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## Regional potential of coastal ocean alkalization with olivine within 100 years

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## LETTER

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Regional potential of coastal ocean alkalization with olivine  
within 100 yearsMurugan Ramasamy<sup>1,\*</sup> , Thorben Amann<sup>2</sup> and Nils Moosdorf<sup>1,3</sup> <sup>1</sup> Department of Biogeochemistry and Geology, Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany<sup>2</sup> Center for Earth System Sciences and Sustainability, Institute for Geology, Universität Hamburg, Hamburg, Germany<sup>3</sup> Institute of Geosciences, Kiel University, Kiel, Germany

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E-mail: [murugan.ramasamy@leibniz-zmt.de](mailto:murugan.ramasamy@leibniz-zmt.de)**Keywords:** CDR, alkalinity enhancement, CO<sub>2</sub> sequestration, enhanced weathering, geochemical modelingSupplementary material for this article is available [online](#)**Abstract**

The spreading of crushed olivine-rich rocks in coastal seas to accelerate weathering reactions sequesters atmospheric CO<sub>2</sub> and reduces atmospheric CO<sub>2</sub> concentrations. Their weathering rates depend on different factors, including temperature and the reaction surface area. Therefore, this study investigates the variations in olivine-based enhanced weathering rates across 13 regional coasts worldwide. In addition, it assesses the CO<sub>2</sub> sequestration within 100 years and evaluates the maximum net-sequestration potential based on varying environmental conditions. Simulations were conducted using the geochemical thermodynamic equilibrium modeling software PHREEQC. A sensitivity analysis was performed, exploring various combinations of influencing parameters, including grain size, seawater temperature, and chemistry. The findings reveal significant variation in CO<sub>2</sub> sequestration, ranging from 0.13 to 0.94 metric tons (t) of CO<sub>2</sub> per ton of distributed olivine-rich rocks over 100 years. Warmer coastal regions exhibit higher CO<sub>2</sub> sequestration capacities than temperate regions, with a difference of 0.4 t CO<sub>2</sub>/t olivine distributed. Sensitivity analysis shows that smaller grain sizes (10 μm) exhibit higher net CO<sub>2</sub> sequestration rates (0.87 t/t) in olivine-based enhanced weathering across all conditions, attributed to their larger reactive surface area. However, in warmer seawater temperatures, olivine with slightly larger grain sizes (50 and 100 μm) displays still larger net CO<sub>2</sub> sequestration rates (0.97 and 0.92 t/t), optimizing the efficiency of CO<sub>2</sub> sequestration while reducing grinding energy requirements. While relying on a simplified sensitivity analysis that does not capture the full complexity of real-world environmental dynamics, this study contributes to understanding the variability and optimization of enhanced weathering for CO<sub>2</sub> sequestration, supporting its potential as a sustainable CO<sub>2</sub> removal strategy.

**1. Introduction**

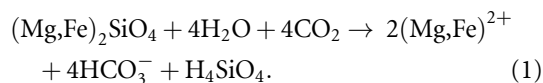
The continuous increase in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations over the past 120 years has raised concerns about its impact on climate change and its far-reaching consequences for human society (Keeling *et al* 2001, Gattuso *et al* 2015). In response to this global challenge, the COP21 climate change conference declared that global warming should be limited to well below 2 °C above preindustrial levels by 2100. Achieving this ambitious target requires not

only reducing CO<sub>2</sub> emissions but also actively sequestering CO<sub>2</sub> from the atmosphere through negative emissions strategies (Friedlingstein *et al* 2020, IPCC 2021).

The Earth's carbon cycle is profoundly influenced by natural rock and mineral weathering, playing a crucial role in the long-term removal of CO<sub>2</sub> from the atmosphere (Berner 1991, Schlesinger 1991). Terrestrial and marine weathering processes significantly contribute to carbon sequestration over geological timescales (Lenton and Britton 2006), and rock

weathering consumes approximately 0.3 gigatons of carbon (GtC) annually (Gaillardet *et al* 1999, IPCC 2021).

One method for carbon dioxide removal (CDR) is to enhance naturally occurring rock weathering by dispersing finely ground silicate and/or carbonate minerals on land (enhanced weathering) or in the sea (ocean alkalinity enhancement, OAE) (Seifritz 1990, Oelkers 2001, Hartmann and Kempe 2008, Meysman and Montserrat 2017, Montserrat *et al* 2017, Renforth and Henderson 2017). Through chemical weathering, for example, olivine minerals ((Mg, Fe)<sub>2</sub>SiO<sub>4</sub>) initiate a slow dissolution process, producing alkalinity and binding CO<sub>2</sub> as bicarbonate in aqueous form (equation (1)), enabling the ocean to store more CO<sub>2</sub> (Schuiling and Krijgsman 2006, Hangx and Spiers 2009). Olivine-rich rocks have garnered significant attention due to their naturally occurring, fast dissolution rate and relative abundance (Griffioen 2017, Meysman and Montserrat 2017). Various rocks contain olivine in different concentrations, such as dunite (over 90% olivine) and peridotite (~40% olivine) (Philpotts and Ague 2022). Moosdorf *et al* (2014) outline the availability of global distribution of olivine-rich ultramafic rocks. This OAE technique demonstrates significant potential in the open ocean (Ilyina *et al* 2013, Köhler *et al* 2013) and coastal areas (Hangx and Spiers 2009, Feng *et al* 2017). Coastal sea deployments of olivine-rich rocks offer cost-effective and energy-efficient logistics due to shorter transport distances than open ocean alternatives (Hangx and Spiers 2009, Köhler *et al* 2013, Feng *et al* 2017). Additionally, it could benefit from specific physicochemical conditions along coastlines,



Abundant mafic and ultramafic rocks on Earth's surface suggest that the material quantity may not be a limiting factor (Hartmann *et al* 2013); however, the weathering rate varies considerably depending on environmental conditions. While there is growing interest in OAE, studies on how regional environmental conditions affect olivine weathering remain scarce. For instance, chemical weathering rates of olivine-rich powder were addressed in lab settings over timescales of up to a year (e.g. Montserrat *et al* 2017, Fuhr *et al* 2022). The olivine chemical weathering rates are significantly influenced by temperature and grain size (Hangx and Spiers 2009, Köhler *et al* 2013, Feng *et al* 2017, Oelkers *et al* 2018), with larger particles dissolving more slowly than smaller ones (Rigopoulos *et al* 2018). While global models have explored olivine's overall weathering potential, they often overlook the time dimension (Hangx and Spiers 2009, Köhler *et al* 2010). The practical

applicability of enhanced weathering requires achieving specific CO<sub>2</sub> sequestration targets within policy-relevant timeframes, such as by 2100 (IPCC 2021). However, Feng *et al* (2017) emphasized the importance of conducting more refined regional studies to assess the technological and environmental feasibility of specific coastal deployment scenarios.

