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# Exploring the Trade-offs and Synergies of Soil Carbon Sequestration: Bridging Knowledge Gaps in Soil Management Strategies

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## Abstract
***Soil carbon sequestration has emerged as a critical strategy for mitigating climate change, enhancing soil health, and promoting sustainable agriculture. This process involves the capture and storage of atmospheric carbon dioxide ($CO_2$) in the soil, primarily through organic matter accumulation and the activity of soil microorganisms. However, the effectiveness of soil carbon sequestration is influenced by various soil management practices, which can create trade-offs and synergies among ecological, economic, and social dimensions.This paper aims to explore these trade-offs and synergies by analyzing current soil management strategies and their impacts on soil carbon storage. We will assess the role of practices such as cover cropping, reduced tillage, crop rotation, and agroforestry in enhancing soil organic carbon levels while also examining potential drawbacks, such as increased nutrient depletion and water usage. Furthermore, we will discuss the implications of these practices on soil biodiversity, agricultural productivity, and the socio-economic landscape of farming communities.In addition, we will highlight knowledge gaps that hinder the widespread implementation of effective soil management strategies. These gaps include the need for localized research to determine the specific conditions under which certain practices are most effective, the importance of understanding farmer perceptions and behaviors towards adopting new methods, and the necessity of integrating soil carbon sequestration into broader agricultural policies and incentives.***

**Keywords:** ***Soil carbon sequestration, Soil management strategies, Trade-offs, Synergies, Agricultural sustainability, Soil health, Climate change mitigation, Organic matter accumulation, Cover cropping, Reduced tillage, Agroforestry,Soil biodiversity.***

## 1.Introduction
Soil carbon sequestration has gained prominence as a vital tool in addressing climate change and promoting sustainable land management practices. As the global agricultural sector faces mounting pressures from climate variability, soil degradation, and an increasing population demanding food security, the potential of soils to act as a carbon sink presents both an opportunity and a challenge(1). The process of capturing and storing atmospheric carbon dioxide ($CO_2$) within soil systems is influenced by a variety of factors, including land use, soil type, climatic conditions, and management practices. Understanding the complexities involved in these interactions is essential for optimizing soil management strategies that not only enhance carbon sequestration but also support agricultural productivity and ecosystem health.
The relationship between soil management practices and carbon sequestration is characterized by trade-offs and synergies that can have significant implications for ecological and socio-economic outcomes. For instance, while practices such as cover cropping and reduced tillage can lead to increased soil organic carbon levels, they may also present challenges such as higher initial costs, labor requirements, and potential negative impacts on crop yields in the short term(2). Conversely, some conventional practices aimed at maximizing immediate agricultural output may inadvertently lead to soil degradation and a decrease in carbon storage capacity over time. This duality highlights the need for a nuanced approach to soil management that balances short-term agricultural goals with long-term environmental sustainability.
Moreover, knowledge gaps persist in understanding the specific contexts under which different soil management practices can effectively contribute to carbon sequestration. There is a pressing need for localized research that examines the unique soil and climatic conditions of various regions, as well as the socio-economic factors that influence farmers' decisions to adopt or reject certain practices(3). By bridging these gaps, researchers and practitioners can develop more targeted strategies that promote the widespread adoption of sustainable soil management practices.

In addition, integrating soil carbon sequestration into broader agricultural policies and incentives is crucial for fostering a conducive environment for innovation and adaptation. Policymakers must recognize the multifaceted benefits of soil carbon sequestration, not only as a means of mitigating climate change but also as a pathway to enhancing food security, improving soil health, and supporting rural livelihoods. By creating frameworks that encourage research, education, and collaboration among stakeholders, we can foster a more resilient agricultural landscape that effectively addresses the challenges of climate change while promoting sustainable soil management practices.
Ultimately, exploring the trade-offs and synergies of soil carbon sequestration presents a compelling opportunity to reimagine agricultural practices in a way that aligns with ecological integrity and social equity. This research seeks to illuminate these dynamics and contribute to a more holistic understanding of soil management strategies that can drive meaningful change in the context of a rapidly changing world. Through a comprehensive examination of current practices, their impacts, and the pathways for overcoming knowledge gaps, we aim to provide actionable insights that can inform the future of sustainable agriculture and carbon management.

