more responsive to long-term climatic shifts and less vulnerable to market or policy disruptions.

Walker [4] expanded on Holling's concept by introducing the idea of adaptive cycles, emphasizing the importance of transformation in socio-ecological systems. Carbon farming aligns with this perspective by fostering innovation in sustainable land-use practices that not only recover from environmental stresses but build the capacity to thrive under new conditions.

## 2.2. Carbon Sequestration Dynamics

Carbon sequestration in agricultural systems occurs through two primary mechanisms: biological sequestration and soil carbon sequestration. These processes underpin the potential of carbon farming to mitigate climate change while enhancing soil health.

***Biological Sequestration***

Plants absorb atmospheric $CO_2$ via photosynthesis, converting it into organic carbon stored in biomass (roots, stems, and leaves) and subsequently transferred to the soil. This process is central to carbon farming practices such as:

- **Agroforestry**: Trees integrated with crops sequester carbon in their woody biomass while contributing organic matter to the soil through leaf litter and root turnover.
- **Cover Cropping**: Fast-growing cover crops capture $CO_2$ efficiently and transfer carbon to the soil as they decompose.

## 2.3. Soil Carbon Sequestration

The process of soil carbon sequestration involves the stabilization of organic carbon in the soil, driven by microbial activity, soil structure, and management practices. Ref. [5] emphasized the role of soil organic carbon (SOC) as a cornerstone of sustainable agriculture. Key benefits of SOC include:

- **Water Retention and Infiltration**: SOC improves soil porosity, allowing better water infiltration and retention, which is crucial for drought-prone regions.
- **Nutrient Cycling**: SOC serves as a reservoir of essential nutrients, supporting plant growth and microbial activity.
- **Microbial Activity**: Carbon-rich soils foster diverse microbial communities that enhance nutrient availability and suppress pathogens.

The capacity of soils to sequester carbon is influenced by factors such as climate, soil type, and management practices. Ref. [5] estimated that restoring degraded soils through carbon farming could offset a significant portion of global $CO_2$ emissions, with sequestration rates ranging from 0.1 to 1.0 Mg C $ha^{-1}$ $year^{-1}$, depending on the intervention.

## 2.4. Interlinking Resilience and Sequestration

The synergy between ecological resilience and carbon sequestration underpins the effectiveness of carbon farming. Practices like reduced tillage minimize soil disturbance, preserving carbon stores while reducing erosion. Compost application not only increases SOC but also improves soil buffering capacity, making systems more resilient to environmental stresses.

By coupling resilience-building practices with carbon capture mechanisms, carbon farming creates a selfreinforcing system that mitigates emissions while adapting to climate impacts. This theoretical framework provides a foundation for understanding the multifaceted benefits of carbon farming and its role in promoting sustainable smallholder agriculture.

# 3. Conceptual Framework

## 3.1. General

The conceptual framework positions carbon farming as a transformative strategy within smallholder agriculture, addressing environmental, economic, and social dimensions to enhance climate resilience and sustainability. This integrative model highlights the interconnected benefits and challenges of carbon farming, offering a holistic perspective for its adoption in smallholder contexts.

### 3.1.1. Environmental Resilience

Carbon farming plays a pivotal role in fostering environmental resilience by improving ecosystem functions, reducing environmental degradation, and enhancing the adaptive capacity of smallholder systems. Key elements include:

- **Soil Organic Carbon (SOC) Enhancement**: Carbon farming practices, such as reduced tillage, compost application, and agroforestry, significantly increases SOC levels. Improved SOC leads to enhanced soil structure, better water retention, and nutrient availability, contributing to sustainable crop productivity.
- **Erosion Mitigation**: Techniques like cover cropping and contour farming reduce soil erosion by stabilizing soil and promoting water infiltration. These practices are particularly critical for sloped and degraded lands common in smallholder systems.
- **Biodiversity Promotion**: Carbon farming supports biodiversity both above and below ground. Intercropping and agroforestry create diverse habitats, fostering pollinators and beneficial organisms, while increasing microbial diversity improves soil health and resilience to pests and diseases.
- **Climate Mitigation**: By sequestering atmospheric $CO_2$ in soil and biomass, carbon farming offsets greenhouse gas emissions and contributes to climate change mitigation.

### 3.1.2. Economic Viability

The economic dimension of carbon farming focuses on enhancing the livelihoods of smallholder farmers by ensuring financial sustainability and reducing economic vulnerabilities.

