Ecological implications of ocean alkalinity enhancement with olivine: Nickel release and bioaccumulation in *Arenicola marina*

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Ocean alkalinity enhancement (OAE) through the addition of silicate minerals, such as olivine, is a promising marine carbon dioxide removal (CDR) strategy. Chemical weathering of silicate minerals increases oceanic carbon uptake through the release of alkalinity. However, when using olivine for OAE, trace metals (notably Ni and Cr) can be released as well. Elevated concentrations of these metals in sediment or seawater can pose ecological risks, particularly to benthic organisms inhabiting sedimentary environments. This study investigates the release dynamics of Ni and Cr to the water column and sediment, and assesses their bioaccumulation in the common bioturbating lugworm *Arenicola marina*, using a long-term mesocosm approach simulating olivine application under natural conditions.

Lugworms were collected from a large experimental infrastructure investigating the CDR potential of olivine. Fourteen benthic mesocosms featuring four treatments were used: control (natural marine sediment), fine-grained olivine (10-63 µm) in a 6% or 10% w/w loading and coarse-grained olivine (63-180 µm) in a 10% w/w loading. Worms were exposed for 15-21 months, depending on their time of addition to the mesocosms. After collection, worms were digested in HNO_3 and analyzed for Ni and Cr, together with porewater and surface water samples, via inductively coupled plasma mass spectrometry (ICP-MS). Additionally, worm population numbers were tracked over the course of the experiment. Results indicate a significant release of Ni to both pore water and surface water following olivine addition, with a considerably stronger effect observed for the fine-grained olivine treatments. Ni fluxes in surface water were an order of magnitude higher in these fine-grained conditions (6.5±2.6 and 4.3±1.3 nmol/m^{2}day for 10% and 6%, respectively) compared to coarse-grained conditions (0.5±0.4 nmol/m^{2}day) and two orders of magnitude higher compared to the control (0.07±0.2 nmol/m^{2}day). A likely cause is the higher dissolution rate of finer olivine particles. While Cr is present in olivine, its release into pore and surface waters was negligible across treatments, likely due to its occurrence in olivine as the insoluble mineral chromite ($FeCr_2O_4$).

Metal analysis of lugworm tissues revealed substantial uptake of Ni across all olivine treatments, with the highest concentrations in fine-grained treatments (88±25 and 87±20 µg/g for 10% and 6%, respectively). Ni concentrations also increased in the coarse-grained treatments compared to the control (44±15 vs. 8±3 µg/g, respectively), but were considerably lower compared to the fine-grained treatments, although this difference was less pronounced than for the Ni fluxes. Cr bioaccumulation was limited, with tissue concentrations being two orders of magnitude lower compared to Ni. These results are consistent with the flux data and reflect the minimal solubility of chromite. Beyond trace metal accumulation, lugworm populations showed a notable decline in population size after olivine addition, with the strongest effects observed in the fine-grained treatments.

These findings highlight the ecological risks of OAE using olivine and underscore the need for future studies to investigate the toxic effects of olivine exposure on benthic communities. Fine-grained olivine released substantial amounts of Ni over the time period of our experiment. Olivine grain size should therefore be carefully considered in real-world application scenarios. Our results emphasize the need for a balanced approach that accounts for the potential ecological trade-offs when using olivine in marine CDR approaches.

Keywords
Marine Carbon Dioxide Removal; Ocean Alkalinity Enhancement; Olivine Weathering; Trace Metal Release; Metal Bioaccumulation