Therefore, this study aims to provide insights into the CO<sub>2</sub> sequestration efficiency of ocean alkalization by olivine-rich rocks dissolution. The study covers different grain sizes and temperatures, representing 13 distinct coastal regions worldwide. By simulating weathering in a 100 year timeframe using geochemical thermodynamic equilibrium modeling (PHREEQC), we show the sequestration potential of olivine-rich rocks spreading under different conditions in policy-relevant timeframes. These findings support mitigation efforts by identifying regions with the highest physicochemical potential for coastal enhanced weathering, contributing to sustainable solutions to climate change challenges.

## 2. Methodology

### 2.1. Model description

Carbon sequestration was modeled utilizing the software PHREEQC version 2 (Parkhurst and Appelo 2013) following the approach outlined by Zhang *et al* (2019) utilizing its multicomponent geochemical model code and databases. For this study, the Lawrence Livermore National Laboratory thermodynamic database was used, which includes olivine (in the form of forsterite (Mg<sub>1.682</sub>Fe<sub>0.31</sub>Ni<sub>0.008</sub>SiO<sub>4</sub>)) equilibrium constants (Griffioen 2017). A box model was developed to simulate the dissolution of 1 g of forsterite with a grain size of 100 μm in 1 kg of seawater. The 1:1000 water-rock ratio was chosen to balance realism, ensuring that the experimental conditions mirrored real-world scenarios as closely as possible, while also maintaining solubility control and practicality in laboratory settings. The model integrates forsterite mineralogy and incorporates thermodynamic data, including the dissociation constant (log *k* = 27.86) and enthalpy (−205.61 kJ mol<sup>−1</sup>) determined for forsterite (Zhang *et al* 2019).

The model considered various factors for forsterite dissolution in seawater across 13 regions (table 1). This included the composition of seawater, including concentrations of Na, K, Mg, Ca, Cl, SO<sub>4</sub>, HCO<sub>3</sub>, and Si, in addition to pH and temperature. Seawater pH and their chemistry data were sourced from literature and governmental datasets (table S1 in supplementary material). Sea surface temperature (SST) data were obtained from NOAA's daily satellite observations (Huang *et al* 2021). Table 1 summarizes input seawater temperatures and pH used in the models for the thirteen regional seas, representing a range of

**Table 1.** Modeled locations and input temperature for different scenarios.

Climate	Location/Sea	SST (°C)			pH		
		Mean SST of the coldest month	Annual mean SST	Mean SST of the warmest month	Cold	Average	Warm
Temperate Region	Black Sea	3.1	7.2	26.7	8.35	8.38	8.41
	Mediterranean Sea	7.6	14.7	29.2	8.03	8.34	8.53
	North Sea	3.0	11.1	18.7	7.87	8.15	8.49
	Baltic Sea	1.6	10.9	20.2	7.90	8.20	8.50
	Marmara Sea	8.8	17.0	25.1	7.90	8.20	8.50
Tropical Region	Mexico Gulf	13.2	22.1	30.9	8.20	8.22	8.22
	Caribbean Sea	24.8	27.7	30.5	7.93	8.00	8.16
	Red Sea	19.5	26.0	32.5	8.20	8.45	8.70
	Arabian Gulf	22.1	27.6	33.0	7.80	8.20	8.10
	Bay of Bengal	25.3	28.4	30.9	7.47	7.75	7.93
	Arabian Sea	25.3	28.4	31.2	7.87	8.03	8.10
	South China Sea	21.5	26.6	30.0	7.66	8.04	8.40
	Banda Sea	27.7	29.3	31.2	8.20	8.20	8.20

coastal environments, including annual averages and extremes.

In PHREEQC, kinetic modeling involves two primary data blocks: KINETICS and RATES (Parkhurst and Appelo 2013). The KINETICS data block defines the initial moles of the reacting phase, in this case, forsterite (0.0066 mol), and initial mineral surface area ( $0.2291 \text{ m}^2 \text{ g}^{-1}$ ) calculated based on Strefler *et al* (2018) with a scaling factor of 0.131. The RATES data block specifies kinetic parameters, including rate constants, activation energies, and reaction orders (Parkhurst and Appelo 2013). This model utilizes BASIC language scripts developed by Zhang *et al* (2019) for forsterite.

The model simulates the gradual dissolution of forsterite while maintaining equilibrium with atmospheric  $\text{O}_2$  and  $\text{CO}_2$  concentrations in the form of gases and minerals. It also allowed for the precipitation of goethite, calcite, aragonite, magnesite, talc, sepiolite, and amorphous silica if they become saturated. The model prescribes that water and atmosphere are in equilibrium ( $\text{pCO}_2 = 400 \text{ ppm}$  and  $\text{pO}_2 = 20\,000 \text{ ppm}$ ), as described by Griffioen (2017).

## 2.2. Calculation of $\text{CO}_2$ sequestration

PHREEQC tracked the moles of reactants, representing the amount of olivine that had reacted over time, following the dissolution kinetics defined for the system (Parkhurst and Appelo 2013, Zhang *et al* 2019). The stoichiometry of the reactions governing olivine dissolution and the subsequent conversion of dissolved species to solid carbonate minerals was considered, allowing for the calculation of  $\text{CO}_2$  sequestration. The corresponding moles of  $\text{CO}_2$  involved in the reactions were determined for each mole of forsterite consumed. These mole-based calculations were then converted to mass units using the molar mass of  $\text{CO}_2$ .

