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Silicate Rock Weathering Drives Calcium-Mediated Stabilization of Soil Organic Carbon: Insights from Mesocosm Experiments and Synchrotron Spectromicroscopy

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Enhanced rock weathering (ERW), the application of crushed silicate rock to soil, is a proposed carbon dioxide removal strategy that accelerates the conversion of atmospheric CO_2 to (bi)carbonate ions and/or carbonate minerals. As ERW has been primarily evaluated for inorganic carbon sequestration, key uncertainties remain regarding how ERW affects the stability of soil organic carbon (SOC) across soils with contrasting properties. In particular, it remains an open question whether calcium released during silicate mineral dissolution promotes SOC accrual by facilitating stable organo-mineral complex formation.

Plant mesocosm experiments (±basalt amendment, three soil types, 60 days) revealed that basalt weathering rates vary substantially across soils, with faster dissolution in acidic, SOC-rich soils. In these soils, exchangeable Ca^{2+} increased by 30-70% relative to unamended controls. Despite pronounced shifts in soil pH and exchangeable calcium, we detected no significant changes in soil respiration rates or the quantity of mineral-associated C. If calcium-mediated SOC stabilization is indeed occurring, it likely initiates at discrete sites within the soil matrix. Such interactions may only become detectable by bulk methods once sufficient SOC has accumulated over time.

To resolve these potential small-scale interactions, we first analyzed sectioned soil aggregates using spatially correlated SEM-EDS and NanoSIMS, revealing microscale associations between Ca and ^{13}C-enriched plant root inputs. We also performed scanning transmission X-ray microscopy coupled with C (K-edge), Ca (L-edge), and Fe (L-edge) near-edge X-ray absorption fine structure spectroscopy (STXM-NEXAFS). STXM-NEXAFS revealed the micron-scale physical and chemical association of C, Ca, and Fe in clay-size particles from three soils (±basalt amendment, ±plant litter). While C composition varied with soil type, Ca-associated C was often enriched in aromatic and phenolic functional groups relative to non-Ca-associated C. This indicates that Ca can influence not only the quantity but also the molecular composition of mineral-stabilized organic matter.

Collectively, these findings suggest that Ca^{2+} released during silicate weathering promotes organo-mineral associations, although the composition of this stabilized carbon pool can vary. Further work is needed to understand the persistence of these Ca-mediated organo-mineral associations. We show that spectromicroscopy can complement conventional bulk analyses to reveal fine-scale SOC dynamics that would otherwise remain undetected.