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Advances in Soil Carbon Sequestration: Implications for climate change mitigation

Ashutosh Majhi
M.Sc. (Ag) Research Scholar, Department of Soil Science and Agricultural Chemistry, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha

Abstract

Enhancing the storage of atmospheric carbon dioxide (CO_2) in soil organic matter in soil has become a key strategy in mitigating climate change through soil carbon sequestration. Soil management strategies to control global temperature rise become essential as global temperatures continue to rise. This piece discusses modern advancements in sequestering soil carbon, all the while providing an insight over the sustainable land-use practices, microbial interventions and technological innovations for significant carbon storage in diverse soil ecosystems. Conservation agriculture practices, like minimum tillage, cover crops, and agroforestry, have large scope in enhancing the SOC level and reducing greenhouse gas emissions. Biochar applications and organic soil amendments have also been considered to improve C stabilization and soil fertility because of their ability to amass biochar. Ultimately, the role of microbial communities in soil carbon dynamics is also becoming recognized as doing their share, if not more, in carbon cycling or long term sequestration of carbon. However, there are still obstacles in harnessing soil carbon sequestration to worldwide extent. There are constraints including economic, policy gaps and a need for standardization of measurement methodologies. At the same time, policy incentives in the sphere of carbon credit markets are knocking on doors and enabling them to integrate soil carbon sequestration into sustainable agricultural practices. Additionally, this article includes case studies of some of the successful soil carbon sequestration programs and discusses lessons learnt and potential best practices that can be utilized in wide range of agroecosystems. The future research directions are to integrate artificial intelligence with remote sensing technologies to monitor and verify the soil carbon

stocks in a better way. In the last analysis, increasing soil carbon sequestration will reduce climate change and food security. Achieving the goal of utilizing soil to sequester its maximum level of carbon as a resilient sink will require strengthening of efforts to collaborate among scientists, policymakers, and farmers.

Introduction

Accumulation of greenhouse gases (GHG) like carbon dioxide (CO_2) in the atmosphere is one of the most pressing global challenges of the 21st century for the climate change. With an increasing effort on the part of all of us to slow down climate change, soil carbon sequestration, the ability of soils to build organic matter that stores atmospheric carbon, have also received attention as a natural, no cost method to take carbon out of the atmosphere and place it in a living complex called soil organic matter. Soils are the biggest terrestrial carbon reservoir and have bigger carbon content than the atmosphere and biosphere together. Enhancing soil carbon storage is a way of decreasing atmospheric CO_2 levels and at same time improving soil fertility, water retention and agricultural productivity. The process of soil carbon sequestration is the absorption of CO_2 from the atmosphere by plant photosynthesis and conversion of it into soil organic matter. However, the carbon is stored in the form of the inorganic carbon and soil organic carbon (SOC) and stays in the ground for decade's even centuries depending on the land management practices and environmental conditions. Unsustainable agricultural practices (intensive tillage, monocropping, excessive use of chemical fertilizer) however have led to large carbon loss from the soils as if Environmental consequence was not bad enough – excessive use of chemical fertilizer on soils is making land degrade.

New opportunities have recently been opened for soil carbon sequestration by recent advances in soil management techniques. No till farming, cover cropping and crop rotation are some of the methods of conservation agriculture that have been found to increase SOC levels without increasing erosion and nutrient depletion. Further, the carbon stabilization can be enhanced by the application of organic amendments like biochar, compost and manure. Moreover, it is understood that the soil microbial community also play a role in carbon cycling as their activity involves decomposition of organic matter into nutrient form and storage of carbon in the soil over the long term. Although soil carbon sequestration is a potential warming solution, barriers exist to its general use. Barriers to adoption include economic reasons, policy limitations, uncertainty of carbon measurement and permanence. Although carbon credit markets are just emerging, governments are providing incentivizes, and climate change conventions are international, there is a bright future for expansion of the scale of soil based carbon sequestration. When it comes to rumpus monitoring and verification of soil carbon stocks, research and technological innovations such as remote sensing and artificial intelligence are also improving this process.

Current Understanding of Soil Carbon Sequestration

Soil carbon sequestration means the process of capturing and storing atmospheric carbon dioxide (CO_2) in soil's organic matter and reducing greenhouse gases concentration and therefore mitigating climate change. It is a highly important component of the global carbon cycle and is subject to effects from many biological, chemical, and physical factors. Explaining the mechanisms by which carbon is sequestered in the soil is necessary to improve land management strategies toward enhancing the capacity for carbon storage.

Forms of Soil Carbon

There are two main forms in which soil carbon exist.