## 2.3. Sensitivity analysis

A sensitivity analysis was conducted using 42 simulations, varying temperature from  $5 \text{ }^\circ\text{C}$  to  $30 \text{ }^\circ\text{C}$  in  $5 \text{ }^\circ\text{C}$  increments and grain size from 1 to  $1000 \text{ }\mu\text{m}$  (1, 10, 50, 100, 300, 500, 1000), to determine weathering efficiency within a 100 year timeframe in annual time steps. The specific surface area for the material of the mentioned grain sizes was calculated based on Strefler *et al* (2018). For example, the calculated specific surface area ranges from  $69.18 \text{ m}^2 \text{ g}^{-1}$  for  $1 \text{ }\mu\text{m}$  grain size down to  $0.013 \text{ m}^2 \text{ g}^{-1}$  for  $1000 \text{ }\mu\text{m}$  grain size.

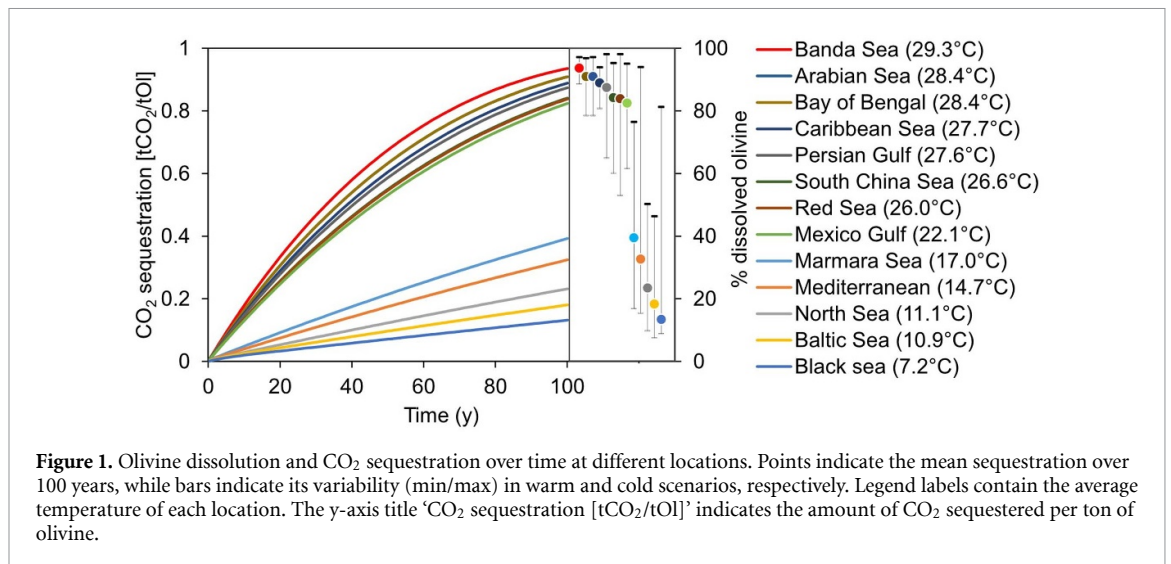
## 2.4. Mapping of $\text{CO}_2$ sequestration

To calculate the annual  $\text{CO}_2$  sequestration potentials of olivine-based enhanced weathering in coastal areas, those were identified by masking the GEBCO bathymetry dataset (GEBCO 2021) with depths between 0 and  $-200 \text{ m}$ , representing shelf areas. Monthly mean SST data from NOAA NCDC OISST 1991–2020 (Huang *et al* 2021) were combined to create an annual mean SST map. All rasters were resampled to a 10 km resolution to harmonize the datasets and improve computing efficiency. SST data were related to the bathymetry raster using zonal statistics. Spatial data were processed with ArcGIS Pro 3.

## 3. Results

### 3.1. Regional variability of $\text{CO}_2$ sequestration over 100 years

Sequestration of  $\text{CO}_2$  exhibits significant regional variability during the simulated period (figure 1). The annual average conditions sequestration capacity ranges from 0.13 to  $0.94 \text{ t CO}_2/\text{t olivine}$ .  $\text{CO}_2$  sequestration through olivine weathering depends on the forsterite content. The results presented here assume an olivine composition of 80% forsterite



**Figure 1.** Olivine dissolution and CO<sub>2</sub> sequestration over time at different locations. Points indicate the mean sequestration over 100 years, while bars indicate its variability (min/max) in warm and cold scenarios, respectively. Legend labels contain the average temperature of each location. The y-axis title 'CO<sub>2</sub> sequestration [tCO<sub>2</sub>/tOlivine]' indicates the amount of CO<sub>2</sub> sequestered per ton of olivine.

and 20% fayalite, as calculated using Equation in the methodology. If the forsterite content were 90%, CO<sub>2</sub> sequestration would range from 0.14 to 1.04 tons per ton of olivine. In practice, olivine-rich rock, rather than pure olivine, would be applied to the waters. The amount of olivine-rich rock needed to achieve the same sequestration rates is inversely proportional to the rock's olivine content. For example, for a peridotite containing 40% olivine, 2.5 times more rock would be needed compared to pure olivine to achieve the same CO<sub>2</sub> sequestration. The Banda Sea exhibits the highest sequestration rates, while the lowest are calculated for the Black Sea (figure 1). Sequestration rates in temperate seas range 0.13–0.32 t CO<sub>2</sub>/t olivine, in the Black and Mediterranean Sea, respectively. Warmer seas show higher sequestration rates, with the Red Sea and South China Sea averaging 0.84 t CO<sub>2</sub>/t olivine.

In the annual average cold conditions across different seas, the CO<sub>2</sub> sequestration within 100 years ranges from 0.07 to 0.88 t CO<sub>2</sub>/t olivine (figure 1). In temperate seas, the CO<sub>2</sub> sequestration rates range from 0.07 t CO<sub>2</sub>/t olivine removed in the Baltic Sea to 0.17 t CO<sub>2</sub>/t olivine removed in the Marmara Sea. For tropical seas, the range extends from 0.53 t CO<sub>2</sub>/t olivine removed in the Red Sea to 0.88 t CO<sub>2</sub>/t olivine removed in the Banda Sea.

