

# Influence of Ocean Alkalinity Enhancement with Olivine or Steel Slag on a Coastal Plankton Community in Tasmania

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**Abstract.** Ocean alkalinity enhancement (OAE) aims to increase atmospheric CO<sub>2</sub> sequestration in the oceans through the acceleration of chemical rock weathering. This could be achieved by grinding rocks containing alkaline minerals and adding the rock powder to the surface ocean where it dissolves and chemically locks CO<sub>2</sub> in seawater as bicarbonate. However, CO<sub>2</sub> sequestration during dissolution coincides with the release of potentially bio-active chemicals and may induce side effects. Here, we used 53 L microcosms to test how coastal plankton communities from Tasmania respond to OAE with olivine (mainly Mg<sub>2</sub>SiO<sub>4</sub>) or steel slag (mainly CaO and Ca(OH)<sub>2</sub>) as alkalinity sources. Three microcosms were left unperturbed and served as a control, three were enriched with olivine powder (1.9 g L<sup>-1</sup>), and three with steel slag powder (0.038 g L<sup>-1</sup>). Olivine and steel slag powders were of similar grain size, but the amount of added olivine needed to be much higher than the steel slag because less alkalinity is released by the olivine than the steel slag over the 3-week experiment. Phytoplankton and zooplankton community responses as well as some biogeochemical parameters were monitored for 21 days. Olivine and steel slag additions increased total alkalinity by 29 μmol kg<sup>-1</sup> and 361 μmol kg<sup>-1</sup> respectively, which corresponds to a theoretical increase of 0.9 % and 14.8 % of the seawater storage capacity for atmospheric CO<sub>2</sub>. Olivine and steel slag released silicate nutrients into the water column, but steel slag released considerably more and also significant amounts of phosphate. After 21 days, no significant difference was found in dissolved iron concentrations (>100 nmol L<sup>-1</sup>) in the treatments and the control. Both minerals released dissolved aluminium (>50 nmol L<sup>-1</sup>). The slag addition increased dissolved manganese concentrations (771 nmol L<sup>-1</sup>), while olivine increased dissolved nickel concentrations (37 nmol L<sup>-1</sup>). The slag treatment increased the total particulate manganese concentrations (22 nmol L<sup>-1</sup>), while olivine increased the total particulate nickel (5 nmol L<sup>-1</sup>), which was consistent with the increase in the dissolved concentrations of these trace metals in seawater. There was no significant difference in total chlorophyll *a* concentrations between the treatments and the control, likely due to nitrogen limitation of the phytoplankton community. However, flow cytometry results indicated an increase in the cellular abundance of several smaller (~<20 μm) phytoplankton groups in the olivine treatment compared to the slag treatment and the control. The abundance of larger phytoplankton (~>20 μm) decreased much more in the control than in the mineral addition treatments after day 10. Furthermore, the maximum quantum yields of photosystem II (F<sub>v</sub>/F<sub>m</sub>) were higher in slag and olivine treatments, suggesting that mineral additions increased photosynthetic performance. The zooplankton community composition was also affected with the most notable changes being observed in the dinoflagellate *Noctiluca scintillans* and the appendicularian

37 *Oikopleura* sp. Overall, steel slag is much more efficient for CO<sub>2</sub> removal with OAE than olivine and appears to induce  
38 less change in the plankton community when relating the CO<sub>2</sub> removal potential to the level of environmental impact that  
39 was observed here.

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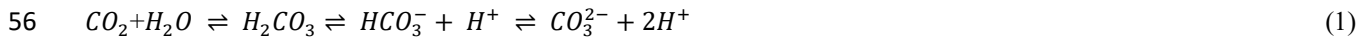
## 41 **1 Introduction**

42 Keeping global warming below 2 °C requires immediate emissions reduction. Additionally, between 450-1100 Gigatonnes  
43 of carbon dioxide (CO<sub>2</sub>) need to be removed from the atmosphere by 2100 (Smith et al., 2023). This could be achieved  
44 with a portfolio of terrestrial and marine Carbon Dioxide Removal (CDR) methods. Ocean alkalinity enhancement (OAE)  
45 is a marine CDR method that could theoretically contribute significantly to the global CDR portfolio (Ilyina et al., 2013;  
46 Feng et al., 2017; Lenton et al., 2018).