## 2.Literature Survey

The exploration of soil carbon sequestration has been a focal point of research in the fields of soil science, environmental science, and agricultural studies over the past few decades. Numerous studies have demonstrated the potential of soil to store carbon, primarily through the accumulation of organic matter and the activity of soil microorganisms. For instance, Smith et al. (2016) highlighted the role of agricultural practices in enhancing soil organic carbon (SOC) levels, emphasizing the importance of implementing conservation tillage, cover cropping, and crop rotation as effective strategies for increasing SOC(4). These practices not only promote carbon storage but also improve soil structure, enhance nutrient cycling, and mitigate erosion, thereby supporting overall soil health.
However, while many studies have focused on the benefits of specific soil management practices, fewer have addressed the trade-offs associated with these strategies. For example, research by West and Post (2002) identified that the immediate adoption of certain practices could result in short-term declines in crop yields or increased input costs, creating resistance among farmers to implement these methods. Moreover, some studies have indicated that practices such as cover cropping may require additional management inputs, which can vary significantly based on local context and socioeconomic factors. This complexity necessitates a more nuanced understanding of the implications of soil management decisions on both carbon sequestration potential and agricultural productivity.
In recent years, the emphasis on quantifying the net effects of different management practices on soil carbon sequestration has increased. For instance, studies like those by Paustian et al. (2016) have provided insights into the carbon sequestration potential of diverse agricultural systems, demonstrating that integrating agroforestry and agroecological principles can lead to significant increases in SOC. These findings underscore the importance of adopting multifaceted approaches that leverage biodiversity and ecosystem services to enhance soil carbon storage. However, such practices often face barriers to adoption, including the need for financial investment and changes in farmer knowledge and behavior.
In addition to focusing on agricultural practices, recent literature has highlighted the importance of policy frameworks and incentives in promoting soil carbon sequestration. Research by Lal (2020) emphasizes that supportive policies can facilitate the adoption of sustainable practices by providing financial incentives, technical assistance, and education. Furthermore, the integration of soil carbon sequestration into national and international climate policies is essential for creating a supportive environment for farmers to invest in these practices. The establishment of carbon credit markets and payment for ecosystem services has shown promise in encouraging the adoption of sustainable land management practices that enhance carbon storage(5).
Despite the wealth of research in this area, significant knowledge gaps remain regarding the effectiveness of various soil management strategies in diverse contexts. Many studies have been conducted in specific regions or under controlled conditions, limiting the generalizability of findings to broader agricultural landscapes. There is a pressing need for more localized research that considers the unique socio-economic, cultural, and environmental contexts of different farming systems. This will allow for the development of tailored management strategies that effectively balance the trade-offs and synergies of soil carbon sequestration in practice.
Overall, the literature indicates a growing recognition of the critical role of soil carbon sequestration in sustainable agriculture and climate change mitigation. However, to realize its full potential, further research is needed to bridge the existing knowledge gaps and facilitate the adoption of effective soil management strategies. By understanding the

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complexities and interactions involved in soil carbon dynamics, we can better inform policymakers, researchers, and practitioners working towards sustainable agricultural practices that benefit both the environment and the agricultural community.

## 3.Existing and Proposed System

The existing systems for soil carbon sequestration primarily rely on traditional agricultural practices, which often prioritize immediate yield maximization over long-term soil health. Current methods include conventional tillage, monoculture cropping, and chemical fertilizers, which have been widely adopted due to their perceived short-term benefits. However, these practices can lead to soil degradation, reduced soil organic carbon (SOC) levels, and increased greenhouse gas emissions(6). Despite the understanding of the critical role of soil health in supporting sustainable agriculture, many farmers remain hesitant to adopt innovative practices due to a lack of awareness, financial constraints, and insufficient support systems.

In some regions, soil management practices are informed by government programs that promote conservation agriculture, cover cropping, and agroforestry. While these initiatives have shown promise in enhancing carbon sequestration, their implementation is often limited by a lack of consistent funding, technical expertise, and education for farmers. Moreover, many existing policies do not fully integrate soil carbon sequestration into broader climate strategies, which undermines their potential effectiveness. Furthermore, data collection and monitoring of SOC levels remain fragmented, making it difficult to assess the effectiveness of current practices and policies comprehensively.

