Soil Carbon sequestration: The storehouse of carbon

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One of the primary contributors to global warming is the increase in atmospheric carbon dioxide (CO_2), which is currently estimated to be 400 parts per million and is predicted to reach 600–800 parts per million by the end of the twenty-first century. The negative impacts of CO_2-induced global warming can be lessened by employing trustworthy carbon sequestration techniques. The process of storing carbon from the atmosphere in naturally occurring geological formations, including soils, oceans, forests, etc., is known as sequestration. It is stored in the soil as soil organic matter (SOC) or soil organic carbon. Ninety percent of the total SOC in soil is provided by fungi and bacteria. Different ecosystems, including soils, oceans, and the atmosphere, can store carbon, wherein oceans store the highest amount of carbon (38,400 gigatons), followed by soil (2,344 gigatons). Soil has been revealed to store 2500 pg (pico grams) for every 2 meters of depth. The Intergovernmental Panel on Climate Change has stated that alterations in crop management practices can sequester about 258 MMT (mega million tonnes) of SOC by 2040.

In soil, carbon is stored in the form of soil organic matter (SOM) or soil organic carbon (SOC), which are often referred to as soil organic carbon pools. SOC is a complex mixture of carbon compounds and a measure of all carbonaceous material, which may be decomposing plant tissues, micro-organisms, including bacteria, fungi, protozoa, root exudates derived from plants. Input is the deposition of SOC from atmospheric carbon, whereas output means the release of carbon from SOC and is influenced by various factors. Factors such as continuous tillage, burning of residues, deforestation practices, etc., chiefly contribute towards the output of carbon from soil. Contrarily, practices such as zero-tillage, incorporation of residues, mulching, afforestation led to the input of carbon into the soil. Besides land management practices, climate, seasonal variation, soil structure, physical and chemical conditions of soil also affect the stability and deposition of SOC.

Plants can fix 40% of carbon through rhizodeposition, which acts as the pheromone for microbes in soil. These rhizodepositions can also regulate the microbial composition in the rhizosphere. These also help in improving the beneficial and non-pathogenic microorganisms around the plant roots. Soil microbial communities contribute considerably to the formation of SOC from organic residues and rhizodeposition. The number and activity of the microbiota are in a linear relation with the amount and quality of SOC. Soil microbiota includes fungi, bacteria, protozoa and nematodes, which are presumed to play a key role in the enhancement of carbon sequestration. These microflorae govern the magnitude and direction of carbon flow between the atmosphere and soils in two directions: (i) encouraging the carbon sequestration, and (ii) enhancing the efflux of CO_2 back into the atmosphere.

Soil biota uses carbon from SOC either through mineralization to produce CO_2 or in the production of biomass (new cell materials) or in enzyme production (cellular metabolites). In the absence of fresh residues, microorganisms perform the process of mineralization by utilizing native SOC. Mineralization is a continuous function carried out by soil microorganisms. Chemo-heterotrophic microorganisms are of prime importance in the mineralization process. These chemo-heterotrophs transform organic material into CO_2. Energy required for the mineralization process is provided by ATP, NADP and FAD.

During mineralization, microorganisms, in addition to the nutrient transformations and liberation of CO_2, also assimilate a wide variety of products. Principal among them are extracellular polymeric substances, cell wall polymers and stress release compounds. Extracellular polysaccharides are a significant class of extracellular polymeric substances produced during mineralization. The matrix of extracellular polymeric substances comprises polysaccharides, DNA and proteins. This matrix also encloses certain microorganisms. EPS in dry soils is mostly hygroscopic. It promotes continuous microbial cellular hydration and nutrient replenishment. EPS acts as a biological bridge between the soil microbes and substrates and helps in obtaining energy under dry soil conditions. It promotes as well as constricts the flow of carbon to microbiota. It stimulates the liberation of extracellular enzymes and also endorses the aggregate formation, which creates a favourable growth environment for microorganisms in soils. Microbiota survives either in the soil macro-aggregates or in the macro pores that offer accessibility to substrate. Additionally, EPS enables the survival of microorganisms under low water potential and also in deeper layers of soil.

Soil microbiome, in turn, is influenced by land management practices. SOC can be best sequestered by crop residue addition with conservation tillage practices such as zero tillage and manure. Soil moisture has an indirect effect on the SOC decomposition. Change in soil moisture levels causes shifts in the microbial communities and functions. However, these shifts in microbial communities are not clearly understood.

Conclusion

Soil carbon sequestration represents a promising and sustainable strategy for mitigating the rising levels of atmospheric CO_2 and the associated impacts of global climate change. Among terrestrial ecosystems, soils constitute one of the largest and most dynamic carbon reservoirs, with soil organic carbon playing a central role in regulating carbon fluxes between the atmosphere and the biosphere. The formation, stabilization, and turnover of SOC are strongly governed by soil microbial communities, which mediate both carbon sequestration and carbon release through complex biochemical processes.

Land management practices play a decisive role in determining the balance between carbon input and loss. Conservation-oriented practices such as residue retention, zero or reduced tillage, mulching, organic amendments, and afforestation promote microbial activity conducive to SOC accumulation, whereas intensive tillage and residue burning accelerate carbon depletion. Although factors such as soil moisture, climate, and physicochemical properties significantly influence microbial-mediated carbon dynamics, the mechanisms governing microbial responses to environmental changes remain incompletely understood. Overall, enhancing soil carbon sequestration through informed land management and a deeper understanding of soil microbial processes offers a viable pathway for climate change mitigation while simultaneously improving soil health, productivity, and ecosystem resilience. Continued research focusing on microbial functional diversity and its response to environmental and management-driven changes will be critical for developing effective, long-term carbon sequestration strategies.

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