Soil Organic Carbon (SOC) – SOC derives from plant residues and root exudates, and extra amounts of microbial activity, are the most dynamic, biologically active form of total carbon. Soil Humus is very vital in soil fertility, water retention and nutrient cycle. Unfortunately, SOC is not protected from decomposition and loss by microbial respiration as well as land-use changes.

Soil Inorganic Carbon (SIC) is associated with Arid and semi-Arid areas (the process of creating carbonates by the process of weathering of minerals and chemical complexation between CO_2 with soil material). SIC is more stable than SOC, and can hence persist in soils for thousands of years.

Processes Governing Soil Carbon Sequestration

Carbon inputs and outputs in the soil determine soil carbon sequestration.

Carbon Inputs – The dominant source of carbon in the soil is from the plant organic matter. Because of photosynthesis, plants seize the CO_2 present in the atmosphere and put it into soil as plants decompose and release organic residues into the soil via its root systems and leaf litter. These materials are then broken down by soil microorganisms incorporating carbon into stable organic forms.

Carbon Inputs – Carbon is added to soils through plant and animal inputs of dead organic material (litter) and by photosynthesis in soil by cyanobacteria. SOC depletion proceeds intensively following intensive agricultural practice and land degradation, decreasing the capacity of the soil to sequester carbon.

Factors Influencing Soil Carbon Sequestration

There are several factors that determine the potential of soil to store carbon.

Clay rich soils have more carbon retention than sandier soils because sands lose carbon better. Warm Climate and Temperature (Warmer temperature accelerates microbial decomposition and increases the carbon turnover rate). However, in cooler and wetter climates, carbon is accumulated by slowing decomposition rates. The contributing factor is land use and management, which include the processes, such as reduced tillage, cover cropping, organic amendments, agroforestry, deforestation, overgrazing and intensive farming, all of which increase or reduce the SOC.

Advances in Soil Management Techniques

Carbon sequestration in the soil is a particularly effective option to reduce storage of greenhouse gas across an array of soil management techniques that also promote soil health and agricultural sustainability. Advances in soil management in the recent times have been influenced by the desire to increase soil organic carbon (SOC) levels to reduce greenhouse gas emissions and long term soil fertility. Here are some of the best and most innovative of these soil management techniques that result in increased carbon sequestration.

1. Conservation Agriculture

The conservation agriculture practices are preferred because they help in minimizing the soil disturbance, increasing organic matter content and decreasing the carbon loss. Key techniques include:

Other methods include No-Till and Reduced Tillage, which reduce soil disturbance to maintain soil structure and carbon organic in order to reduce oxidation and erosion. Such benefits from reduced tillage include slowing rates of decomposition and increasing microbial activity, thus, retaining more carbon in the soil. Cover crops like legumes, clover and grasses also enhance soil structure, organic matter input, microbial biomass, and therefore support carbon sequestration. It stabilizes soil degradation and enhances carbon retention by keeping a wide assortment of root structures.

2. Agroforestry and Perennial Systems

The concept of agroforestry (trees and shrub integration into agricultural landscapes) has been shown to be a most effective strategy of carbon sequestration. Trees capture atmospheric carbon and add it to their own biomass, and by drop of leaf litter and root turnover, to that of the soil organic matter. Carbon can also be accumulated in perennial cropping systems, namely any cropping system that involves long lived crops and minimal disturbance of the soil which, due to the long lived nature of the crop, maintain continuous root systems which increase carbon storage.

3. Organic Amendments and Soil Conditioners

A major breakthrough on the enhancing soil carbon storage has been the use of organic soil amendments. Key amendments include:

Biochar Application offers more carbon rich stable material known as biochar produced from pyrolysis of organic matter that stabilizes soil carbon, increases microbial diversity and nutrient retention. Long term soil carbon storage is possible through application of organic waste materials when managed and applied properly, because of increased microbial activity as well as improved soil aggregation.

4. Precision Agriculture and Technological Innovations

The incorporation of precision agriculture technologies has enabled adding soil carbon sequestration to the equation of which helped protect soil carbon. Innovations include:

Advanced satellite and drones technologies have been applied for the remote sensing and AI monitoring of soil carbon assessment and carbon management. Emerging policies provide economic benefits through carbon credit trading as well as government support programs to encourage farmers to adopt carbon sequestration practices by allowing farmers to be paid to sequester carbon into soil.

The second is to use the research to enhance Soil Health and Carbon Storage.