In the annual warm conditions, CO<sub>2</sub> sequestration rates range from 0.46 to 0.98 t CO<sub>2</sub>/t olivine dissolution (figure 1). The Baltic Sea exhibits a sequestration rate of 0.46 t CO<sub>2</sub>/t olivine, while the Red Sea and the Persian Gulf demonstrate the highest rates at 0.98 t CO<sub>2</sub>/t olivine. In temperate seas, rates range from 0.46 (Baltic Sea) to 0.94 (Mediterranean Sea) t CO<sub>2</sub>/t olivine. For tropical seas, rates are 0.94 (Caribbean Sea) and 0.98 (Red Sea and Persian Gulf) t CO<sub>2</sub>/t olivine.

The percentage of olivine weathered in the warmer regions was between 13% and 18% after 10 years, 54%–69% after 50 years, and 84%–95%

after 100 years (figure 1). In temperate regions, the cumulative weathering of olivine would be 2%–5% after 10 years, 7%–22% after 50 years, and 13%–40% after 100 years.

### 3.2. Sensitivity analysis

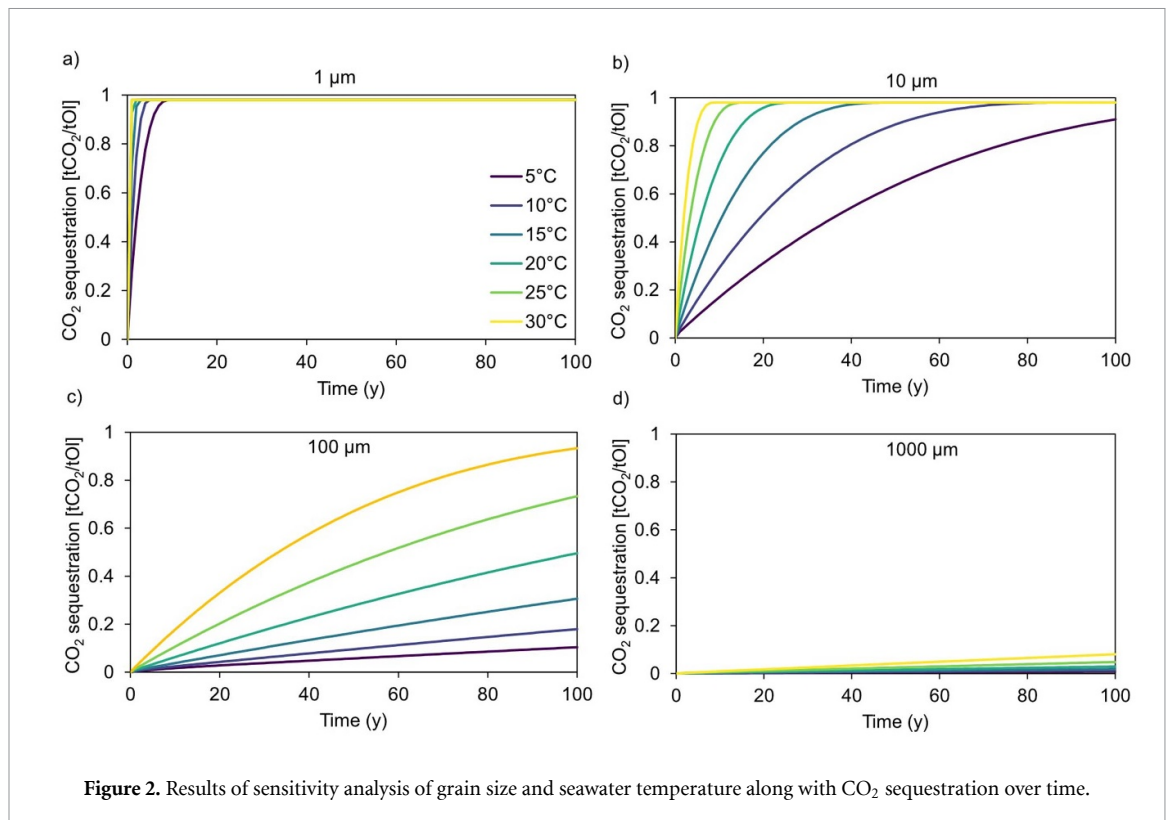
The sensitivity analysis shows that smaller grain sizes and higher temperatures result in significantly higher CO<sub>2</sub> sequestration, while larger grain sizes and lower temperatures lead to lower CO<sub>2</sub> sequestration (figure 2). Among the tested scenarios, grain sizes  $\leq 10 \mu\text{m}$  sequestered CO<sub>2</sub> the fastest (figures 2(a) and (b)). For instance, with a grain size of 1  $\mu\text{m}$  and various temperature combinations, complete dissolution occurs within 1–10 years, resulting in a CO<sub>2</sub> sequestration of 0.98 t CO<sub>2</sub>/t olivine (figure 2(a)). Similarly, for a grain size of 10  $\mu\text{m}$  and temperature combinations ranging from 10 °C to 30 °C, complete dissolution occurs within 9–84 years, while a grain size of 10  $\mu\text{m}$  and temperature 5 °C result in 90% dissolution at 100 years, with a CO<sub>2</sub> sequestration of 0.9 t CO<sub>2</sub>/t olivine (figure 2(b)).

For larger grain sizes, the dissolution rates decrease. For a grain size of 100  $\mu\text{m}$ , dissolution ranges from 10%–90% at the end of the 100 year simulation period (figure 2(c)). In the case of 1000  $\mu\text{m}$  grain size, the dissolution is only 8%, even at temperatures of 30 °C, leading to a relatively lower CO<sub>2</sub> consumption ranging from 0.01 to 0.08 t CO<sub>2</sub>/t olivine throughout the simulation (figure 2(d)).