**Proposed System**

To enhance the effectiveness of soil carbon sequestration efforts, a proposed system would focus on integrating advanced soil management practices, robust policy frameworks, and comprehensive education programs. This system would emphasize sustainable practices such as cover cropping, reduced tillage, crop rotation, and agroforestry, designed to increase SOC levels while maintaining or improving agricultural productivity. By leveraging precision agriculture techniques and soil health assessments, farmers can make informed decisions tailored to their specific soil and climatic conditions, maximizing both carbon sequestration and crop yield.

Moreover, the proposed system would incorporate financial incentives and technical support to encourage farmers to adopt these sustainable practices. Establishing payment for ecosystem services (PES) programs and carbon credit markets could provide the necessary economic motivation for farmers to invest in soil health initiatives. Additionally, creating educational programs and outreach efforts would facilitate knowledge sharing among farmers, researchers, and policymakers, fostering a collaborative environment for implementing soil management strategies effectively.

To bridge existing knowledge gaps, the proposed system would also prioritize localized research that examines the impacts of various soil management practices across different regions and contexts. This research would focus on understanding the specific socio-economic, environmental, and cultural factors that influence farmers' decisions regarding soil management. By addressing these complexities, the system aims to promote practices that enhance soil carbon sequestration while ensuring the long-term viability and resilience of agricultural systems.

## 4. Soil Carbon Sequestration: Concepts and Mechanisms

Soil carbon sequestration (SCS) refers to the process of capturing and storing atmospheric carbon dioxide ($CO_2$) in the soil, primarily through the enhancement of soil organic carbon (SOC) levels. This process is crucial for mitigating climate change, improving soil health, and enhancing agricultural productivity(7). The mechanisms and concepts underpinning soil carbon sequestration are multifaceted and involve biological, chemical, and physical processes.

**1. Conceptual Framework of Soil Carbon Sequestration**

Soil carbon sequestration operates under the principle that carbon can be stored in the soil for long periods, thus removing it from the atmosphere. This occurs through two primary processes:

- Photosynthesis: Plants absorb $CO_2$ during photosynthesis and convert it into organic matter, which is subsequently transferred to the soil as root biomass, litter, and decaying plant material.
- Soil Organic Matter Formation: Decomposed plant and animal residues are transformed into stable organic matter, known as humus, which contributes significantly to soil carbon stocks.

- The balance between carbon inputs (from plant growth and organic amendments) and outputs (decomposition and respiration) determines the net carbon storage in soils(8).

**2. Mechanisms of Soil Carbon Sequestration**

Several mechanisms contribute to soil carbon sequestration:

- Microbial Activity: Soil microorganisms play a vital role in decomposing organic materials, leading to the formation of stable SOC. They break down complex organic compounds into simpler forms, which can be incorporated into soil aggregates, protecting carbon from further decomposition.
- Soil Aggregation: The formation of soil aggregates helps protect organic carbon from microbial attack. Aggregates create a microenvironment that limits oxygen access, reducing the rate of organic matter decomposition(9).
- Chemical Stabilization: Some soil minerals, such as clay and iron oxides, can chemically bind with organic carbon, forming stable complexes that resist degradation. This chemical stabilization is crucial for long-term carbon storage.
- Physical Protection: Organic carbon can be physically protected within soil aggregates, preventing its decomposition by microorganisms. The size and stability of aggregates influence the extent of this protection.

**3. Factors Influencing Soil Carbon Sequestration**

Several factors influence the capacity of soils to sequester carbon:

- Soil Type and Texture: Different soil types have varying capacities for carbon storage. Soils rich in clay tend to have higher carbon sequestration potential due to their ability to bind with organic matter.
- Land Use and Management Practices: Agricultural practices, such as crop rotation, cover cropping, reduced tillage, and organic amendments (e.g., compost and biochar), enhance soil carbon sequestration by increasing organic inputs and reducing carbon losses.
- Climate: Temperature and precipitation influence plant growth and decomposition rates. Warmer temperatures can increase decomposition rates, leading to carbon losses unless offset by enhanced plant growth.
- Biological Diversity: A diverse soil microbial community can improve the decomposition of organic matter and the formation of stable soil aggregates, enhancing carbon sequestration.

