Resolving the Paradox of Rhizosphere Effect on Soil Carbon Cycle

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The rhizosphere, the interface between plant roots, microbes, and their surrounding soil matrix, is a dynamic and complex system that is critical for the functioning of terrestrial ecosystems. One of the most important functions of the rhizosphere is its role in regulating the cycling of carbon between earth and air. On a global scale, the combined activities of plant roots and soil microorganisms within the rhizosphere release an estimated 3–10 fold more carbon dioxide than the emissions from fossil fuel burning but under the right conditions, soil organic carbon (SOC) can be entrapped in soil aggregates, so it is not released back into the atmosphere. Paradoxically, roots contribute to both stabilization and destabilization of SOC. Rhizosphere processes have the intriguing capacity to both enhance and disrupt the preservation of long-lasting SOC, with an estimated global potential for carbon sequestration as substantial as 5.3 gigatons of carbon dioxide annually. This research addresses the core mission of the Carbon Negative Energy Earthshot by understanding how plant roots affect SOC accumulation and the mechanisms that regulate SOC gain and loss in the rhizosphere by the action of roots, microbes, and soil structure. One possible pathway is root-driven soil aggregate turnover, which encompasses processes such as root penetration, drying-rewetting cycles, and the binding of organic compounds to clay minerals. This pathway plays a significant role in SOC stabilization and destabilization. Another possible pathway is exudate-driven microbial turnover, which involves microbial activities fueled by plant exudate. This pathway influences substrate utilization efficiency and the burial of carbon-containing necromass, both of which have implications for SOC dynamics. The objectives of this research are to quantify carbon processes and understand the rhizosphere pathways by using novel high spatial resolution positron emission tomography (PET) and computed tomography for dynamic data collection of the undisturbed sample volumes both at the root surface and in soil away from the root surface. Traditional static PET imaging yields the time-averaged, spatial distribution of carbon radiotracers, permitting estimates of their accumulation in soil aggregates and other rhizosphere volumes of interest. However, static imaging alone falls short in capturing the dynamic nature of biological processes and cannot explain mechanisms of carbon stabilization. In contrast, dynamic imaging provides both radiotracer distribution and temporal changes of radiotracer as carbon moves between stable and unstable forms. Further, and most importantly, the sequential dynamic PET frames enable highly quantitative techniques for mapping and quantifying radiotracer distribution, transport, metabolism, binding, and more. The kinematic modeling of physiological processes is the key advantage of dynamic imaging of carbon radiotracers. Integrating direct observations with various isotope tracers such as carbon-11 labeled carbon dioxide, carbon-13 labeled carbon dioxide, and carbon-14 labeled carbon dioxide reveal pathways and related rhizospheric mechanisms. Simultaneously quantifying SOC stabilization and destabilization rates in the inter-connected soil matrix and microbial turnover pathways will facilitate studies in previously unattainable ways and offer valuable insights for improving strategies to enhance soil carbon sequestration. Additionally, these findings hold direct relevance for global soil carbon modeling efforts and have potential to resolve the rhizosphere paradox and the well-documented uncertainty and inconsistencies in existing models.

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