As such, soil health and carbon storage are tightly linked; a healthy soil supports the process of carbon sequestration and also provides for, among other things, agricultural productivity and environmental sustainability. Soils with higher organic matter content that have more and better functional microorganisms and retain more water and are more resistant to the effects of climate change are considered healthy. However, recent biological, chemical and physical mechanisms aimed at improving soil health in order to enhance carbon storage have been the focus of research and innovation.

1. Role of Soil Microbial Communities in Carbon Sequestration

Organic matter is decomposed and SOC stabilized by a crucial function played by soil microbes. Some key microbial process affecting carbon sequestration includes:

- Plant residues are decomposed and humified when soil microorganisms degrade them, incorporating the carbon into long–lasting humic substances of the soil.
- Arbuscular mycorrhizal fungi (AMF) associations are a sub group of mycorrhizal fungi associations that help increase plant nutrient uptake and also shuttle carbon from plant roots to the soil and accumulate carbon in the soil for its stabilization.
- Optimizing microbial CUE through soil amendments and nutrient management could increase the portion of C retained in microbial biomass rather than as CO_2.

2. This leads to improving the Soil Structure and organic matter content.

The carbon storage potential is directly related to soil physical properties. Some of the strategies of improving soil structure and increasing organic matter are:

- Organic Material Protection – Well decomposed soils show higher physical protection of organic matter since aggregation decreases decomposition rates and increases SOC stability. And it's also improved by cover cropping, reduced tillage and organic amendments.
- Retaining crop residues on the soil surface reduces erosion, retention of moisture, as well as provides the continuous organic inputs that help to sequester carbon.
- With regard to practices to conserve water – irrigation management, contour farming, and conservation tillage – proper soil moisture reduces carbon losses when the rates of soil respiration are reduced and the microbial activity is increased.

3. Application of Soil Amendments for Long-Term Carbon Storage

Soil amendments that raise the amount of carbon in soil can make large improvements:

- Biochar – In consumption, biochar is highly stable carbon form that improves water retention, fertility, and microbial activity, ensuring that carbon does not escape from decomposition.
- Organic inputs viz. compost and manure support microbial biomass, increase soil nutrients cycling and contribute to SOC accumulation in the long run.
- Silicate and Rock Amendments: Silicate minerals have been shown in recent studies to promote the formation of mineral associated organic carbon (MAOC) that enhances carbon stabilization.

Conclusion

Sequestration of carbon in soil is a great chance to combat climate change and gradually enhance soil health and agricultural yield, as well as environmental sustainability. With atmospheric carbon dioxide (CO_2) levels increasing and global warming inevitable, how to make the most of the soils' natural inclination to store carbon is a solution the world needs to tap into. Advanced soil management techniques combined with microbial interactions and use of innovative technologies will help tapping storing potential of soils and contribute for long term climate resilience. These recent advances for conservation agriculture, agroforestry, use of organic amendments, and precision farming have greatly reduced our ability to sequester some carbon in the soils. The minimization of disturbance of the soil, increased organic matter input and these factors that support the microbial activity—all of these can contribute to the processes that lead to carbon stabilization. In addition to biochar, compost, and manure amendments, and as a result of the latter, soil organic carbon (SOC) levels are increased and nutrient cycling and soil fertility are boosted. Along with microbes, mycorrhizal fungi have an important role in the soil carbon sequestration by increasing the plant — soil interaction and protecting the organic matter. While these technologies have helped address many of the practical and technical challenges to the science of soil carbon sequestration they have not maintained the promise required for more global scale application. They remain elusive because of economic constraints, policy gaps, as well as uncertainties regarding the permanence and measurement of carbon. Nevertheless, the growth in the interest for carbon credit markets, government incentives and international climate policies provide opportunity to producers, land managers, and policy leaders to consider soil carbon sequestration as a part of broader climate strategies. In addition, technological advances to the likes of remote sensing, artificial intelligence (AI) based monitoring of soil carbon, and advanced soil analysis techniques are making it possible to accurately measure and verify soil carbon stocks. For soil carbon sequestration to be perfected, then, a multi stakeholder approach is necessary. Sustainable land management must therefore be implemented based on farmer research and policy support, and if research in the field of soil–carbon interactions is to advance, it will have to be invested in by farmers, researchers, policymakers, and industry leaders. They will also depend on the education and extension services in equipping land managers with the knowledge and tools for efficient adoption of appropriate carbon sequestration strategies. With this in mind, the ultimate way of solving the environmental problems is not only about enhancing soil carbon sequestration, but it is also part of the strategy for long term food security, ecosystem services, and climate resilience. If we put soil health first, embrace science backed carbon management, then soils are our continuing robust and reliable carbon sink for the benefit of us now and all the generations to come.

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