- **Increased Yields**: Improved soil health and water retention from carbon farming lead to higher and more stable crop yields, even under erratic climatic conditions.
- **Diversified Income Streams**: Practices like agroforestry and rotational grazing enable smallholders to diversify their income through the production of high-value crops, timber, fruits, fodder, and livestock products.
- **Reduced Input Costs**: By enhancing natural fertility and pest control, carbon farming reduces reliance on synthetic fertilizers and pesticides, lowering production costs.
- **Access to Carbon Markets**: Smallholders can monetize the carbon sequestered in their lands by participating in carbon credit programs. These markets offer financial incentives for adopting sustainable practices, though barriers such as certification costs and market access remain significant challenges.

### 3.1.3. Social Inclusivity

The social inclusivity dimension emphasizes empowering marginalized communities, particularly women, youth, and indigenous groups, in adopting and benefiting from carbon farming practices.

- **Participatory Approaches**: Engaging farmers in the design and implementation of carbon farming initiatives ensures that practices align with local needs and cultural contexts. Participatory approaches also foster community ownership and collaboration, which are crucial for long-term sustainability.
- **Knowledge Sharing**: Capacity-building programs, farmer field schools, and peer-to-peer learning platforms disseminate knowledge about carbon farming techniques, enabling widespread adoption and innovation.
- **Empowering Marginalized Groups**: Carbon farming initiatives can provide targeted support to marginalized groups by improving their access to re-

sources, credit, and training. Women, who often play central roles in smallholder farming, can benefit significantly from the additional income and food security that carbon farming offers.

- **Improved Food Security**: By stabilizing yields and diversifying food production, carbon farming enhances household food security, particularly in regions prone to climatic shocks.

### 3.1.4. Integrative Model

This conceptual framework underscores the interplay between environmental, economic, and social dimensions of carbon farming:

- **Environmental Resilience** supports economic viability by ensuring sustainable resource use and productivity.
- **Economic Viability** reinforces social inclusivity by providing financial resources and opportunities for marginalized groups.
- **Social Inclusivity** strengthens environmental resilience through collective action and community-driven approaches that prioritize sustainable practices.

Together, these dimensions create a reinforcing cycle of benefits, highlighting carbon farming as a powerful strategy for smallholder systems. However, the framework also recognizes challenges such as high upfront costs, limited technical expertise, land tenure issues, and the need for enabling policies. Addressing these barriers is critical for scaling up carbon farming and maximizing its potential in smallholder agriculture.

This integrative model provides a comprehensive lens to explore the potential and challenges of carbon farming within smallholder systems, offering a roadmap for research, policy, and practice.

## 3.2. Specific

This conceptual framework situates carbon farming within the overarching paradigm of climate-resilient agriculture, emphasizing its role as a multifaceted strategy to enhance environmental, economic, and social sustainability (**Figure 1**). The framework illustrates how carbon farming practices contribute to ecological processes and deliver measurable outcomes and impacts, ultimately driving adaptive capacity and resilience in smallholder agricultural systems.

### 3.2.1. Inputs: Carbon Farming Practices

The foundation of carbon farming lies in the application of sustainable and regenerative agricultural practices. These practices are tailored to local contexts and leverage natural processes to enhance productivity and resilience. Key inputs include:

- **Agroforestry**: The integration of trees and shrubs with crops or livestock improves carbon storage, provides shade, and diversifies income sources.
- **Cover Crops**: Planting legumes or grasses during fallow periods enhances soil cover, reduces erosion, and increases soil organic matter.
- **Reduced Tillage**: Minimizing soil disturbance prevents carbon loss, conserves moisture, and preserves soil structure.
- **Compost and Organic Amendments**: Adding organic materials enhances soil fertility, supports microbial activity, and boosts soil carbon levels.
- **Rotational and Enhanced Grazing**: Carefully managed grazing cycles improve pasture health, reduce overgrazing, and enhance carbon storage in grasslands.
- **Crop Diversification**: Incorporating a variety of crops promotes resilience to pests and climatic shocks while supporting soil health.

### 3.2.2. Processes: Ecological and Biogeochemical Mechanisms

Carbon farming catalyzes several critical ecological and biogeochemical processes, leading to environmental benefits that underpin climate resilience:

- **Carbon Sequestration**: Atmospheric $CO_2$ is captured through photosynthesis and stored in biomass (roots, stems, leaves) and soil as organic carbon. Agroforestry, for instance, sequesters carbon in woody biomass, while cover crops transfer carbon into the soil.
- **Soil Regeneration**: Enhanced organic matter fosters microbial activity, nutrient cycling, and soil structure, making soils more fertile and resilient to degradation.
- **Biodiversity Enhancement**: Practices like intercropping and agroforestry promote diverse habitats, supporting beneficial organisms that improve ecosystem services such as pollination, pest control, and nutrient

cycling.

