



The Carbon Beneath Us: Potential and Challenges of Soil Sequestration

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Soil carbon sequestration is a powerful natural process that helps tackle climate change by capturing carbon dioxide (CO₂) from the atmosphere and storing it in the soil through plant-soil interactions, where it becomes part of organic and inorganic matter, and in doing so not only reduces greenhouse gases but also enhances soil fertility, improves water retention, supports nutrient cycling, and strengthens ecosystem resilience, making soils vital for sustainable agriculture; in fact, soils store more carbon than the atmosphere and all plant life combined, yet human activities such as deforestation, overgrazing, and intensive farming have significantly depleted these reserves, creating an urgent need for restoration, and while different land-use systems like croplands, grasslands, and forests vary in their carbon storage potential, practices such as conservation agriculture, agroforestry, cover cropping, and integrated nutrient management can effectively rebuild soil carbon while maintaining productivity, although this approach is not without challenges, as soils have a finite capacity to store carbon, the stored carbon can be released if land management changes, and there are difficulties in measurement as well as economic and social barriers, nevertheless, global initiatives like the “4 per 1000” program are promoting improved practices worldwide, and with coordinated efforts in science, policy, and farmer participation, soil carbon sequestration stands out as a promising nature-based solution for improving soil health, ensuring food security, and stabilizing the climate.

Introduction

Soil carbon sequestration is increasingly recognized as one of the most effective nature-based solutions for addressing the dual challenges of climate change and land degradation. It refers to the process of transferring atmospheric carbon dioxide (CO₂) into the soil through biological, chemical, and physical pathways, where it is stored as soil carbon for varying durations. Plants play a central role in this process by capturing CO₂ through photosynthesis and allocating it into biomass, a portion of which eventually enters the soil system via roots, litter, and organic residues. Once incorporated into the soil, carbon becomes part of the soil organic matter (SOM) or contributes to inorganic carbon pools. Soils are the largest terrestrial reservoir of carbon, storing approximately 1500-3000 petagrams (Pg) of carbon to a depth of one meter or more. This amount exceeds the carbon held in the atmosphere and terrestrial vegetation combined. However, since the onset of intensive agriculture and deforestation, a significant proportion of this carbon has been lost to the atmosphere, contributing to the rise in greenhouse gas concentrations. In many agricultural soils, soil organic carbon (SOC) levels have declined below the critical threshold of 1.5–2.0%, resulting in degraded soil structure,

reduced fertility, and diminished ecosystem services Restoring soil carbon stocks is therefore essential not only for climate mitigation but also for improving soil health, enhancing water and nutrient use efficiency, supporting biodiversity, and ensuring long-term food and nutritional security. Soil carbon sequestration offers a “win-win” strategy by simultaneously addressing environmental sustainability and agricultural productivity

Types and Forms of Soil Carbon

Soil carbon exists in two major forms: soil organic carbon (SOC) and soil inorganic carbon (SIC), each differing in origin, dynamics and function.

1. Soil Organic Carbon (SOC)

SOC is derived from biological sources, including plant residues, root biomass, microbial cells, and decomposed organic matter. It is highly dynamic and forms the core of soil fertility and productivity. SOC can be divided into different fractions based on its stability Labile carbon: Easily decomposable, short-lived, and serves as an immediate energy source for soil microorganisms. Particulate organic matter (POM): Intermediate stability, often associated with plant residues. Recalcitrant or stable carbon: Resistant to decomposition, often present as humus or associated with minerals, and can persist for decades to centuries. SOC plays a crucial role in improving soil structure, aggregate stability, water retention, nutrient availability, and microbial activity. It also enhances soil resilience against erosion and environmental stress.

2. Soil Inorganic Carbon (SIC)

SIC consists primarily of carbonate minerals such as calcium carbonate (CaCO_3) and magnesium carbonate (MgCO_3). It originates either from parent material (primary or lithogenic carbonates) or forms during soil development through chemical reactions involving carbonic acid and base cations (secondary or pedogenic carbonates). The global SIC pool in the top one meter of soil is estimated to be around 950 Pg of carbon.

