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Soil management strategies for increasing carbon sequestration: A review

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Abstract
Present review investigates the importance of soil management strategies for improving carbon sequestration in soil which ultimately helps to alleviate the effects of climate change. The process by which CO_2 is either removed from the atmosphere or redirected from emission sources and deposited in the ocean, terrestrial habitats (vegetation, soils, and sediments), and geologic formations is known as "carbon sequestration." This procedure may be purposeful or unintentional. The amount of carbon dioxide (CO_2) in the atmosphere has increased dramatically due to human activities, particularly the combustion of fossil fuels such as coal, oil, and gas. Global warming is being observed as a result of the increase in atmospheric CO_2 over the last 250 years, from approximately 280 to more than 380 parts per million (ppm). Some of the potential negative effects include sea level rise, increased frequency and severity of wildfires, floods, droughts, and tropical storms, changes to the quantity, timing, and distribution of precipitation, snowfall, and runoff, and disruption of coastal marine and other ecosystems. The fundamental mechanisms of soil carbon sequestration, the dynamics of soil organic matter (SOM) and the variables influencing the soil carbon sequestration, such as, climate, soil texture, land use and management techniques are all essential topics. It provides a complete review of soil management strategies, stressing their benefits for increasing soil fertility, structure and carbon storage. Crop rotation, composting and the use of organic amendments (manure, compost and biochar) are examples of such practices. It also investigates how agroforestry and cover crops might increase soil health and sequester carbon. The paper emphasizes the importance of technological advancements in monitoring and validating soil carbon sequestration, as well as the technical, economic, and environmental challenges associated with implementing these methods.

Keywords: Soil management strategies, carbon sequestration, soil organic matter

Introduction
Carbon sequestration is basically a naturally occurring process which permits carbon dioxide (CO_2) to be removed from the atmosphere and stored in carbon sinks on Earth including soil, oceans and forests ecosystem [1]. Carbon sequestration is a vital process because it can mitigates the consequences of climate change by lowering down the atmospheric concentration of CO_2, a substantial greenhouse gas (GHG) that contributes to global warming [2]. Soil acts as a significant carbon sink as it stores three times as much carbon as the atmosphere and four times as much as the biota [3]. Soil carbon sequestration occurs when plants absorb CO_2 during photosynthesis and then transport it to the soil via root biomass and litter fall. Here it is as soil organic carbon (SOC) in storage [4]. Land use and agricultural practices have a considerable impact on the carbon movement which is quantified as the amount of carbon transferred between soil and atmosphere. Although natural ecosystems are typically carbon sinks, soil tillage and other agricultural activities have the potential to convert these sinks into sources of carbon emissions. While, deforestation for agricultural development causes significant carbon losses, excessive tillage accelerates the breakdown of organic matter and emits CO_2 into the atmosphere. To highlight the potential of well managed soils to operate as efficient carbon sinks, and therefore, plays a vital role in climate change mitigation. The review delves into the nuances of soil management strategies that increase carbon sequestration rates. The scope of study includes an examination of various soil management practices, the variables that influence the soil organic carbon dynamics and the challenges and successes in tracking and encouraging soil

carbon sequestration. This extensive research enables a full investigation of how different land uses and agricultural methods affect carbon flux. An in depth examination of soil's role as a carbon sink is offered, noting the wide range of variables that influence the soil potential to store carbon, such as, soil type, climate, land use and management approaches. In addition, the study summarizes the regulations, financial incentives and technological innovations that supports the sustainable soil management goal and increases the soil carbon sequestration rates. It underlines the importance of farmers and land managers implementing cost-effective and ecologically friendly soil conservation practices.