- **Water Regulation**: Improved soil structure and organic matter increase water infiltration and retention, reducing water stress and preventing runoff and erosion.

### 3.2.3. Outcomes: Tangible Benefits of Carbon Farming

The processes initiated by carbon farming practices yield tangible outcomes that address key challenges faced by smallholder farmers. These include:

- **Reduced Emissions**: By sequestering carbon and minimizing practices that release GHGs, carbon farming mitigates climate change. Methane emissions from livestock can be reduced through improved grazing management, while nitrous oxide emissions decrease with organic fertilization techniques.
- **Enhanced Soil Fertility**: Increased SOC enriches the nutrient profile of soils, supporting plant growth and reducing the need for synthetic fertilizers.
- **Improved Water Management**: Practices that enhance soil structure and organic matter help conserve water, ensuring steady crop growth even in drought-prone areas.
- **Economic Productivity**: Healthy soils and diverse cropping systems lead to more stable and higher yields, boosting farm incomes.

### 3.2.4. Impacts: Long-Term Transformative Effects

The cumulative outcomes of carbon farming practices contribute to transformative impacts on smallholder agriculture, enabling farmers to navigate and adapt to climate challenges. These include:

- **Increased Adaptive Capacity**: Carbon farming equips smallholder farmers with tools and strategies to cope with climatic variability, ensuring food security and economic stability. Resilient soils, diverse cropping systems, and reduced dependency on external inputs allow farmers to adapt to droughts, floods, and shifting growing seasons.
- **Enhanced Climate Resilience**: The integration of biodiversity, water conservation, and carbon storage creates agroecosystems that are better equipped to withstand and recover from extreme weather events and long-term climatic shifts.
- **Social Benefits**: Carbon farming practices that prioritize inclusivity empower marginalized groups by improving access to resources, creating new income opportunities, and fostering community collaboration.

### 3.2.5. Diagrammatic Representation of the Framework

Below is a hierarchical flow representing the framework (**Figure 1**):

1. **Inputs**: Carbon farming practices (e.g., agroforestry, cover cropping, reduced tillage).
   ↓
2. **Processes**: Carbon sequestration, soil regeneration, biodiversity enhancement, and water regulation.
   ↓
3. **Outcomes**: Reduced emissions, enhanced soil fertility, improved water management, and increased yields.
   ↓
4. **Impacts**: Increased adaptive capacity, enhanced climate resilience, improved food security, and economic stability.

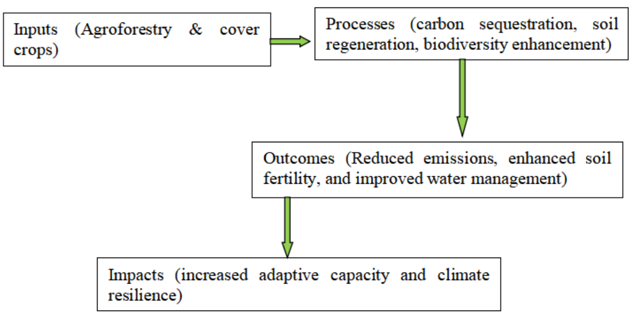


**Figure 1.** Conceptual framework of carbon farming & resilience outcomes.

Source: Authors' own design.

This conceptual framework highlights the interconnected nature of carbon farming's benefits, demonstrating how targeted practices can generate ripple effects that support both environmental sustainability and socio-economic development. It serves as a guiding structure for evaluating the potential of carbon farming in smallholder agriculture while identifying areas for further research and policy interventions.

# 4. Research Methodology

The present study relied on secondary data sourced from journals, conference proceedings, articles, manuals, monographs, edited books, newspapers, internet to generate data. Furthermore, to have an insight into the research review, the collected data were systematically analyzed.

# 5. Results and Discussion

This section provides a synthesis of empirical evidence on the application of carbon farming in smallholder agriculture, focusing on its benefits, challenges, and feasibility. The analysis highlights its potential for improving productivity and resilience while identifying the constraints that hinder widespread adoption.

## 5.1. Carbon Farming Practices and Their Benefits

### 5.1.1. Agroforestry

Agroforestry, which integrates trees with crops and livestock, is foundational to carbon farming. Trees sequester carbon in their biomass and root systems while providing ecosystem services such as reducing wind erosion and improving microclimates.

