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Resolving Mineral-Associated Organic Carbon Pools Across Contrasting Ecosystems

QIAN ZHAO[1] AND OLUWASEUN ADEYEMI[2]

[1]The University of Texas at Dallas
[2]University of Texas at Dallas

Mineral phase reactivity exerts first-order control on soil organic matter (SOM) persistence and thus on terrestrial carbon cycling and redox-mediated biogeochemical processes. However, the persistence of soil organic carbon (SOC) among distinct reactive mineral phases remains poorly constrained across ecosystems. We quantified mineral-associated organic carbon (MAOC) in four contrasting soils: agricultural, grassland, peat, and permafrost systems, using a selective dissolution framework that resolves carbon bound to discrete iron (Fe) and aluminum (Al) mineral pools.

Sodium pyrophosphate mobilized the largest C fraction across all soils, reaching ~25 mg g^{-1} in grassland and permafrost systems, indicating widespread stabilization through organo-metal complexation. Carbon release showed strong, systematic coupling with Fe and Al across weakly bound, amorphous, and crystalline pools, whereas relationships with Si and Ca were weaker and more variable. These patterns suggest that ligand exchange, cation bridging, and physical occlusion within Fe- and Al-rich mineral matrices dominate SOC stabilization, while Ca-mediated associations primarily influence more labile fractions. Reductive dissolution using sodium dithionite and acid extraction with 0.5 M HCl liberated additional mineral-associated C (up to ~15 mg g^{-1}), isolating organic matter associated with crystalline Fe oxides, short-range-order phases, and surface-reactive Fe species. These pools exhibited strong correlations with Fe and Al but weaker coupling with Si and Ca, consistent with stabilization through mineral sorption and redox-sensitive occlusion mechanisms rather than freely extractable organic matter. X-ray diffraction (XRD) and scanning electron microscopy (SEM) confirmed the presence of abundant reactive mineral assemblages consistent with the observed extraction behavior.

Across ecosystems spanning temperate to permafrost environments, our results reveal substantial, previously unresolved MAOC pools governed by Fe- and Al-mediated biogeochemical interactions. By explicitly linking SOC mobilization to mineral phase chemistry and redox reactivity, this study provides a mechanistic framework for interpreting mineralogical and geochemical signatures of carbon stabilization and for predicting MAOC vulnerability under climate-driven shifts in redox conditions.