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Carbon dioxide removal via enhanced weathering: Modelling the effect of soil properties

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Abstract: In enhanced weathering (EW), alkaline minerals with small particle size e.g., some industrial by-products and crushed rocks like basalt and olivine, are applied to soils to accelerate natural carbon dioxide capture (CDC) processes and improve soil health. As a novel negative emissions technology, the promise of significant CDC via EW and soil improvements in agriculture has led to proliferation in related research and businesses. However, most research conducted so far has focused on the properties of the material applied and taken little account of the soil, although it has been assumed that benefits will be maximised in tropical climates (Edwards et al. 2017). Our work highlights that soil properties, particularly acidity, carbon dioxide concentrations, and leaching have significant implications for CDC via EW.

Using a one-dimensional reactive transport model in the geochemical modelling software PHREEQC (Parkhurst & Appelo, 2013), we extended upon previous modelling studies (Kelland et al., 2020; Lewis et al., 2023; Green et al., 2024) using data from a range of agricultural soils. Key developments include the simulation of: a) soil properties typical under different climate conditions (soil pH, solution and exchange chemistry, soil mineralogy, infiltration rate, and evapotranspiration), b) nitrification reactions and addition of nitrogen fertilisers, c) changes in soil properties with depth (carbon dioxide concentrations, plant uptake of water and nutrients, organic exchange sites, and incorporation depth of weatherable material), and d) mechanisms of pH buffering capacity using exchange site chemistry.

Based on our geochemical modelling, the optimum soil pH for CDC via EW is between 6.5 and 7.0. Highly weathered acidic soils have a large pool of reserve acidity that convert any bicarbonate produced back into carbon dioxide. In alkaline soils, slower weathering and conversion of bicarbonate to carbonate result in lower capture efficiency. Addition of nitrogen fertilisers generated strong acids during nitrification that rapidly weather applied materials without CDC. For significant CDC to occur, optimal conditions must be maintained over time and throughout the soil profile, and measurement of bicarbonate and carbonate leaching from and accumulating throughout the profile is necessary to quantify CDC.

We also demonstrate that directly measured CDC can be orders of magnitude lower than CDC estimated by commonly used methods that assume cations released by mineral weathering are a suitable proxy for CDC. Crucially, use of this proxy in modelling and the field will significantly overestimate CDC via EW and lead to fundamental misunderstandings about which soil and climatic conditions are optimal. Owing to the relationship between climate and soil properties, optimal conditions for CDC are unlikely to be found in tropical locations, highlighting the need for spatial analyses of soil conditions.

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