- **Empirical Evidence**: Studies in **sub-Saharan Africa**[6] reveal that agroforestry can enhance soil carbon stocks by 0.2–0.5 Mg/ha annually while providing economic co-benefits such as timber, fruits, and fodder.
- **Additional Benefits**: Agroforestry systems can serve as windbreaks, stabilize soils on sloped terrains, and enhance biodiversity by creating habitats for pollinators and beneficial insects. These features increase overall system productivity and resilience.
- **Recent Findings**: A global meta-analysis by[7] found that agroforestry systems can store up to **9.5 Mg C/ha/year**, with greater sequestration potential in tropical regions.
- **Additional Benefits**: In East Africa, agroforestry systems have been linked to improved soil fertility, reduced dependence on synthetic fertilizers, and increased household income from timber and fruit sales[8].

### 5.1.2. Cover Cropping

The use of cover crops like legumes, clovers, and grasses plays a significant role in carbon farming by improving soil structure, fixing atmospheric nitrogen, and reducing erosion.

- Empirical Evidence: A meta-analysis by[9] reports that cover cropping can boost soil organic carbon (SOC) storage by up to 30% compared to fallow systems.
- Climate Mitigation: By reducing the need for synthetic fertilizers, cover crops lower nitrous oxide emissions, contributing to GHG reductions.
- Recent Findings:[10] reported that cover crops can increase SOC by **5–10% annually** in degraded soils. Additionally, they reduce nutrient leaching, mitigating water pollution.
- Additional Benefits: Cover crops like legumes and clovers also fix nitrogen biologically, reducing the need for chemical fertilizers and lowering agricultural emissions.

### 5.1.3. Reduced Tillage

Conservation tillage minimizes soil disruption, preserves organic matter, and reduces $CO_2$ emissions from exposed soils.

- Empirical Evidence: A review by[11] estimates that reduced tillage can sequester up to 1.1 Mg C/ha annually. This practice also decreases fuel use for mechanical tillage, reducing indirect emissions.
- Long-Term Impacts: Reduced tillage improves soil structure, enabling better root penetration and water infiltration, which are critical for crop resilience during droughts.
- Recent Findings: Recent studies by[12] emphasize that reduced tillage increases microbial diversity, which enhances nutrient cycling and soil health.
- Economic Impacts: Reduced tillage practices also lower operational costs by decreasing fuel consumption and labor requirements, making them more accessible for smallholders.

### 5.1.4. Composting and Organic Amendments

Applying compost and organic residues enriches SOC, improves soil fertility, and recycles agricultural waste.

- Empirical Evidence: Field trials in **India**[13] found that compost application increased crop yields by 20%, enhanced SOC levels, and improved microbial diversity in the soil.

- Additional Benefits: Composting reduces reliance on synthetic fertilizers and provides an effective way to manage organic waste, thus contributing to circular agriculture.
- Recent Findings: Experiments in sub-Saharan Africa [14] revealed that compost application increased maize yields by **25–30%** while enhancing SOC levels.
- Circular Economy: Composting promotes a circular approach by recycling agricultural waste, thus reducing methane emissions from unmanaged organic residues.

#### 5.1.5. Enhanced Grazing Management

Rotational grazing systems, which allocate specific recovery times for pastures, prevent overgrazing, reduce soil compaction, and enhance carbon storage.

- Empirical Evidence: Ref. [15] found that well-managed grazing systems significantly increased SOC levels, improved forage quality, and boosted livestock productivity.
- Additional Benefits: Enhanced grazing management promotes pasture regeneration, reduces erosion, and increases water infiltration, supporting the overall resilience of pastoral systems.
- Recent Findings: A study by [16] found that rotational grazing increased SOC by **15%** over ten years in semiarid rangelands.
- Additional Benefits: Enhanced grazing improves forage quality, supports livestock productivity, and reduces soil compaction, which is critical in preventing land degradation.

### 5.2. Challenges in Implementing Carbon Farming

Despite its benefits, carbon farming faces significant barriers that limit its adoption among smallholder farmers.

#### 5.2.1. Technical Constraints

- **Lack of Knowledge and Skills**: Smallholders often lack technical expertise to implement carbon farming practices effectively. Weak extension services and limited access to training exacerbate this issue [17]. Reports by [18] highlight insufficient access to training and extension services as a critical bottleneck.
- **Knowledge Gaps**: Misconceptions about the time required for benefits to materialize or uncertainty about the compatibility of practices with local farming systems hinder uptake.
- **Access to Resources**: Limited availability of tools, quality seeds, and organic inputs further restricts adoption, particularly in resource-poor regions.