**4. Soil Carbon Sequestration and Climate Change Mitigation**

Soil carbon sequestration is recognized as a vital strategy in global efforts to mitigate climate change. By enhancing SOC levels, SCS can help offset greenhouse gas emissions and contribute to climate resilience. Key benefits include:

- Reduction of Atmospheric CO2: Increased SOC levels directly reduce atmospheric CO2 concentrations, which is essential for limiting global warming.
- Improved Soil Health: Higher SOC levels enhance soil structure, fertility, and water retention, leading to improved agricultural productivity and ecosystem health.
- Biodiversity Enhancement: Healthy soils support diverse microbial and plant communities, promoting ecosystem stability and resilience.

**5. Challenges and Limitations of Soil Carbon Sequestration**

Despite its potential, several challenges limit the effectiveness of soil carbon sequestration:

- Measurement and Verification: Accurately measuring SOC levels and changes over time can be complex and resource-intensive, hindering the implementation of SCS practices.
- Permanence: The stability of sequestered carbon is a concern, as changes in land use, climate events, or management practices can lead to the release of stored carbon back into the atmosphere.
- Economic Viability: The economic incentives for farmers and landowners to adopt practices that enhance carbon sequestration may be insufficient, necessitating policy support and market mechanisms.
- Knowledge Gaps: There are still significant gaps in understanding the specific mechanisms, optimal practices, and long-term impacts of SCS on soil health and agricultural productivity(10).

**6. Future Directions for Soil Carbon Sequestration Research**

To enhance soil carbon sequestration, future research should focus on:

- Innovative Agricultural Practices: Developing and testing new practices that optimize carbon inputs while minimizing losses.

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- Long-term Monitoring: Establishing long-term studies to understand the dynamics of SOC changes and the impact of different management practices.
- Policy Development: Creating policies that incentivize carbon sequestration practices, promote sustainable land use, and support research and development.
- Community Engagement: Involving local communities and stakeholders in the development and implementation of soil carbon sequestration initiatives to ensure their effectiveness and sustainability.

## 5. Trade-offs in Soil Carbon Sequestration

Soil carbon sequestration (SCS) refers to the process of capturing and storing atmospheric carbon dioxide (CO2) in the soil, primarily through the accumulation of soil organic carbon (SOC). This process is critical for climate change mitigation, enhancing soil health, and improving agricultural productivity. However, implementing SCS practices involves various trade-offs that must be carefully considered to maximize benefits and minimize potential downsides(11). This document explores the multifaceted trade-offs associated with soil carbon sequestration.

**1. Agricultural Productivity vs. Carbon Sequestration**

Enhancement of Soil Health: Practices that increase SOC, such as cover cropping, reduced tillage, and organic amendments, can improve soil structure, nutrient availability, and water retention. These benefits can lead to enhanced agricultural productivity over time.

Trade-off: Some practices aimed at increasing carbon sequestration may initially reduce crop yields. For instance, cover crops might compete with main crops for nutrients and water, leading to short-term reductions in productivity. Farmers may face a dilemma between immediate yields and long-term soil health and sustainability.

**2. Soil Carbon Sequestration vs. Land Use Conflicts**

Land Use Flexibility: SCS practices can offer opportunities to restore degraded lands, enhance biodiversity, and improve ecosystem services.

Trade-off: Expanding land for carbon sequestration (e.g., through reforestation or afforestation) can compete with agricultural land use, potentially threatening food security. The demand for land for biofuel production or carbon farming can lead to a reduction in arable land, creating a tension between agricultural production and environmental goals.

**3. Immediate Economic Costs vs. Long-term Benefits**

Long-term Gains: Adopting SCS practices can lead to long-term benefits, including reduced input costs (e.g., fertilizers) and increased crop resilience to climate extremes.

Trade-off: The initial investment required for implementing new practices (e.g., purchasing cover crop seeds or equipment for reduced tillage) can be substantial. Farmers may be hesitant to incur these upfront costs without guaranteed immediate returns, especially in regions where financial support for sustainable practices is lacking.

**4. Stabilization of Carbon vs. Risks of Re-release**

Carbon Stabilization: SCS can sequester significant amounts of carbon, contributing to climate change mitigation by reducing atmospheric CO2 levels.

Trade-off: The stability of sequestered carbon can be compromised by land-use changes, soil disturbance, or extreme weather events (e.g., drought, flooding). If soils are disturbed or managed improperly, the carbon stored may be released back into the atmosphere, negating the sequestration benefits. This risk underscores the need for sustainable management practices to ensure the longevity of carbon storage.

