

Project: 1258

Project title: **RETAKE—Carbon Dioxide Removal by Alkalinity Enhancement: Potential, Benefits and Risks**

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The report of the outcome from the last year are divided into two parts:

1) We have refined the simulation of olivine weathering scenarios by incorporating a more realistic representation of sediment effects, particularly the influence of lower pH conditions within sediments that enhance olivine dissolution. The updated setup includes three sediment-related applications, each representing distinct physical environments and dissolution mechanisms: a) Bedload application/scenario: Olivine is applied on top of coarse-grained (gravel) sediments in high-energy environments, where collisions during bedload transport create a natural grinding effect. This mechanical abrasion reduces olivine grain size and consequently enhances its dissolution rate. b) Permeable and cohesive applications/scenarios: Olivine is mixed into sandy and muddy sediments respectively, where dissolution is accelerated by the lower sediment pH compared to the overlying water. In these settings, advective porewater transport (in permeable sands) and bioturbation (in cohesive muds) are key processes driving alkalinity dispersion and dilution.

The main improvement in this year's simulations compared to last year lies in the explicit consideration of pH-dependent dissolution in the permeable and cohesive applications. Since the current model does not explicitly resolve sediment pH variations, we assumed a constant sediment pH of 7 for these scenarios. In contrast, the bedload scenario retains a pH equal to the overlying water but includes updates to other parameters, such as the intrinsic dissolution rate constant, derived from new mesocosm experiments provided by L. Geerts (University of Antwerp, Project DE-HEAT).

For the bedload and permeable applications, the initial olivine grain size was set to 120 μm to maintain a cost-effective balance between dissolution efficiency and processing effort. In the cohesive application, a smaller grain size of 29 μm was used to match the mean grain size of the surrounding sediments.

The spatial pattern of the sediment applications is illustrated in Fig.1(a). Four experiments were conducted: Bedload only, Permeable only, Cohesive only and the simultaneous implementation of all the three types. At the beginning of the simulations, 1 kg/m^2 of olivine was added to the sediment, with initial grain size varying according to sediment types. The four simulations all cover the period of 2001 to 2010.

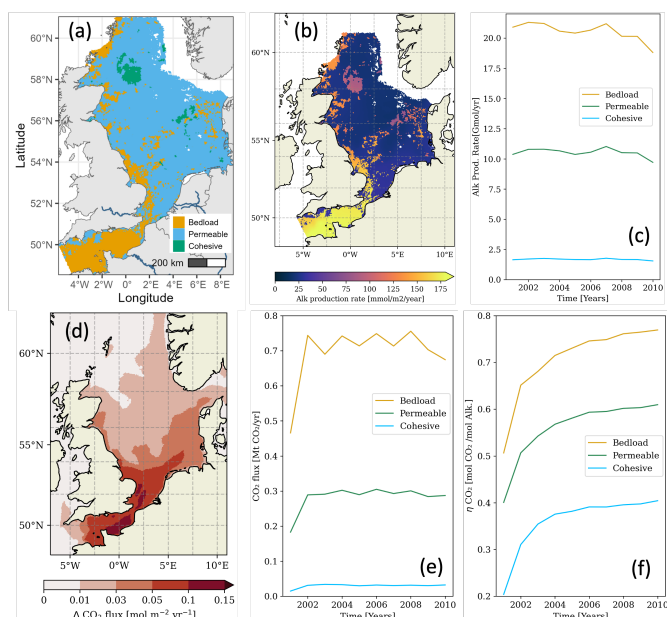


Fig.1 (a) the map of the sediment types. (b) the spatial pattern of alkalinity production rate due to olivine weathering. (c) the spatially integrated alkalinity production rate over the area of the three sediment types respectively. (d) the spatial pattern of the enhanced oceanic CO₂ uptake due to olivine weathering. (e) the spatially integrated oceanic CO₂ uptake increase due to the olivine weathering. (f) the CO₂ uptake efficiency, defined as the total additional oceanic CO₂ uptake to the total alkalinity production.

