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INVITED COMMENTARY

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Inorganic and organic synergies in enhanced weathering to promote carbon dioxide removal

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Scientifically verifiable, durable, and scalable carbon dioxide removal (CDR) technologies are essential to reducing atmospheric CO_2 concentrations and avoiding the most dangerous impacts of climate change this century. Within the nature-based solution portfolios, the soil system provides promising CDR and sequestration potential, including in both organic and inorganic forms at time scales that reflect durable removals (Smith et al., 2023)—those that exceed 100 years or longer. Soil organic carbon (SOC) and inorganic carbon (SIC) collectively preserve more than eight times as much carbon as does vegetation. Their changes determine the magnitudes of soil carbon sequestration and have profound impacts on the global carbon cycle. A critical challenge is to grow the total amount of carbon in soil pools in a way that is scientifically verifiable and scalable to the billions of tons of CDR needed to stabilize and reverse global warming. Buss et al. (2024) revealed a key interface—organo-mineral association—between soil inorganic and organic carbon dynamics to promote soil carbon sequestration, highlighting a bridge between inorganic and organic soil carbon chemistry.

Soils in the first 2 m store more than 2000 billion tons carbon as organic matter globally. While plants provide the very original carbon source for soils via their litterfall, root exudation, and mortality, the formation and stabilization of SOC involves more complex belowground processes such as microbial activities and organo-mineral interactions (Schmidt et al., 2011; Tao et al., 2023). While increasing plant primary productivity can partially counterbalance the elevated atmospheric CO_2 concentration as a natural land carbon sink (Yang et al., 2023), the short turnover nature of vegetation carbon that ranges from annual to decadal scales limits its magnitude to store carbon persistently. In contrast, SOC has a characteristic turnover time varying from decades to centuries worldwide. Effectively transferring plant carbon to stable forms of SOC potentially boosts land carbon sequestration.

However, human activities, including land use changes in agriculture, have measurably altered the soil carbon cycle, mainly causing losses of SOC in croplands in recent decades (Nabuurs et al., 2022). Contemporary climate change further increases people's concerns about the accelerated SOC decomposition triggered by surging temperature, where organic matter is mineralized as CO_2 back into the atmosphere, exacerbating climate change. This climate sensitivity can increase the turnover time of SOC, casting doubts on the durability of this approach vis-à-vis long term climate goals. Alternatively, many CDR methods, such as biochar and ecosystem restoration, are established to enhance SOC formation, stabilization, or both.

Enhanced rock weathering makes managing SIC possible to sequester billions of tons of CO_2 over a short period. Inorganic carbon, including soluble bicarbonate and solid carbonates, is even more stable than SOC, with turnovers in the Earth system over thousands of years. With Earth's geologic activities, silicate minerals exposed to air dissolve with water and CO_2, exchanging silicic acid, releasing cations such as Ca^{2+} and Mg^{2+}, and, importantly, locking CO_2 as bicarbonates (Hilton, 2023). Bicarbonates can either precipitate as pedogenetic carbonates or move to deeper soils, rivers and eventually the ocean via transport. This set of stabilizing feedbacks to Earth's climate happens naturally at millennium to longer time scales to balance the CO_2 released from volcanic eruptions and sedimentary rock weathering.

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Thus, compared to the organic carbon cycle on land, the natural weathering rate and its influence on inorganic carbon is extremely slow. However, by applying crushed basic rock (e.g. basalt) dust to cropland with appropriate irrigations, finer dust particles that create a larger reaction surface area together with more favorable water environments contribute to an increased weathering rate. In theory, this "enhanced weathering" rate could result in 0.3–0.8 ton CO_2 removed per ton rock (Renforth, 2012). Process-based models simulated global CO_2 removal rate from enhanced rock weathering applications with croplands ranges from 0.5 to 2 billion tons of CO_2 per year (Beerling et al., 2020).