#### 5.2.2. Economic Barriers

- **High Upfront Costs**: Investments in agroforestry seedlings, composting infrastructure, or biochar production can be prohibitively expensive for smallholders.
- **Market Access**: Farmers often face challenges in accessing carbon credit markets due to high certification costs and a lack of intermediaries to facilitate transactions. In other words, smallholders face significant challenges in accessing carbon markets due to high transaction costs, complex verification requirements, and limited institutional support [19].

#### 5.2.3. Policy and Institutional Gaps

- Lack of Incentives: The absence of subsidies or financial support for sustainable farming practices limits adoption. Carbon pricing mechanisms are often underdeveloped in regions with high smallholder populations. In other words, in many developing countries, the lack of supportive policies, such as subsidies for sustainable practices or incentives for carbon sequestration, limits the scalability of carbon farming [1].
- Tenure Security: Unclear land ownership or user rights discourage farmers from investing in long-term carbon farming practices, such as agroforestry.

#### 5.2.4. Measurement and Verification Challenges

- SOC Quantification: Accurately measuring SOC increases is complex, requiring advanced tools and expertise. This complicates farmers' ability to link their efforts to climate finance or carbon credit programs.
- Baseline Data: Lack of historical soil carbon data further complicates monitoring and reporting. The absence of robust baseline data complicates efforts to quantify and monetize carbon sequestration [20].

## 5.3. Evidence of Climate Resilience

Empirical studies underscore the role of carbon farming in enhancing the resilience of smallholder systems to climate variability and shocks.

### 5.3.1. India

- **Findings**: Cover cropping systems enriched with organic carbon demonstrated a **40% higher water retention capacity** during drought conditions[21].
- **Implications**: Increased water retention stabilizes yields during periods of low rainfall, ensuring food security.

### 5.3.2. Kenya

- **Findings**: Agroforestry systems reduced surface runoff by **30%** and increased crop yields under erratic rainfall[22].
- **Implications**: Improved water management reduces soil erosion and enhances productivity in rainfed systems.

### 5.3.3. Latin America

- **Findings**: Conservation tillage practices reduced the vulnerability of maize farms to extreme weather events, stabilizing household incomes during climatic shocks[23].
- **Implications**: Sustained production under adverse conditions highlights the potential of carbon farming to mitigate economic risks for smallholders.

### 5.3.4. West Africa

- **Findings**: A recent study[24] reported that farmer-managed natural regeneration of trees increased SOC by **0.5 Mg/ha/year** and reduced wind erosion by **40%**.
- **Community Engagement**: The participatory nature of these practices also fostered community collaboration and knowledge sharing, strengthening social resilience.

**Cross-Cutting Themes**

### 5.3.5. Gender and Social Equity

Carbon farming presents opportunities for empowering marginalized groups, particularly women, who play critical roles in smallholder agriculture. Targeted interventions, such as training programs and access to credit, can enhance women's participation and benefit distribution.

- **Recent Evidence**: Women-led composting initiatives in India have increased household incomes by **30%** while improving food security[25].

### 5.3.6. Ecosystem Services

Beyond carbon sequestration, practices like agroforestry and cover cropping enhance ecosystem services, including water filtration, pest control, and biodiversity conservation.

### 5.3.7. Co-Benefits of Carbon Markets

Linking carbon farming to climate finance through carbon credits can provide additional income streams for smallholders. However, ensuring equitable access to these markets remains a challenge that requires institutional support and streamlined verification processes.

- **Income Diversification**: Linking carbon farming with carbon credits can provide a steady income stream for smallholders.
- **Recent Developments**: Projects like Kenya's Livelihoods Carbon Fund have shown that smallholder farmers can earn up to **$20/ha/year** from carbon credits while adopting sustainable practices[26].

## 5.4. Case Studies

This section presents case studies from different regions, highlighting the application and outcomes of carbon farming practices in smallholder systems. These examples provide empirical evidence of the environmental, economic, and social benefits, as well as challenges faced in implementation.