## 4. Discussion

### 4.1. Sequestration variability

The regional differences in CO<sub>2</sub> sequestration rates across the 13 studied seas indicate that the geographical location strongly controls the effectiveness of olivine-based enhanced weathering. Each region has its unique combination of climate and environmental factors, contributing to the observed variability



**Figure 2.** Results of sensitivity analysis of grain size and seawater temperature along with CO<sub>2</sub> sequestration over time.

in CO<sub>2</sub> sequestration. Seawater temperature was the variable that controlled most of the process. Warmer waters provide more favorable conditions for enhanced weathering (Köhler *et al* 2013). The increased temperature accelerates chemical reactions, leading to faster dissolution of olivine particles and more efficient conversion of CO<sub>2</sub> into carbonate minerals (Oelkers *et al* 2018). Our results underline that these differences amount to an additional 0.4 t CO<sub>2</sub>/t olivine dissolved in seawater in warm seas in 100 years (figure 1).

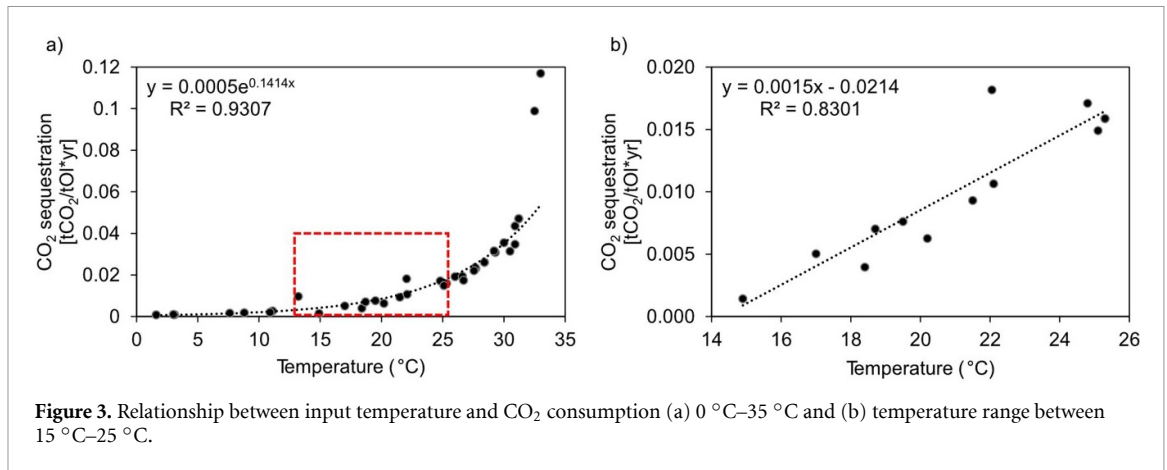
Furthermore, the simulations estimated the total mass of weathered olivine (figure 1), which aligns with the analytical solutions given by Hangx and Spiers (2009) and the Earth system model assessed by Feng *et al* (2017). Grain size was the second variable strongly influencing olivine dissolution. Hangx and Spiers (2009) found that 100 μm olivine grains would require more than 100 years to dissolve at a tropical SST of 25 °C, consistent with the results obtained for the Red Sea in the current simulation (SST: 26 °C). Similarly, the complete dissolution of olivine in temperate regions at the same grain size may take more than 1000 years (similar to the Black Sea). This highlights the importance of reducing the grain size to accelerate the dissolution and achieve significant CO<sub>2</sub> sequestration, even in colder regions.

#### 4.2. Impact of seawater temperature

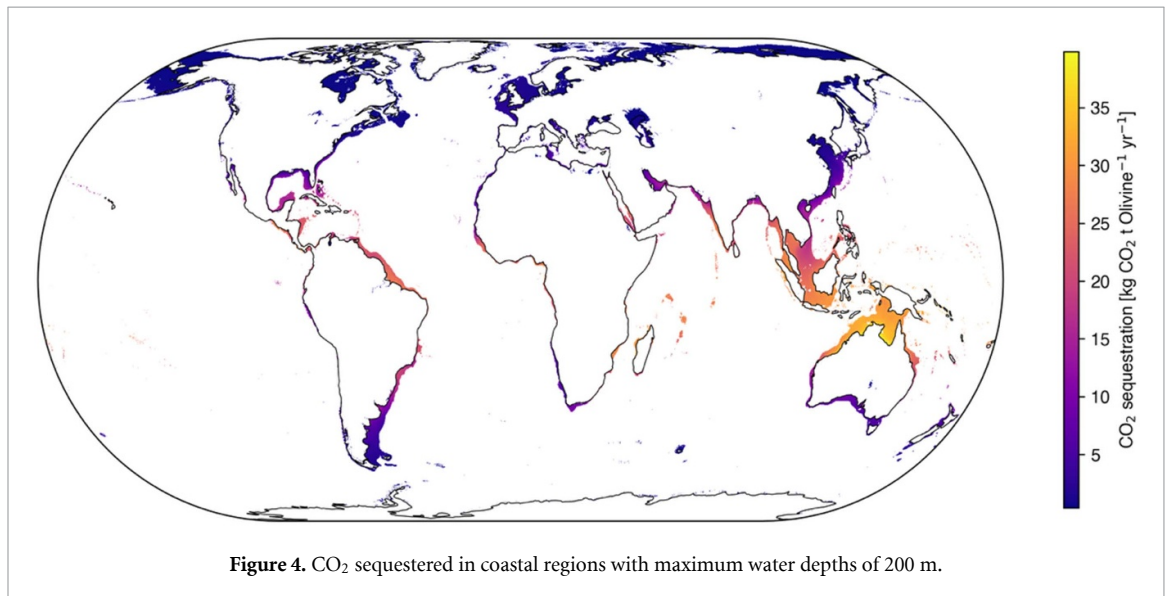
CO<sub>2</sub> sequestration rates of enhanced olivine-rich rock weathering are susceptible to seawater temperature

(figure 3(a)). Lower temperatures lead to slower reactions, and higher temperatures accelerate the process. The CO<sub>2</sub> sequestration rates follow an exponential function, which can be approximated by a linear relation of a seawater temperature range of 15 °C–25 °C (figure 3(b)). At these temperatures, an additional 1.5 kg CO<sub>2</sub>/t olivine is sequestered per year in the sea per degree of temperature increase (figure 3(b)). The linear correlation can be used to compare or correct field results at different temperature levels.