Although SIC is more stable than SOC and contributes to long-term carbon storage, its role in actively removing atmospheric CO_2 is less direct. However, in arid and semi-arid regions, the formation of secondary carbonates can act as an important mechanism for carbon sequestration over geological timescales.

Soil Carbon Distribution and Depth Dynamics

Contrary to the common perception that soil carbon is concentrated near the surface, a substantial proportion of both SOC and SIC is stored in deeper soil layers. Studies indicate that more than 50% of total soil carbon up to a depth of one meter is located below 30 cm. Subsoils often have lower carbon concentrations but a higher capacity for additional storage due to lower saturation levels. Deep-rooted plants play a significant role in enhancing carbon sequestration at depth by depositing carbon through root biomass and exudates. Therefore, breeding crops with deeper root systems and adopting management practices that promote subsoil carbon storage are important strategies for increasing total soil carbon stocks.

Mechanisms of Soil Carbon Sequestration and Stabilization

The persistence of carbon in soil depends on various stabilization mechanisms that protect it from rapid decomposition:

- Physical Protection: Carbon is physically protected within soil aggregates, particularly micro-aggregates, which shield organic matter from microbial attack. Tillage disrupts these aggregates, exposing protected carbon to decomposition and accelerating carbon loss.
- Chemical Stabilization: Organic carbon interacts with mineral surfaces such as clay particles and metal oxides (iron and aluminum), forming stable organo-mineral complexes. These interactions enhance the resistance of carbon to decomposition and increase its mean residence time
- Biological Processes: Microorganisms play a central role in transforming organic inputs into more stable forms of carbon. Through microbial metabolism, simple organic

compounds are converted into complex substances such as humus. Biological activity also contributes to the formation of aggregates, further stabilizing carbon.

The effectiveness of these mechanisms depends on environmental factors such as climate, soil texture, moisture, pH and microbial community composition.

Role of Land Use Systems in Soil Carbon Sequestration

Land use systems play a crucial role in determining the potential and efficiency of soil carbon sequestration. In croplands, agricultural soils have undergone substantial depletion of soil organic carbon (SOC), often losing about 25–75% of their original carbon stocks due to continuous cultivation, intensive tillage, and soil disturbance; however, this degradation also creates a significant opportunity for re-carbonization through improved management practices such as conservation agriculture, crop rotation, and residue retention, which enhance carbon inputs and reduce losses. Grasslands, which occupy a large proportion of the Earth's terrestrial surface, possess a high capacity for carbon sequestration primarily due to their extensive and deep root systems that continuously add organic matter to the soil; appropriate management practices such as controlled grazing, fertilization, and restoration of degraded lands can further increase SOC levels in these ecosystems. Forest ecosystems serve as major carbon sinks by storing large amounts of carbon both aboveground in biomass and belowground in soil; natural forests typically contain higher SOC stocks compared to plantations, but sustainable forest management practices—including controlled harvesting, careful species selection, and fire management—can significantly enhance soil carbon storage while maintaining ecosystem stability.

Strategies for Enhancing Soil Carbon Sequestration

Enhancing soil carbon sequestration requires the adoption of sustainable land management practices that improve carbon inputs while minimizing losses. Conservation agriculture, which involves minimal soil disturbance, permanent soil cover, and diversified crop rotations, helps maintain soil structure and reduce carbon loss. Agroforestry integrates trees with crops and livestock, thereby increasing biomass input and promoting long-term carbon storage. Integrated nutrient management ensures a balanced use of organic and inorganic fertilizers, improving soil fertility and supporting microbial activity. Practices such as cover cropping and mulching protect the soil surface from erosion while adding organic matter to the soil. Efficient water management, including proper irrigation and moisture conservation techniques, further supports plant growth and carbon input. Additionally, afforestation and land restoration efforts play a significant role in reclaiming degraded lands and enhancing carbon sequestration. Together, these practices aim to increase carbon inputs, reduce carbon losses, and improve overall soil structure and function.