### 5.4.1. India: Organic Carbon Management through Cover Cropping

- **Location**: Maharashtra, India
- **Practice**: Smallholder farmers adopted leguminous cover crops to improve soil organic matter and reduce dependency on chemical fertilizers.
- **Findings**:
  - **Water Retention**: SOC-enriched soils demonstrated **40% higher water retention** during severe drought periods[27].
  - **Yield Stability**: Yields increased by **20–25%** in rainfed systems due to improved soil fertility.
- **Challenges**: Initial costs for seeds and lack of techni-

cal support slowed adoption in some areas.

- **Implications**: Scaling cover cropping in semi-arid regions could significantly enhance climate resilience and reduce input costs for farmers.

#### 5.4.2. Kenya: Agroforestry for Soil and Water Conservation

- **Location**: Central and Western Kenya
- **Practice**: Farmers incorporated fast-growing tree species such as *Grevillea robusta* and *Sesbania sesban* in agroforestry systems to combat soil erosion and enhance productivity.
- **Findings**:
  - **Runoff Reduction**: Surface runoff was reduced by **30%**, lowering the risk of soil erosion during heavy rains [22].
  - **Economic Benefits**: Tree products like timber and fuelwood contributed an additional **15–20%** to household income.
  - **Biodiversity Gains**: Agroforestry provided habitats for pollinators and pest predators, reducing crop losses.
- **Challenges**: Weak land tenure systems discouraged long-term investments in tree planting.
- **Implications**: Policies ensuring land rights and subsidies for seedlings could accelerate adoption.

#### 5.4.3. Latin America: Conservation Tillage for Maize Farmers

- **Location**: Central and South America (Mexico and Brazil)
- **Practice**: Adoption of no-till farming with crop residues to preserve SOC and improve water use efficiency in maize systems.
- **Findings**:
  - **Yield Stability**: Farms experienced **15% less yield variability** during drought years [23].
  - **SOC Gains**: SOC levels increased by **0.8 Mg/ha/year** after five years of continuous practice.
  - **Economic Savings**: Reduced fuel and labor costs led to a **10–15% reduction in production expenses**.
- **Challenges**: Adoption was slow among smallholders due to limited access to no-till machinery.
- **Implications**: Providing affordable equipment and training could enhance adoption rates.

#### 5.4.4. Ethiopia: Composting and Soil Fertility Enhancement

- **Location**: Amhara Region, Ethiopia
- **Practice**: Community-led composting initiatives focused on improving soil fertility using crop residues, manure, and kitchen waste.
- **Findings**:
  - **Yield Improvement**: Maize and teff yields increased by **30%**, attributed to enhanced nutrient availability [28].
  - **Carbon Sequestration**: SOC levels rose by **0.6 Mg/ha/year** after three years of compost application.
  - **Economic Co-Benefits**: Farmers reduced dependency on chemical fertilizers, saving **25% of production costs**.
- **Challenges**: Labor-intensive composting processes and limited access to organic residues hindered scaling.
- **Implications**: Promoting farmer cooperatives and knowledge-sharing platforms could improve uptake and efficiency.

#### 5.4.5. West Africa: Farmer-Managed Natural Regeneration (FMNR)

- **Location**: Niger and Burkina Faso
- **Practice**: FMNR involves regenerating native tree species by protecting and managing natural root systems and saplings.
- **Findings**:
  - **SOC Sequestration**: SOC levels increased by **0.4 Mg/ha/year** [24].
  - **Erosion Control**: Tree roots reduced wind erosion by **35–40%**, preserving topsoil.
  - **Community Engagement**: Participatory approaches fostered collaboration and collective decision-making.
- **Challenges**: Resistance to reducing grazing areas and weak policy support limited the spread of FMNR.
- **Implications**: Integrating FMNR into national reforestation programs could amplify its impact.

#### 5.4.6. Australia: Rotational Grazing in Semi-Arid Grasslands

- **Location**: Queensland, Australia
- **Practice**: Rotational grazing with planned rest periods allowed pastures to recover, promoting carbon storage and biodiversity.
- **Findings**:
  - **SOC Increase**: SOC levels increased by **1.2 Mg/ha/year** over a decade[16].
  - **Livestock Productivity**: Improved pasture quality led to a **25% increase in livestock weight gain**.
- **Challenges**: Initial investments in fencing and monitoring equipment were prohibitive for smaller ranchers.
- **Implications**: Subsidies for fencing and technical assistance could make rotational grazing more accessible.