From a global perspective, fast weathering is evident in East Asian Seas (e.g. Banda Sea, South China Sea), while the coastal seas of the Northwest Pacific (e.g. Yellow Sea, East China Sea) and North-East Atlantic (e.g. Baltic, and North Sea) exhibit relatively slower weathering but encompass extensive areas (figure 4). The total considered coastal area is 26.6 Mkm<sup>2</sup> (figure 4), of which 6.53 Mkm<sup>2</sup> are kinetically favorable for EW by allowing more than 80% of olivine (grain size 100 μm) to dissolve within 100 years. Despite reduced weathering speeds, other regions still hold significant potential for olivine-based enhanced weathering due to their extensive coastal coverage (see figure S2.1 in supplementary material for regional CO<sub>2</sub> sequestration). The observed trends in various regions on the global map contribute to the overarching theme emphasizing the importance of a tailored, region-specific approach in olivine-based enhanced weathering strategies (figure 4).



**Figure 3.** Relationship between input temperature and CO<sub>2</sub> consumption (a) 0 °C–35 °C and (b) temperature range between 15 °C–25 °C.

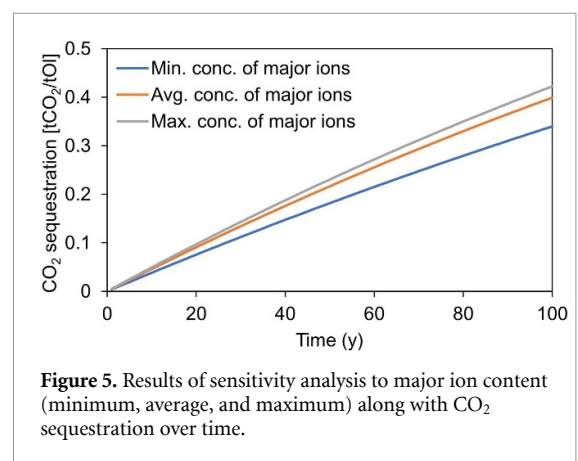


**Figure 4.** CO<sub>2</sub> sequestered in coastal regions with maximum water depths of 200 m.

#### 4.3. Other controlling factors of CO<sub>2</sub> sequestration efficiency

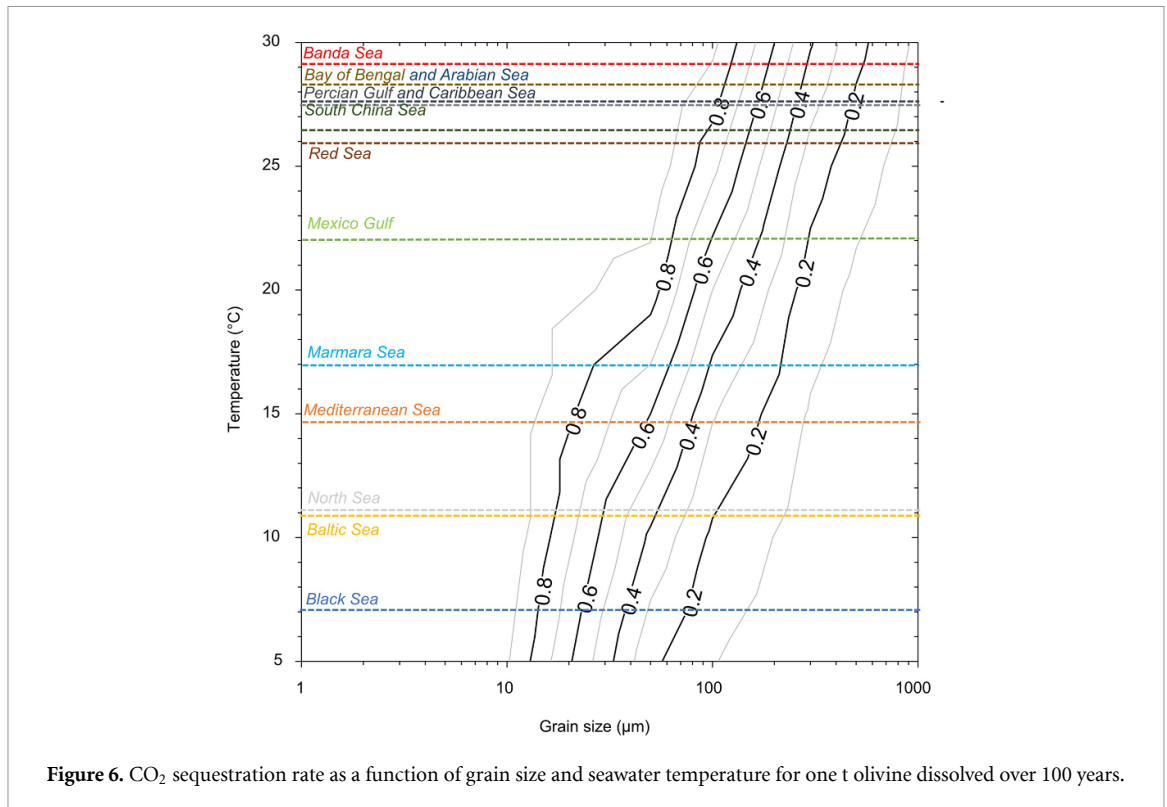
The second key influencing factor is the grain size of the olivine-rich rocks. A smaller grain size increases the CO<sub>2</sub> sequestration rate of olivine weathering (figure 2) due to the exponential increase of mineral surface area with a decrease in grain size (Strefler *et al* 2018). Grains with a size of  $\leq 10 \mu\text{m}$  show a very high CO<sub>2</sub> sequestration efficiency (figures 2(a) and (b)). Larger grain sizes, especially in temperate conditions, experience a decline in CO<sub>2</sub> sequestration due to slower reaction rates in colder waters (figures 2(c) and (d)). The reduced efficiency of olivine weathering in these conditions leads to a decreased rate of CO<sub>2</sub> sequestration. Thus, in cold regions, more energy needs to be invested in milling to allow weathering rates high enough to be relevant at timescales of decades.