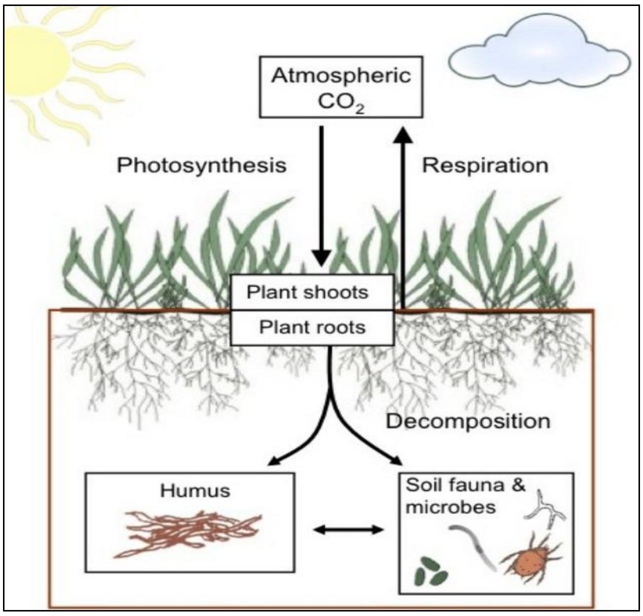

Image 1: Soil carbon storage

Concepts of soil carbon sequestration

Soil organic matter (SOM) is composed of the decomposing remains of former living creatures, such as plant and animal tissues, excrement and the compounds produced during their decomposition. Soil microbes *i.e.* bacteria and fungi majorly contributes to organic matter. SOM is a diverse mix of components with varying degrees of decomposition, ranging from newly harvested plant remnants to humus, a highly degraded substance. SOM is made up of extremely concentrated carbon organic compounds. The amount of organic matter in soil is closely related to the amount of soil organic carbon (SOC), and SOC is commonly used to quantify organic matter in soils. The interplay of various ecological processes including photosynthesis, respiration and decomposition leads to SOC levels. Photosynthesis is the process by which atmospheric CO_2 is fixed and converted into plant biomass. The biomass of a plant's roots influences its SOC input rates, which also include the litter that plant branches deposit. Soil carbon comes from both, the direct growth and death of plant roots, as well as the indirect transport of carbon-rich compounds from roots to soil microbes. For example, many plants form symbiotic associations known as mycorrhizae with specific fungi in the soil via their roots. While the fungi feed the plant with frequently rare nutrients such as phosphorus, the roots provide the fungi with energy in the form of carbon. A small percentage of the initial carbon is retained in the soil by the creation of humus, a process that frequently lends carbon-rich soils their distinguishing black hue (Fig. 1). The breakdown of biomass by soil microbes leads in carbon loss as CO_2 from the soil via microbial respiration. The resistance to breakdown, or recalcitrance, varies between these different forms of SOC. Humus dissolves slowly in soil due to its resistance to decomposition. Because plant detritus is less resistive, it remains in the soil for much shorter periods of time. Soil erosion and the leaching of dissolved carbon into groundwater are two more ecological processes that can cause carbon loss. When carbon inputs and outputs are balanced, SOC levels remain constant. SOC levels gradually rise as carbon inputs from photosynthesis outweigh carbon losses.

Mechanism of carbon sequestration in soil

The yearly average temperature and precipitation have an impact on the amount and vertical distribution of organic carbon in soil as well as its storage. These variables affect soil carbon uptake as well as soil organic carbon breakdown on a worldwide and sub-regional scale [5]. Vegetation cover which in turn affects how much carbon is stored in the soil. Organic matter that is added to the soil by vegetation eventually makes up a sizable portion of the soil carbon storage capacity. In addition, to being important topographical features, altitude and slope are also important for regulating the erosive processes and forming the vegetation patterns [6]. The rhizosphere is a complex web of life that is home to a wide variety of micro and macro-organisms. Because of this diversification, organic matter is both broken down and added to in a dynamic ecosystem that directly affects SOC levels. Therefore, the rhizosphere vigor solidifies its significance as a key component in SOC sequestration [7]. For a number of reasons, including erosion, decreased carbon inputs into the soil and degradation of organic matter stability, cultivated soils frequently suffer losses in SOC. The intense tilling and ploughing methods used in intensive farming cause erosion, which leads to the loss of organic carbon rich topsoil. This phenomena damages soil fertility, speeds up the depletion of SOC reserves and interferes with the carbon cycle. Moreover, decreased SOC levels can results from decreased carbon inputs in croplands, mostly from a drop in the return of crop residues and soil system organic manure [8]. To meet their nutritional and energetic needs, heterotrophic soilmicroorganisms such as bacteria, fungus, and protozoa break down organic substances. In the process of aggressively breaking down organic substrates, they create byproducts that are essential to the development of soil organic matter.