#### 5.4.7. Southeast Asia: Biochar Application in Rice Systems

- **Location**: Vietnam and Indonesia
- **Practice**: Application of biochar derived from rice husks to enhance soil fertility and reduce methane emissions from flooded fields.
- **Findings**:
  - **Emission Reduction**: Methane emissions dropped by **30–50%** compared to traditional rice farming[29].
  - **SOC Levels**: SOC increased by **1 Mg/ha/year**, enhancing soil health.
  - **Yield Gains**: Rice yields rose by **15%** due to improved nutrient availability.
- **Challenges**: The high cost of biochar production technology limited its adoption.
- **Implications**: Expanding low-cost biochar production units and providing subsidies could drive uptake.

#### 5.4.8. Europe: Carbon Sequestration through Perennial Grasses

- **Location**: Northern Europe (Sweden and Denmark)
- **Practice**: Planting perennial grasses such as switch grass and miscanthus on degraded lands to improve carbon sequestration and reduce soil erosion.
- **Findings**:
  - **SOC Gains**: SOC levels increased by **0.7–1.0 Mg/ha/year** within three years of establishment[30].
  - **Erosion Control**: Perennial grasses reduced soil loss by **50%** on sloped terrains.
  - **Economic Benefits**: Farmers earned additional income by selling biomass for bioenergy production.
- **Challenges**: Limited awareness and market linkages for biomass hindered broader adoption.
- **Implications**: Policy support for biomass energy markets could incentivize the use of perennial grasses.

#### 5.4.9. Tanzania: Agroforestry with Faidherbia Albida

- **Location**: Southern Highlands, Tanzania
- **Practice**: Integration of *Faidherbia albida* (a nitrogen-fixing tree) in maize and sorghum fields.
- **Findings**:
  - **Soil Fertility**: SOC levels increased by **0.8 Mg/ha/year**, enhancing nutrient availability for crops[31].
  - **Yield Gains**: Maize yields increased by **40%** due to improved soil fertility and reduced competition for water during the growing season.
  - **Water Use Efficiency**: Tree canopies reduced evaporation, retaining soil moisture longer.
- **Challenges**: Limited availability of quality saplings and inadequate farmer awareness of agroforestry benefits.
- **Implications**: Establishing nurseries and community-led awareness programs can enhance adoption rates.

#### 5.4.10. Malawi: Soil Cover through Mulching in Smallholder Farms

- **Location**: Central Malawi
- **Practice**: Use of maize stover and grass as mulch to retain soil moisture and enhance organic matter.
- **Findings**:
  - **Erosion Control**: Mulched fields experienced **70% less soil erosion** during heavy rainfall compared to unmulched plots[32].
  - **SOC Levels**: SOC increased by **0.5 Mg/ha/year**, supporting sustainable crop growth.

- **Crop Yields**: Mulching improved maize yields by **15–20%**, particularly in degraded soils.
- **Challenges**: Competing uses of crop residues (e.g., animal fodder) limited the availability of materials for mulching.
- **Implications**: Encouraging balanced residue management could address competing demands and promote mulching adoption.

### 5.4.11. China: Biochar for Paddy Fields

- **Location**: Guangxi Province, China
- **Practice**: Application of biochar derived from bamboo in rice fields to improve soil properties and reduce methane emissions.
- **Findings**:
  - **Emission Reduction**: Methane emissions decreased by **40%** due to improved soil aeration [33].
  - **SOC Sequestration**: SOC levels increased by **1.5 Mg/ha/year**, exceeding conventional practices.
  - **Yield Stability**: Rice yields increased by **25%**, even during drought years.
- **Challenges**: High costs of biochar production limited scaling among smallholders.
- **Implications**: Government subsidies for biochar production could make it more accessible to smallholder farmers.

### 5.4.12. Uganda: Rotational Grazing for Pastoral Systems

- **Location**: Karamoja Region, Uganda
- **Practice**: Controlled rotational grazing to improve grassland productivity and prevent soil compaction.
- **Findings**:
  - **Pasture Regeneration**: Biomass production increased by **30%**, supporting larger livestock populations [34].
  - **SOC Storage**: SOC levels increased by **0.6 Mg/ha/year** in rotationally grazed pastures.
  - **Livestock Health**: Improved pasture quality resulted in healthier livestock and higher milk yields.
- **Challenges**: Resistance from traditional grazing communities and lack of fencing infrastructure slowed adoption.
- **Implications**: Integrating traditional knowledge with rotational grazing systems could increase acceptance.