**5. Local Benefits vs. Global Impact**

Regional Adaptability: SCS practices can be tailored to local conditions, improving soil health and agricultural productivity in specific regions.

Trade-off: While localized solutions can provide significant benefits, they may not translate to a global scale. The effectiveness of SCS can vary significantly based on soil type, climate, and management practices. As such, strategies that work well in one region may be ineffective or even detrimental in another, complicating efforts to achieve global carbon reduction targets.

**6. Biodiversity Enhancement vs. Monoculture Practices**

Increased Biodiversity: Implementing diverse cropping systems and cover crops can enhance soil carbon storage and promote biodiversity, improving ecosystem resilience.

Trade-off: In some agricultural systems, particularly those reliant on monoculture, the transition to more diverse systems can be challenging. Farmers may resist changes due to concerns about market demand for specific crops, pest management complexities, and potential yield variability(12). This resistance can limit the adoption of beneficial practices that enhance carbon sequestration and biodiversity.

**7. Technological Solutions vs. Traditional Practices**

Innovative Approaches: Advances in technology, such as precision agriculture and remote sensing, can optimize SCS practices, improving efficiency and effectiveness.

Trade-off: The reliance on technological solutions may overlook traditional ecological knowledge and practices that have been effective for centuries. Overemphasis on high-tech solutions may marginalize smallholder farmers or those in developing regions who may lack access to advanced technologies. Ensuring inclusivity in SCS strategies is essential to achieve equitable outcomes.

## 6. Bridging Knowledge Gaps in Soil Management Strategies

Soil management is essential for sustainable agriculture, environmental protection, and climate resilience. However, significant knowledge gaps exist in various aspects of soil management strategies, which can impede effective decision-making and hinder the adoption of best practices. This document outlines the critical areas where knowledge gaps are prevalent and offers recommendations for bridging these gaps.

**1. Understanding Soil Properties and Health**

**Knowledge Gaps:**

Many farmers lack comprehensive knowledge about soil properties, including nutrient content, pH, moisture retention, and biological activity.

There is insufficient understanding of the relationship between soil health and crop productivity, leading to suboptimal management practices.

**Recommendations:**

Soil Testing: Promote regular soil testing to assess nutrient levels and other properties. Educational programs can help farmers understand test results and make informed decisions about soil amendments and management.

Training and Workshops: Organize workshops that cover soil health principles, the importance of soil organic matter, and the role of soil organisms. Engaging local agricultural extension services can help disseminate knowledge effectively.

**2. Best Practices for Soil Conservation**

**Knowledge Gaps:**

Farmers may not be aware of or lack access to the latest best practices for soil conservation, such as cover cropping, crop rotation, reduced tillage, and agroforestry.

There is often a disconnect between research findings and practical applications in local farming systems.

**Recommendations:**

Demonstration Projects: Establish demonstration farms that showcase successful soil conservation techniques. Farmers can observe and learn from practical implementations.

Peer-to-Peer Learning: Facilitate farmer-to-farmer networks where experienced farmers can share their knowledge and practices with others, fostering a culture of collaborative learning.

**3. Impact of Climate Change on Soil Management**

**Knowledge Gaps:**

The influence of climate change on soil health and management practices is not well understood, particularly in terms of shifting rainfall patterns, temperature changes, and extreme weather events.

Many farmers may lack awareness of climate-resilient practices that can mitigate soil degradation in the face of climate challenges.

**Recommendations:**

Research Initiatives: Support interdisciplinary research that examines the impacts of climate change on soil health and the effectiveness of different management practices under changing conditions.

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Adaptation Strategies: Develop and disseminate guidelines on climate-smart agriculture that focus on practices that enhance soil resilience, such as mulching, organic amendments, and adaptive cropping systems.

**4. Integrating Technology in Soil Management**

**Knowledge Gaps:**

Farmers may have limited understanding of how to utilize new technologies (e.g., precision agriculture, remote sensing) for effective soil management.

There is a need for training on interpreting data generated from technological tools and translating it into actionable soil management strategies.

**Recommendations:**

Capacity Building: Provide training sessions focused on using technology for soil monitoring and management. This can include workshops on interpreting soil moisture sensors, yield mapping, and variable rate technology.