Management strategies

a) **Tillage:** It is evident that continuous cultivation has reduced natural SOC globally, with estimates indicating a loss of 60–75 percent of the original SOC in tropical regions and 75 percent in temperate regions [9]. Tillage techniques caused the worldwide soil carbon content to drop from 30 to 50 percent [10] to as low as 20 percent [11]. Under zero-tillage, the only soil disturbance that occurs is from the movement of the farming equipment that is often used for harvesting, seeding and weeding. The stability and quantity of soil aggregates are frequently increased by no tillage, although traditional tillage damages soil structure and accelerates the breakdown of soil organic matter. With conservation tillage, fewer tillage passes are needed each season and less aggressive tillage implements are used leaving more left over on the surface and less disturbance of soil aggregates. Adopting the zero tillage system results in a significant reduction of soil pressure which has several positive effects on the soil over time including improved water infiltration and an increase in the proportion and stability of macro-aggregates [12], lowering of erosion [13] and increased soil aeration [14]. The organic carbon stored in soil aggregates is less vulnerable to oxidation and subsequent release as CO_2 because they are not broken down by tillage [15].

b) Crop rotation: A series of crops cultivated on the same plot of land in a regularly occurring succession is known as crop rotation. It is closer to the diversity of natural eco-systems than intensive mono-cropping techniques. The amount of organic matter in the soil can be raised by changing the crops that are planted. Nevertheless, the kind of crops and the frequency of crop rotation determine how effective crop rotation is. Various legume crops, including sesbania, peas, lentils, alfalfa, and chickpeas, can be used as nitrogen substitutes. Crop rotation can help stabilize soil carbon, particularly when applied with legume cover crops, which contain carbon molecules that are probably more resistant to microbial degradation. [16] Syswerda *et al*., [17] presented the findings of a 12-year study conducted on an organic management system with a variety of crop rotations. Their study reported that significant tillage for weed management resulted in an increase in soil carbon sequestration. More diversified crop rotations consistently have higher soil carbon and soil microbial biomass than less diverse systems, according to a new meta-analysis, especially when cover crops are incorporated into the rotation (McDaniel *et al*., 2014) [18].

- **Cover crop**: Cover crops are plant species that are cultivated primarily to reduce soil compaction, promote microbial activity, enhance soil structure and improve soil health and agricultural sustainability rather than for the primary purpose of producing grain or fodder and accessible nutrients. They can also lessen soil erosion, enhance soil hydraulic characteristics, and replenish the soil with nitrogen. Because cover crops can absorb carbon dioxide from the atmosphere and release organic matter into the soil during their decomposition, they have a major impact on raising the carbon content of the soil. Lowering soil borne pathogen activity, improving soil quality metrics and reducing nutrient loss. In addition to reducing soil erosion and improving crop yields, their presence is crucial for sustainable farming methods. Several often utilized species of cover crops in agriculture chiefly Leguminous Broadleaves such as lentil (*Lens culinaris*), Pea (*Pisum sativum*), Sunn hemp (*Crotalaria juncea*), Clovers (*Trifolium spp.)*, Cowpea (*Vigna unguiculata*), Faba bean (*Vicia faba*), Hairy vetch (*Vicia villosa*), and Soybean (*Glycine max*).
  Broadleaves that are not legumes *i.e.* Buckwheat (*Fagopyrum esculentum*), Flax (*Linum usitatissimum*), Radish (*Raphanus sativus*), Rapeseed (*Brassica napus*), Safflower (*Carthamustinctorius*), and Sunflower (*Helianthus annuus*). (*Phaceliatenacetifolia*).
- Grasses: Oats (*Avena sativa*), Millet (*Pennisetumglaucum*), Rye (*Secale cereal*), Ryegrass (Loliumperenne), Barley (*Hordeumvulgare*), and Forage sorghum (*Sorghum biocolor*).