### 5.4.13. Indonesia: Multi-Strata Agroforestry for Cocoa Production

- **Location**: Sulawesi, Indonesia
- **Practice**: Cocoa farms incorporated shade trees and undergrowth species in multi-strata agroforestry systems.
- **Findings**:
  - **SOC Gains**: SOC increased by **0.9 Mg/ha/year** as a result of organic matter inputs from tree litter [35].
  - **Biodiversity**: Increased tree and plant diversity supported pollinators and natural pest predators, reducing dependency on chemical pesticides.
  - **Economic Benefits**: Cocoa yields were stabilized, and shade trees provided additional income from timber and fruit sales.
- **Challenges**: Farmers faced challenges in managing tree densities to balance shade and crop productivity.
- **Implications**: Providing training on agroforestry management could optimize system benefits.

### 5.4.14. Niger: Zaï Pits for Water Conservation and Carbon Storage

- **Location**: Sahel Region, Niger
- **Practice**: Use of Zaï pits-small water-harvesting pits filled with organic matter-to regenerate degraded soils and store water.
- **Findings**:
  - **SOC Increase**: SOC levels rose by **0.4 Mg/ha/year**, supporting millet and sorghum production [36].
  - **Yield Gains**: Crop yields improved by **50–100%**, particularly in previously unproductive lands.
  - **Water Retention**: Zaï pits retained water longer, enabling crop growth during short rains.
- **Challenges**: Labor-intensive digging of pits limited adoption in resource-constrained households.
- **Implications**: Introducing mechanized tools for Zaï pit construction could reduce labor requirements.

#### 5.4.15. United States: Perennial Grasses for Carbon Farming

- **Location**: Midwest United States
- **Practice**: Planting switch grass and prairie grasses on marginal lands to sequester carbon and restore degraded soils.
- **Findings**:
  - **SOC Gains**: SOC levels increased by **1.2 Mg/ha/year**, enhancing soil fertility and stability [37].
  - **Economic Co-Benefits**: Farmers generated additional income by selling biomass for biofuel production.
  - **Erosion Control**: Perennial grasses reduced soil erosion by **60%**, especially on sloped lands.
- **Challenges**: Competition with food crops for land use limited expansion.
- **Implications**: Promoting perennial grasses on marginal lands could optimize land use without affecting food production.

#### 5.4.16. Senegal: Participatory Composting Programs

- **Location**: Dakar Region, Senegal
- **Practice**: Community-led composting programs used agricultural and urban waste to improve soil fertility in peri-urban farming.
- **Findings**:
  - **SOC Gains**: SOC levels increased by **0.5 Mg/ha/year** in compost-amended soils [38].
  - **Food Security**: Vegetable yields increased by **35%,** supporting urban food systems.
  - **Waste Management**: Composting diverted significant organic waste from landfills, reducing methane emissions [39].
- **Challenges**: Limited infrastructure for organic waste collection hindered scaling.
- **Implications**: Municipal partnerships could enhance waste management and composting initiatives.

## 6. Conclusions

Carbon farming presents a transformative opportunity for smallholder agriculture by combining climate mitigation with resilience-building. Practices such as agroforestry, cover cropping, and composting not only sequester carbon but also enhance soil fertility, water management, and biodiversity. However, realizing its full potential requires addressing technical, economic, and policy barriers. Multilateral collaborations, carbon financing mechanisms, and capacity-building initiatives will be crucial for scaling carbon farming across smallholder landscapes.

## 7. Recommendations

- **Capacity Building**: Governments and NGOs should invest in farmer education programs to promote knowledge of carbon farming techniques.
- **Incentives for Adoption**: Subsidies, grants, and carbon credits can lower entry barriers for smallholders.
- **Policy Support**: National policies should integrate carbon farming into agricultural strategies and provide institutional frameworks for carbon credit markets.
- **Research and Development**: Continued research on low-cost, locally adapted carbon farming practices is essential for success.
- **Public-Private Partnerships**: Collaborations can enhance resource mobilization and innovation in carbon farming technologies.

## Author Contributions

Conceptualization, S.M.S. and I.P.S.; methodology, M.M.A.; software, S.M.S.; validation, I.P.S., M.M.A. and B.S.S.; formal analysis, S.M.S.; investigation, B.S.S.; resources S.M.S.; data curation, I.P.S.; writing—original draft preparation, S.M.S.; writing—review and editing, I.P.S. and M.M.A.; visualization, B.S.S.; supervision, S.M.S.; project administration, S.M.S., I.P.S. and B.S.S.; funding acquisition, No funding. All authors have read and agreed to the published version of the manuscript.

## Funding

No external funding.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

Desk review of journals, books, internets etc, as provided in the reference section.

## Conflicts of Interest

The authors declare no conflict of interest.

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