In terms of alkalinity production, the spatial pattern remains generally consistent with last year's simulations (Fig. 1b). However, in the updated runs, the permeable and cohesive applications produce more alkalinity due to the inclusion of lower sediment pH conditions (figure not shown). Overall, the bedload application

contributes the largest share of total alkalinity production (~50%), despite not covering the largest application area (Fig. 1c). The spatial pattern of CO₂ uptake does not align perfectly with that of alkalinity production (Fig. 1b, d). The strongest CO₂ uptake occurs along the French coast, whereas in the northern British coastal region, CO₂ uptake remains moderate even though substantial alkalinity is released there by both the bedload and cohesive applications. This mismatch is primarily controlled by the horizontal circulation of the North Sea, which follows a characteristic anti-clockwise pattern.

Overall, the bedload application accounts for the highest total CO₂ uptake, with its relative contribution exceeding its share of alkalinity production (Fig. 1c, e). This is directly reflected in the CO₂ uptake efficiency, defined as the ratio of total CO₂ uptake to total alkalinity production. The efficiency is highest for the bedload application and lowest for the cohesive case, primarily due to differences in vertical alkalinity transport, which controls how efficiently alkalinity produced at the sediment is transferred to the upper ocean.

2) We further conducted a series of scenarios involving chemical reactors that make use of wastewater treatment plant (WWTP) discharge. In these setups, additional alkalinity is introduced to the discharge, which is then allowed to fully equilibrate with the atmosphere before being released into the ocean system via the river (Fig. 2a). The different combinations of DIC and alkalinity concentrations in the reactor-treated water for these scenarios are summarized in Table 1.

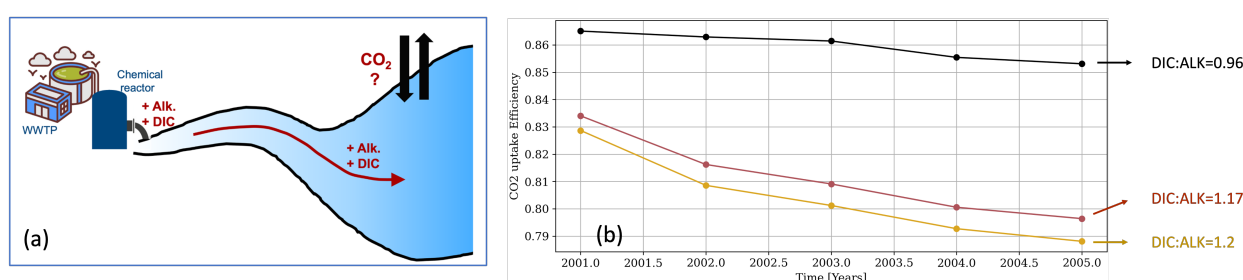


Fig.2 (a) Schematic illustration of the chemical reactor implementation scenario. (b) Simulated CO₂ uptake efficiency in the North Sea following the injection of reactor-treated water through the Elbe River.

Table1: Summary of the three chemical-reactor scenarios

Scenario	High oversaturated discharge	Medium oversaturated discharge	Equilibrated/undersaturated discharge
Additional discharge	32 M m ³ /yr	32 M m ³ /yr	32 M m ³ /yr
Alk (uM)	6014	7674	7674
DIC (uM)	7194	8943	7362
Ratio (DIC/ALK)	1.20	1.17	0.96

All three scenarios exhibit a tendency toward CO₂ outgassing (i.e., reduced net CO₂ uptake) after the reactor-treated water is injected into the North Sea (figure not shown). We define the enhanced DIC storage in the ocean as the difference between the added DIC and the portion lost through outgassing, and we express the ratio of this net DIC increase to the added alkalinity as the CO₂ uptake efficiency. The results show that a higher DIC-to-alkalinity ratio in the reactor-treated water leads to a lower overall efficiency.

The mechanism behind this outgassing—particularly in the scenario with a DIC/ALK ratio below 1—is not yet fully understood, and the analysis is still ongoing. One possible explanation is a mass conservation issue in the model, potentially related to the treatment of wetting and drying elements. We are currently investigating this technical aspect to ensure a robust interpretation of the results. This work will be continued in the coming year.

In summary, olivine weathering in the North Sea shows great potential, particularly through the bedload application. However, the effects of particle movement are still not well quantified and require further investigation. The chemical reactor approach, which discharges high-alkalinity solutions, also presents uncertainties. The fate of the reactor-treated water after injection remains unclear due to complex mixing and transport processes and possible biogeochemical feedbacks, highlighting the need for continued research.