Buss et al. (2024) examined the connections between SOC and enhanced weathering by applying a blend of basalt and granite at 50 t ha^{-1} to loamy sand soils in a short-term, controlled pot experiment, demonstrating a 46% relative increase in SIC content (an absolute increase of 0.0002%) with elevated pH and exchangeable metal cation concentrations, such as Mg^{2+} and Ca^{2+}, after 6 months. The Mg^{2+} and Ca^{2+} released from enhanced weathering and pre-weathered minerals in the dust further contributed to the stabilization of SOC via promoted organo-mineral interactions. By the end of their experiment, Buss et al. (2024) measured 32% higher SOC stock in pots with rock dust application (without plants) than unamended controls, suggesting that metal cations acted as mediators between soil clay surfaces and organic matter to promote micro-aggregation and formation of mineral associated SOC with stronger persistence to environmental disturbance. Organo-mineral interactions have long been addressed in SOC persistence (Schmidt et al., 2011), yet Buss et al. (2024) brought us critical originality on how SIC and SOC can be synergistically promoted via rock dust application. Future evaluation of CDR potential of enhanced rock weathering may not be limited to SIC formation but outreach to its positive influence in SOC stabilization.

Challenges remain despite the promising CDR potential of enhanced rock weathering. First, the enhanced SOC stabilization effect by rock dust amendment relies on consistent and accelerated weathering rates to release cations, yet results reported by Buss et al. (2024) were modest. While the consistently elevated pH and exchangeable cation concentrations suggested ongoing weathering, the increased SIC content over the 6 months corresponds to 0.01 t CO_2 ha^{-1}year^{-1}, hitting the low end of previous estimations—even under controlled conditions. The relatively low content of fast-weathering minerals such as olivine (2%) in the applied rock dust and sandy soil texture with weaker water-holding capacity may explain the limited potential. Meanwhile, diverging methods reported in the literature for determining weathering rates make inter-study comparison difficult (Almaraz et al., 2022). A consistent and reliable protocol to measure SIC stock and weathering rate becomes necessary to evaluate the CDR potential of enhanced rock weathering in a verifiable fashion.

Second, the interplay between plants, rock dust and soil carbon is intriguing but requires much investigation, especially in diverse cropland soils in the field. Buss et al. (2024) reported a counteracting role of plants (i.e. wheat in this study) in rock dust's positive effect on SOC stabilization. Plants are the very origin of organic carbon for the soil system, yet Buss et al. (2024) provided an interesting angle on how changes in soil chemistry may alter the effect of plants on SOC. Increasing soil pH driven by rock dust weathering enhanced cation adsorption on the soil surface and thus decreased the availability of exchangeable micronutrients, such as Mn and Zn, to plants. Micronutrient deficiencies further forced organic acid exudation by plant roots to solubilize micronutrients for a normal uptake. The presence of plant-derived acid contributes to the destabilization of SOC aggregates and/or weakens organo-mineral interactions, eventually offsetting part of the SOC stabilization effect brought by rock dust application. While this hypothesis is theoretically plausible and supported by related evidence reported by Buss et al. (2024), such as changes in exchangeable Mn and Zn, a lack of direct evidence of plant's increased oxalic acid/oxalate exudation under rock dust adds extra uncertainties in disentangling plant-rock-carbon nexus in soils.

Third, combined field data and process-based modeling—leveraging AI and machine learning—are essential to large scale efficacy of enhanced rock weathering and its connection to crop and soil health and SOC. Emerging evidence has shown the efficacy of enhanced rock weathering to remove CO_2 from the atmosphere in acre-scale field trials, even in arid regions, where bicarbonate alkalinity can increase rapidly after rock dust additions (Holzer et al., 2023). Results by Buss et al. (2024) further highlight the importance of future field studies that measure both SIC formation and SOC, including the various pools involved. Further, the modeling community needs to bridge the biotic (organic carbon cycle) and abiotic (inorganic carbon cycle) worlds in simulating the potential of soil-based CDR methods. In the future, key processes such as changes in organo-mineral interactions and micronutrient-plant feedbacks should also be considered in model simulations to better quantify the carbon sequestration by enhanced rock weathering at large scales and guide appropriate soil management.

AUTHOR CONTRIBUTIONS

Feng Tao: Writing – original draft; writing – review and editing. **Benjamin Z. Houlton:** Writing – review and editing.

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