c) Soil biota: Microorganisms found in soil, especially heterotrophs like bacteria, fungus and protozoa are essential for boosting the soil carbon sequestration. They accomplish this by participating in the breakdown of organic materials which produces microbial exudates and residues. These by-products aids in the process of sequestering carbon and can make up a sizable amount of the carbon in the stable fraction of soil organic matter. Furthermore, soil microbes contributes to the stabilization of organic matter by turning degraded materials into humus, a stable form of organic matter and to the mineralization of organic matter, turning it into inorganic nutrients like nitrogen and phosphorus. Furthermore, carbon turnover, a decrease in carbonate, nitrogen mineralization, nutrient availability and metal mobility are all influenced by the interactions between soil microbes and other soil constituents, such as soil animals. These microbial activities increase soil fertility and structure, which in turn increases the soil's ability to store carbon. This helps to maintain soil biodiversity, which is crucial for ecosystem resilience and eventually lessens the impact of greenhouse gas emissions. Thus, the increase in carbon sequestration in the soil environment is largely due to soil microbes.

d) Residue management: Following crop harvesting, crop residues are the detached vegetative sections of crop plants that are purposefully allowed to decompose in the agricultural areas. Crop residue management is essential for increasing the soil carbon sequestration which provides a long term way to reduce global warming and increase soil fertility. Crop residue retention has been identified as a viable strategy to enhance soil organic carbon (SOC) levels highlighting the important role of crop residues in increasing carbon content in soil. The efficient retention and incorporation of crop residues into the soil can significantly contribute to the increase in SOC levels [19]. Moreover, it has been demonstrated that adding agricultural wastes to soil changes the labile and passive soil carbon pools, reducing gaseous emissions and assisting in carbon sequestration [20]. Minimum tillage techniques have also been proposed as a successful way to store carbon in dry land soils and thus reducing the possible loss of fertility and soil quality linked to traditional tillage techniques [21]. As per the Chaki *et al*. (2022) [23] their study highlighted the potential for crop residue management to improve soil carbon sequestration by showing how conservation farming methods, such as residue addition can have a substantial impact on soil carbon reservoirs. Thus, it is clear that crop residue management can play a vital role in raising the SOC levels in soils through efficient residue management techniques like residue retention, minimum tillage and the use of intercropping systems. This offers a sustainable approach to agricultural productivity, soil health and efforts to mitigate climate change.

Challenges and limitations

The practical implementation of carbon sequestration in soil faces significant hurdles, primarily stemming from the intricate and costly processes required for measuring and verifying carbon levels. Detecting even small changes in carbon, such as a 10 percent increase is challenging due to sampling errors, measurement uncertainties and soil property variations. Additionally, the minimal annual increase in soil carbon complicates accurate monitoring and attribution to specific land management practices. Soil's finite capacity to retain carbon, reaching saturation over time, further complicates sustainable sequestration efforts. Another obstacle arises from the distribution of sequestered carbon in different soil pools, each with varying residence times. These pools, including passive, active and slow pools, exhibit different decomposition rates and turnover times, adding complexity to predicting and managing soil carbon sequestration levels. Moreover, the non-permanence of sequestered carbon in soils presents a significant challenge, as carbon can easily be released back into the atmosphere through decomposition processes, undermining long-term sequestration reliability. Factors such as climate conditions, land use practices, and management strategies influence the rate of carbon loss from the soil. Lastly, the difficulty in distinguishing between naturally sequestered carbon and carbon stored due to human interventions complicates accurate assessment and monitoring. Advanced methods for precise measurement and identification are necessary to differentiate carbon captured through management practices from naturally sequestered carbon

Conclusion

Soil carbon sequestration is an effective solution to mitigate the alterations in climate. Soil ability to absorb and store carbon through natural processes and sustainable land management approaches holds greater potential for lowering down the atmospheric CO_2 levels. In addition to boosting the soil fertility, water retention and climate change resilience, we may boost soil carbon stores through strategies such as agroforestry, conservation agriculture, cover crops and organic amendments. Soil carbon sequestration offers benefits in addition to climate change mitigation. They include improved ecological services, enhanced biodiversity and higher agricultural outputs. These benefits help farmers, communities and the environment while also contributing to worldwide climate change mitigation efforts. However, challenges must be overcome such as the approaches scalability, the need for widespread acceptability and the importance of long term monitoring and assessment. Governments, agricultural groups and stakeholders must collaborate to support research, extension and education on sustainable land management approaches and provide incentives. Carbon sequestration in soil is a vital and effective tool in our arsenal as we navigate the complexities of climate change. We may take big steps towards a healthy future by utilizing the potential.

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