Another influence factor is seawater chemistry, which may affect CO<sub>2</sub> sequestration. The model incorporated a comprehensive range of seawater chemistry data collected from 13 distinct regional



**Figure 5.** Results of sensitivity analysis to major ion content (minimum, average, and maximum) along with CO<sub>2</sub> sequestration over time.

seas. The simulations maintained a constant average seawater temperature of 17 °C and a pH of 8.1. The range spanned minimum, maximum, and average seawater conditions (based on major ion content, see table S1), with corresponding sequestration rates of 0.34, 0.40, and 0.42 t CO<sub>2</sub>/t olivine (figure 5). This



**Figure 6.** CO<sub>2</sub> sequestration rate as a function of grain size and seawater temperature for one t olivine dissolved over 100 years.

variation is attributed to the availability of reactants in the surrounding water, which influences olivine dissolution rates. In regions where seawater chemistry deviates from the average, whether due to natural variations (geological and climatic differences) or anthropogenic influences (like industrial discharges), the efficiency of olivine-based enhanced weathering can be notably impacted.

#### 4.4. Optimizing CO<sub>2</sub> sequestration: grain size and temperature interplay

Selecting the appropriate grain size based on specific environmental conditions becomes crucial for maximizing CO<sub>2</sub> sequestration efficiency (Strefler *et al* 2018). Figure 6 shows a 2D mapping of CO<sub>2</sub> sequestration rates as a function of grain size and seawater temperature over 100 years. For instance, enhanced weathering with olivine in the Black Sea would require a grain size of 15 μm to reach a CO<sub>2</sub> consumption ratio of 0.8 t CO<sub>2</sub>/t olivine after 100 years, while the Banda Sea achieves the same ratio with a grain size of 150 μm (figure 6). This aligns with previous findings emphasizing the significance of small-grained olivine (2–6 μm) to achieve substantial CO<sub>2</sub> sequestration rates over several decades (Hangx and Spiers 2009).

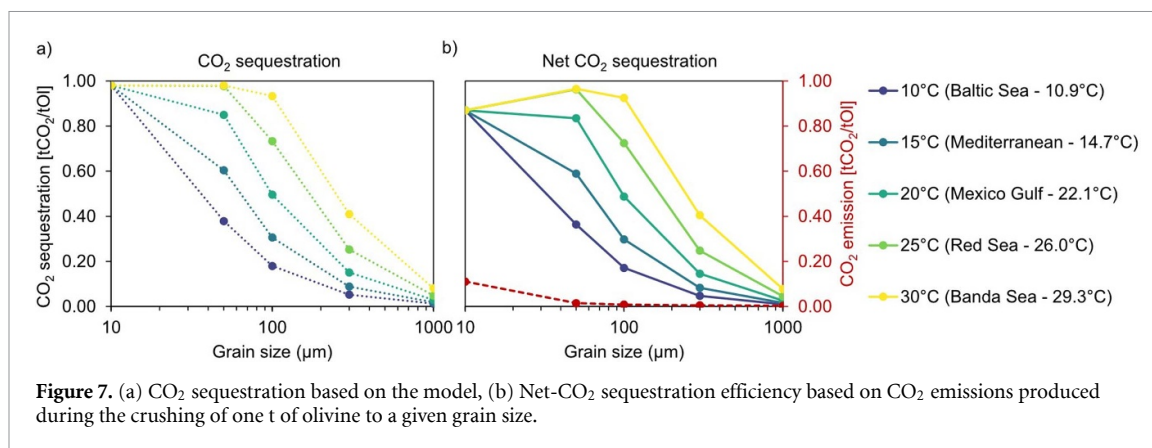
However, reducing the material grain size requires energy input from crushing, grinding, or milling. This energy requirement will to some extent incur CO<sub>2</sub> emissions, a penalty that can diminish the efficiency of olivine-rich rocks spreading for CO<sub>2</sub> sequestration (Hangx and Spiers 2009, Moosdorf *et al* 2014). Renforth (2012) highlights the impracticality

of grinding olivine to a size below 10 μm in most locations due to cost and time constraints. Despite this, the CO<sub>2</sub> emissions resulting from the grinding and crushing of olivine are generally low compared to the achieved sequestration (Moosdorf *et al* 2014). The emissions associated with primary crushing and secondary grinding of olivine range from 3.1 to 110.5 kg of CO<sub>2</sub> per t of CO<sub>2</sub> sequestered, depending on olivine particle size (Hangx and Spiers 2009). In an energy mix with more renewables, the associated CO<sub>2</sub> penalty would be lower.

Net CO<sub>2</sub> sequestration (i.e. sequestration after 100 years (figure 7(a)) minus the above-mentioned CO<sub>2</sub> emissions) of grain sizes of 10 μm was consistently 0.87 t CO<sub>2</sub> /t olivine for all scenarios (figure 7(b)). Warmer regions, such as the Banda Sea and Red Sea, show higher maximum net CO<sub>2</sub> sequestration rates (0.97 t CO<sub>2</sub> /t olivine) at a grain size of 50 μm. In the Banda Sea, even net CO<sub>2</sub> sequestration rates of olivine with a grain size of 100 μm (0.93 t CO<sub>2</sub> /t olivine) exceed that of 10 μm particles (figure 7(b)). These findings highlight that in warmer regions, higher net-CO<sub>2</sub> sequestration ratios per time can be reached using coarser grains, thereby optimizing the efficiency of CO<sub>2</sub> sequestration. Extrapolating these ratios and material application rates across diverse coastal surface areas in various regions allows for a robust estimate of the broader-scale CO<sub>2</sub> sequestration potential.

In the context of policy making, with specific CO<sub>2</sub> sequestration targets to be met in a defined timeframe, this study shows that by prioritizing regions with higher net CO<sub>2</sub> sequestration rates





(nearly 1 t CO<sub>2</sub> /t olivine), legislation can strategically focus efforts on maximum CO<sub>2</sub> sequestration. Additionally, adopting smaller grain sizes ( $\leq 10 \mu\text{m}$ ) in colder regions (like the European Union) presents an adaptive approach to optimizing weathering rates under less favorable temperature conditions at the cost of efficiency. By incorporating these scientific insights into policy frameworks, policymakers can make informed decisions and allocate resources effectively to regions and strategies with the highest potential for achieving CO<sub>2</sub> sequestration goals.