47

48 Alkalinity is generated naturally when rock weathers and it has control on the ocean's chemical capacity to store CO<sub>2</sub>  
49 (Schuiling and Krijgsman, 2006). Natural rock weathering is currently responsible for about 0.5 Gt of atmospheric CO<sub>2</sub>  
50 sequestration every year (Renforth and Henderson, 2017). The idea behind OAE is to accelerate natural rock weathering  
51 by extracting calcium- or magnesium-rich rocks, such as olivine, pulverizing them, and spreading them onto the sea surface  
52 to increase chemical weathering rates (Hartmann et al., 2013). The weathering (i.e., dissolution) of these alkaline minerals  
53 will consume protons (H<sup>+</sup>), which shifts the carbonate chemistry equilibrium in seawater from CO<sub>2</sub> towards increasing  
54 bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate ion (CO<sub>3</sub><sup>2-</sup>) concentrations:

55



57

58 thereby making new space for atmospheric CO<sub>2</sub> to be dissolved in seawater and permanently stored. Previous model studies  
59 have shown that OAE can mitigate climate change significantly by increasing the oceanic uptake of CO<sub>2</sub> from the  
60 atmosphere (Kohler et al., 2010; Paquay and Zeebe, 2013; Keller et al., 2014; Lenton et al., 2018). For example, the study  
61 by Burt et al. (2021) suggested that the total global mean dissolved inorganic carbon (DIC) inventories would increase by  
62 156 GtC after total alkalinity is enhanced at a rate of 0.25 Pmol year<sup>-1</sup> in 75-year simulations.

63

64 There are a variety of alkaline minerals that could be used for OAE. A widely considered naturally occurring mineral is  
65 forsterite, a (Mg<sub>2</sub>SiO<sub>4</sub>)-rich olivine. This type of olivine is abundant in ultramafic rock such as dunite, constituting at least  
66 88 % of the rock composition (Ackerman et al., 2009; Su et al., 2016). Olivine occurs in the Earth's crust but is more  
67 abundant in the upper mantle. There are at least several billion tons of olivine resources on Earth (Caserini et al., 2022).  
68 However, the extraction of olivine in 2017 was only around 8.4 Mt year<sup>-1</sup> (Reichl et al., 2018), which is about two orders  
69 of magnitude below the mass needed for climate-relevant OAE with olivine (Caserini et al., 2022). The net reaction for  
70 CO<sub>2</sub> sequestration with Mg<sub>2</sub>SiO<sub>4</sub> is:

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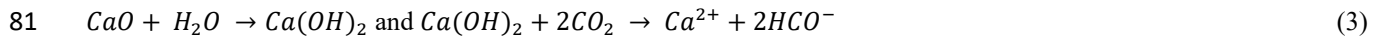


73

74 Another potential OAE source material is steel slag (Renforth, 2019), a by-product of steel manufacturing. During steel

75 manufacturing, high-purity calcium oxide (CaO) is used to improve the quality of the steel through accumulation of  
76 unwanted materials such as sulphur and phosphorus. Steel slag mainly contains CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, and MnO  
77 (Kourounis et al., 2007), and the chemical composition can vary depending on the manufacturing process (Wang et al.,  
78 2011). Due to the presence of CaO and potentially other alkaline components, steel slag can increase alkalinity when  
79 dissolved in seawater. The chemical reaction for CO<sub>2</sub> sequestration with CaO is:

80



82

83 Some of the steel slag that is produced during steel manufacturing is further used (e.g., for road construction and civil  
84 engineering) but in some countries like China, 70.5 % of steel slag is left unused and stored in dumps (Guo et al., 2018).  
85 In 2016, more than 300 million tons of steel slag was not used effectively, thereby occupying the land and raising  
86 environmental concerns (Guo et al., 2018). The effective alkaline composition, availability, and relatively low cost of the  
87 raw materials make olivine and steel slag potential source materials for OAE.