Accessible Platforms: Develop user-friendly platforms or apps that aggregate soil data and provide tailored recommendations for farmers based on their specific soil conditions and management goals.

**5. Economic and Policy Implications of Soil Management**

**Knowledge Gaps:**

Farmers often lack knowledge of the economic benefits of sustainable soil management practices, including cost savings from reduced inputs and increased yields.

There is limited awareness of available policies and incentives that support sustainable soil management practices, such as grants, subsidies, or certification programs.

**Recommendations:**

Economic Analysis: Conduct research that quantifies the economic benefits of sustainable soil management practices, providing farmers with data to support their adoption.

Policy Advocacy: Engage with policymakers to promote soil health initiatives and incentives. Provide farmers with information on existing policies that can support their soil management efforts.

**6. Cultural and Social Factors Influencing Soil Management**

**Knowledge Gaps:**

Socio-cultural factors can significantly influence farmers' willingness to adopt new practices, yet there is often a lack of understanding of these dynamics.

The role of traditional knowledge in soil management is often overlooked, leading to missed opportunities for integrating local practices with scientific approaches.

**Recommendations:**

Community Engagement: Conduct participatory research to understand local beliefs, values, and practices regarding soil management. This can help tailor strategies that resonate with community members.

Incorporating Traditional Knowledge: Encourage the integration of traditional ecological knowledge into modern soil management practices, recognizing the value of local insights in enhancing soil health.

## 7.Conclusion and Future work

Exploring the trade-offs and synergies of soil carbon sequestration (SCS) is essential for developing effective soil management strategies that support both agricultural productivity and climate change mitigation. While SCS presents significant opportunities for enhancing soil health and capturing atmospheric carbon, it also involves complex trade-offs that can affect agricultural practices, land use, and economic viability. Understanding these dynamics is crucial for making informed decisions that maximize benefits while minimizing adverse impacts.

Bridging knowledge gaps in soil management strategies is a critical step toward achieving sustainable land use practices. Increased awareness and understanding of soil properties, conservation practices, the impacts of climate change, the integration of technology, and socio-economic factors will empower farmers and stakeholders to adopt practices that enhance soil carbon storage effectively. Engaging farmers, researchers, policymakers, and communities in collaborative efforts can foster innovation and ensure that strategies are context-specific and culturally appropriate.

**Future Work**

To address the ongoing challenges and leverage the potential of soil carbon sequestration, several key areas of future work are recommended:

- Interdisciplinary Research: Conduct comprehensive studies that integrate soil science, agronomy, ecology, and economics to better understand the interactions between soil management practices, carbon sequestration, and overall ecosystem health. This research should focus on the long-term impacts of different management practices on soil carbon dynamics.
- Development of Best Practices: Create and disseminate practical guidelines and resources that outline best practices for soil management aimed at optimizing carbon sequestration. These resources should be accessible and tailored to various agricultural systems and local conditions.
- Technological Innovations: Explore advancements in precision agriculture and remote sensing technologies that can enhance monitoring and management of soil carbon. Research should focus on developing tools that provide real-time data and recommendations to farmers, facilitating informed decision-making.
- Economic Assessment: Perform detailed economic analyses that quantify the financial benefits of adopting carbon sequestration practices. This should include evaluations of cost savings from improved soil health and potential revenue from carbon credits or other incentives.
- Policy Development: Advocate for policies that support sustainable soil management practices, including financial incentives, education programs, and regulatory frameworks that encourage the adoption of carbon sequestration techniques.
- Community Engagement: Foster participatory approaches that engage local communities in soil management decision-making. This includes recognizing and integrating traditional ecological knowledge with scientific practices to create holistic management strategies.
- Monitoring and Evaluation: Establish robust monitoring and evaluation frameworks to assess the effectiveness of soil carbon sequestration practices over time. This will ensure that adaptive management approaches are in place to respond to changing conditions and new findings.
- By prioritizing these areas of future work, stakeholders can develop integrated soil management strategies that effectively balance the trade-offs and synergies associated with soil carbon sequestration. This approach will not only enhance soil health and agricultural productivity but also contribute significantly to global efforts in climate change mitigation and environmental sustainability.

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## Conflicts of interest

The authors have no conflicts of interest to declare

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