Challenges and Limitations

Soil carbon sequestration faces several important challenges that limit its effectiveness and large-scale adoption. One major constraint is the finite storage capacity of soils, as they can only store carbon up to a certain level, after which sequestration rates begin to decline. Additionally, the process is reversible, meaning that stored carbon can be rapidly lost due to disturbances such as intensive tillage, deforestation, or changing climatic conditions. There is also significant spatial variability, as sequestration rates differ widely depending on soil type, climate, vegetation, and management practices, making it difficult to generalize outcomes. Accurate measurement and monitoring of soil organic carbon (SOC) changes present further challenges, as these processes are complex, time-consuming, and often costly. Beyond technical issues, socio-economic constraints such as lack of awareness among farmers, limited financial resources, insecure land tenure, and weak policy support hinder the adoption of sustainable land management practices. Moreover, there are trade-offs and uncertainties associated with some sequestration strategies, as they may involve hidden environmental or economic costs, and their long-term impacts are not always fully understood.

Global Initiatives and Policy Perspectives

Global initiatives and policy perspectives on soil carbon sequestration have gained significant momentum as part of broader climate change mitigation and sustainable land management strategies. One of the most prominent efforts is the “4 per 1000” initiative launched during the COP21 climate conference in 2015, which proposes increasing global soil organic carbon (SOC) stocks by 0.4% annually in the top soil layers. The rationale behind this target is that even a small annual increase in SOC, when applied globally, could substantially offset a portion of anthropogenic CO₂ emissions while simultaneously improving soil fertility, water retention, and agricultural productivity. Achieving this ambitious goal requires strong collaboration among governments, research institutions, farmers, and international organizations to promote science-based soil management practices and improve carbon accounting systems. Policy frameworks are therefore essential in translating scientific understanding into practical implementation. Governments are increasingly exploring mechanisms such as incentives for sustainable land management, subsidies for conservation agriculture, and payments for ecosystem services (PES), which reward farmers for maintaining or enhancing soil carbon stocks. Carbon credit markets and climate-smart agriculture programs are also being developed to integrate soil carbon sequestration into broader climate mitigation strategies. In addition, improved land governance, secure land tenure rights, and farmer participation are critical to ensuring long-term adoption of sustainable practices. In developing countries, these challenges are more pronounced due to widespread land degradation, poverty, limited access to technology, and inadequate infrastructure, which restrict the ability of smallholder farmers to invest in soil restoration practices. Therefore, successful implementation of soil carbon sequestration at a global scale depends not only on scientific and technical advancements but also on strong institutional support, equitable policy design, financial incentives, and capacity-building programs that empower local farming communities.

Conclusion

Soil carbon sequestration stands out as a highly significant and multifaceted strategy for addressing interconnected global challenges such as climate change mitigation, land degradation, declining soil fertility, and food insecurity. By increasing soil organic carbon levels, it not only reduces atmospheric carbon dioxide concentrations but also strengthens a wide range of soil functions, including improved nutrient cycling, enhanced water-holding capacity, better soil structure, increased microbial activity, and greater biodiversity. These improvements collectively contribute to more resilient and productive agroecosystems capable of sustaining growing population demands under changing climatic conditions. However, the success of soil carbon sequestration is strongly dependent on maintaining a consistent positive carbon balance, which requires the careful selection and implementation of site-specific land management practices that match local soil, climate, and socio-economic conditions. At the same time, several constraints—including the finite capacity of soils to store carbon, the risk of carbon reversal due to land-use change or climate extremes, and uncertainties in long-term monitoring—must be effectively addressed through scientific innovation and adaptive management. Moving forward, the future of soil carbon sequestration will rely on integrating advanced soil science with practical agricultural approaches, strengthening institutional and policy frameworks, and ensuring active participation of farmers and land managers. Global cooperation, financial incentives, and knowledge-sharing platforms will be essential to scale up successful practices. Ultimately, by recognizing soils as a vital natural resource and carbon reservoir, humanity can transform degraded landscapes into productive, climate-resilient systems, thereby shifting soils from net carbon sources to powerful carbon sinks that support long-term environmental sustainability and human well-being.

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