88

89 To assess whether OAE is viable, it needs to be understood how its application may affect marine biota such as plankton  
90 and the biogeochemical fluxes they drive. Some data on the effects of OAE with sodium hydroxide (NaOH) on plankton  
91 communities have recently been published (Ferderer et al., 2022; Subhas et al., 2022), but to the best of our knowledge, no  
92 such data are available for olivine- and/or slag-based OAE. Chemical perturbations via olivine and slag should be like  
93 those by NaOH in that they increase seawater pH and shift the carbonate chemistry equilibrium (see Eq. 1). However, there  
94 would be additional chemical perturbations because minerals contain a variety of potentially bioactive elements that are  
95 released into the environment when they dissolve in seawater (Bach et al., 2019). One particular concern is that natural and  
96 anthropogenic minerals such as olivine and steel slag are rich in bioactive metals that are usually scarce in the ocean, such  
97 as iron (Fe), copper (Cu), nickel (Ni), manganese (Mn), zinc (Zn), cadmium (Cd), and chromium (Cr). Many of these trace  
98 metals are essential micronutrients for phytoplankton growth (Sunda, 2000; Sunda, 2012), such as being co-factors for  
99 various metalloenzymes (summarized by Twining and Baines, 2013). It is possible that the addition of alkaline minerals  
100 may benefit phytoplankton by providing trace metals currently limiting phytoplankton growth (Falkowski, 1994; Basu and  
101 Mackey, 2018). For instance, the addition of Fe is well known to stimulate phytoplankton blooms in those vast ocean  
102 regions where Fe levels limit growth (Boyd et al., 2007; Moore et al., 2013). However, some trace metals can also inhibit  
103 phytoplankton growth, and different phytoplankton species have different requirements and tolerances for trace metals  
104 (Sunda, 2012) so the addition of trace metals via OAE may change phytoplankton community composition.

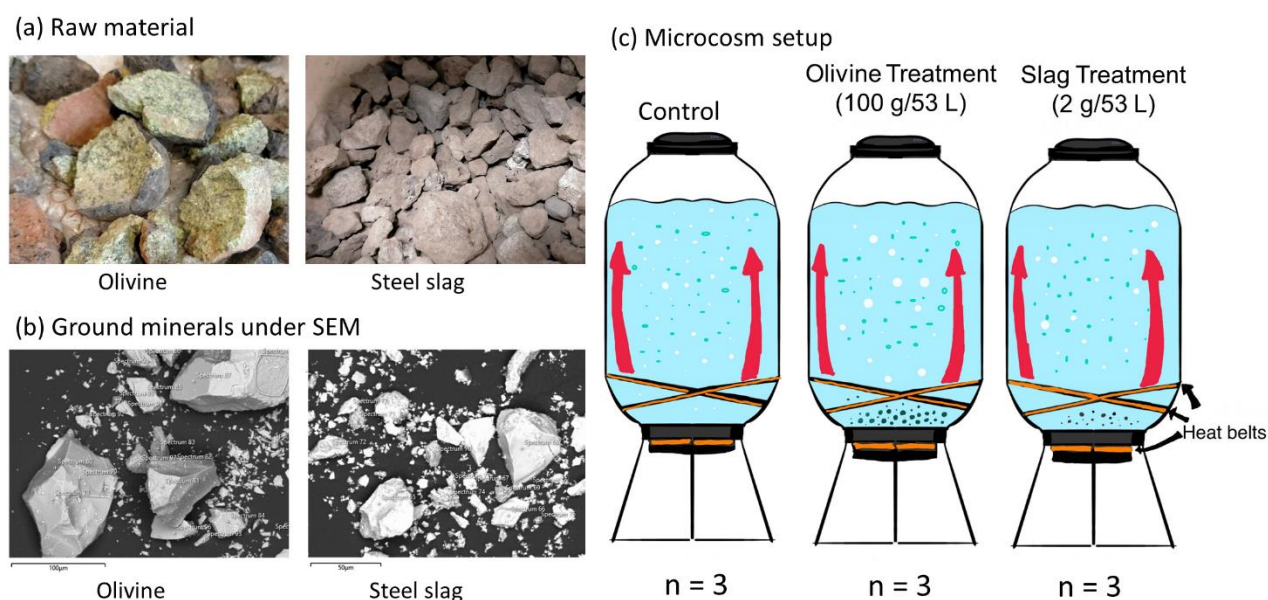
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106 Here, we describe a microcosm experiment with coastal Tasmanian plankton communities that was used to investigate: (1)  
107 how effectively OAE via the application of finely ground olivine and steel slag could sequester atmospheric CO<sub>2</sub>, and (2)  
108 if/how olivine and steel slag additions affect various components of the plankton community.

109

## 110 2 Methodology

### 111 2.1 Microcosm setup



112

113 **Fig. 1.** Experimental design and alkalinity sources. (a) Raw materials used as alkalinity sources: olivine (left) and steel slag (right).  
114 Olivine and steel slag were originally larger than 20 mm. (b) Ground minerals observed with a scanning electron microscope (SEM). (c)  
115 Microcosm setup: each microcosm enclosed ~ 53 L of surface seawater with natural plankton communities. Olivine and steel slag  
116 treatments and the control were kept in a temperature-controlled room and two heat belts were attached to the bottom of each microcosm  
117 to create convective circulation.