#### 4.5. Model assumptions and limitations

The applied model substantially simplifies natural systems, designed only to highlight concepts and trigger discussions. It does not represent exact and detailed conditions at individual locations or cover the complexities of the natural world.

Like others studying marine enhanced weathering, one limitation of this approach is that it assumes the weathering takes place in the water column and the system is far from saturation. As shown, olivine weathering in seawater typically occurs relatively slowly, spanning decades for individual grains (figure 1). Applying the simplified Stokes' Law equation (Stokes 1851), allows to calculate whether the olivine stays in the water column for that time. Round olivine grains with a diameter of  $10 \mu\text{m}$  take a month (26.8 d for 1000 m) to settle, while grains with a diameter of  $100 \mu\text{m}$  take just days (0.26 d for 1000 m). In real-world complexities, ocean currents and turbulences substantially influence settling behavior. The comparison of days to settle and decades to weather indicates that most olivine would weather on the seafloor, especially considering that the general coastal oceans have a water depth of no more than 200 m (Tyler 2003). Therefore, the specific conditions for weathering on the seafloor deserve closer consideration in future analyses.

Additionally, this study neglects dynamic coastal currents, which could impact the olivine weathering rates. The study does not account for the evolving

chemistry of seawater over time due to alkalization through advection, especially in open coastal systems. Furthermore, variations in seawater parameters such as  $p\text{CO}_2$ ,  $p\text{O}_2$ , seawater temperatures, and pH with depth are not fully addressed.

Another important aspect is that understanding environmental and ecological factors is vital for successfully and sustainably implementing coastal enhanced weathering. As olivine-rich rocks dissolves, it can increase seawater alkalinity locally, mitigating ocean acidification caused by excess CO<sub>2</sub> absorption (Feng *et al* 2017). Nevertheless, the introduction of olivine-rich rocks, rich in silicon, iron, and trace heavy metals, may lead to eutrophication, harmful algal blooms, and oxygen depletion, necessitating careful evaluation and effective management strategies (Blain *et al* 2007, Hauck *et al* 2016). Thus, the environmental and ecological implications of coastal enhanced weathering, including benefits and potential risks, must be carefully considered to ensure responsible and sustainable implementation (Bach *et al* 2019). On the other hand, the relevance of microbiology on weathering rates is known from studies of natural chemical weathering on land (Rogers and Bennett 2004). However, this aspect has been neglected in analyses of enhanced weathering in the marine realm. Integrating microbiological aspects into this model would require additional data and a more intricate framework, exceeding the scope of the current investigation.

An increase in alkalinity may lead to calcium carbonate precipitation in the water column. This could counteract the intended benefits of ocean alkalization by removing alkalinity, potentially reducing olivine dissolution efficiency (Moras *et al* 2022, Hartmann *et al* 2023). However, as per the geochemical character as silicate, the re-precipitation only releases 50% of the captured CO<sub>2</sub> (e.g. Hartmann *et al* 2013). Precipitation can be triggered during spreading and would impact olivine dissolution rates (Fuhr *et al* 2022), which is not considered here. Numerous intricate environmental factors (i.e. nutrient availability and microbial activity) affect the mineral

reactivity and weathering rates, requiring consideration for specific enhanced weathering evaluations (Fuhr et al 2022, Wallmann et al 2022).

Lastly, the OAE linked CO<sub>2</sub> costs of mining and transport operations are not considered, given their demonstrated comparably small impact on coastal enhanced weathering (Moosdorf et al 2014). Also, internal transport processes like diffusion within the rock matrix are beyond the study's scope.

## 5. Conclusion

This study highlights the potential of olivine-rich rocks enhanced weathering to reduce atmospheric CO<sub>2</sub> levels along the coast within a defined time frame (100 years). The model simulated the weathering effect of 13 coastal seas worldwide, providing valuable insights into the variability of CO<sub>2</sub> sequestration rates. Each location has a maximum CO<sub>2</sub> sequestration capacity determined by its unique environmental conditions. In warmer regions, the maximum CO<sub>2</sub> sequestration capacity is higher than in cooler regions. For example, in the Banda Sea, the CO<sub>2</sub> sequestration capacity is estimated to be 0.94 t CO<sub>2</sub>/t olivine in 100 years, while in the Baltic Sea, it is estimated to be 0.13 t CO<sub>2</sub>/t olivine, using 100 μm grain size.

The faster reaction rates observed in warmer areas highlight the importance of strategically focusing sequestration efforts on these regions to maximize CO<sub>2</sub> sequestration. Globally, 6.53 Mkm<sup>2</sup> of coastal seas allow for dissolution of 80% of olivine of a grain size of 100 μm within 100 years. Additionally, the selection of the grain size plays a critical role in optimizing weathering rates. For instance, achieving a sequestration efficiency of 80% (0.8 t CO<sub>2</sub> /t olivine) within 100 years requires a grain size of 15 μm in the temperate Baltic Sea, while a larger grain size of 150 μm is needed in the warmer Banda Sea. Achieving fast weathering rates through grain size reduction means putting more energy into crushing, which may introduce a CO<sub>2</sub> penalty if no renewable energy sources are available.

Adding the CO<sub>2</sub> costs of crushing procedures into the equation leads to a theoretical maximum amount of net CO<sub>2</sub> sequestration in a region in 100 years, which is 0.87 t CO<sub>2</sub> /t olivine in colder areas such as the Baltic Sea and close to its stoichiometric maximum with 0.97 t CO<sub>2</sub> /t olivine in warmer regions like the Banda Sea. These findings show that it strongly matters where olivine-rich rocks spread for enhanced weathering to meet specific political CO<sub>2</sub> sequestration targets within designated timeframes.

## Data availability statement

The manuscript contains original contributions that are presented in detail within the article/Supplementary Materials. For additional information or

inquiries, we encourage contacting the corresponding author.

All data that support the findings of this study are included within the article (and any supplementary files).

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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