118

119 We used nine 53 L transparent Kegland® Fermzilla conical unitank fermenters (polyethylene terephthalate) (Fig. 1) as  
120 microcosms to incubate natural plankton communities. All microcosms were prewashed with hydrochloric acid (10 % v/v)  
121 and rinsed five times with 18.2 MΩ Milli-Q water. Seawater with coastal plankton communities was collected at Battery  
122 Point, Tasmania (42.892°S, 147.337°E) within 2 hours by lowering the microcosms into the ocean with a crane and filling  
123 them in a manner similar to a Niskin bottle, as described in detail in Ferderer et al. (2022). A sieve with a mesh size of 2  
124 mm was attached to the top and bottom of the microcosms during filling to avoid the entrapment of large and patchily  
125 distributed organisms in the microcosms. The enclosed seawater weight was initially between 52.35-54.70 kg. After  
126 seawater collection, filled microcosms were immediately transported back to the Institute for Marine and Antarctic Studies  
127 (University of Tasmania) on a truck and transferred within 75 min into a temperature-controlled room set to 7.5-8 °C. Two  
128 heat belts were attached to the bottom of each microcosm to induce a convective mixing current (Ferderer et al., 2022).  
129 Seawater temperature inside the microcosms was about 13.5 °C due to the heating effects of the heat belts and was the  
130 same as the sampled region. LED light strips were used to provide an average light intensity of 236  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$   
131 (ranging from 208 to 267  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) with a daily light-dark cycle of 10:14 hours. The light intensity was the  
132 average light intensity in each microcosm measured with a LICOR light meter at 0.15 m depth within the microcosm.  
133 Microcosms positioned in the temperature-controlled room were shuffled anti-clockwise every day to ensure similar light

134 intensity for each microcosm throughout the experiment. Treatments were established 24 hours after collecting the seawater.  
135 The total alkalinity released per amount of mineral powder added was much higher for the slag powder than the olivine  
136 powder in our preliminary test trials. So, three microcosms were enriched with 100 g of olivine powder, three microcosms  
137 with 2 g of steel slag powder, while the remaining three microcosms were left unperturbed and served as controls.

138

139

## 140 **2.2 Preparation of olivine and steel slag powder**

141 The olivine rocks were provided by Moyne Shire Council who sourced the mineral from a quarry in Mortlake, Victoria,  
142 Australia. The Basic Oxygen Slag (hereafter referred to as “slag”) was provided by Bradley Mansell who sourced the  
143 material from Liberty Primary Steel Whyalla Steelworks in Whyalla, South Australia, Australia. Upon delivery, the olivine  
144 rocks were 40-80 mm in diameter, and slag aggregates were 20-50 mm in diameter. These were crushed to smaller than 10  
145 mm pieces using a hydraulic crusher. The crushed material was further ground with a ring mill with a chrome milling pot.  
146 Afterwards, finely-ground samples were sieved to get samples with 150 ~ 250  $\mu\text{m}$  grain size. The sieved olivine and slag  
147 grains were inspected for their appearance and elemental composition using a Hitachi SU-70 analytical field emission  
148 scanning electron microscope (SEM), and energy dispersive spectrometers (Central Science Laboratory (CSL), University  
149 of Tasmania). Grain size spectra were determined with a Sympatec QICPIC particle size analyser LIXCELL (CSL,  
150 University of Tasmania).

151

## 152 **2.3 Seawater sampling**

153 Seawater was transferred with a peristaltic pump from the microcosms at a depth of about 0.15 m into 1 L acid-washed  
154 sampling bottles (LDPE) using an acid-washed silicon tube. Seawater in these bottles was then subsampled for dissolved  
155 trace metal samples, filtrations, Fast Repetition Rate fluorometry (FRRf), and flow cytometry analysis. Samples for  
156 nutrients and total alkalinity (TA) were transferred using the same pump but through a silicone tube into 80 mL HDPE  
157 bottles. Total alkalinity and macronutrient samples were filtered during this process through a 0.2  $\mu\text{m}$  nylon filter attached  
158 to the silicone tube to remove all particles and organisms  $> 0.2 \mu\text{m}$ .

159

## 160 **2.4 Salinity, nutrients, carbonate chemistry, and trace metal analysis**

161 Salinity was measured before and at the end of the experiment using a HACH HQ40d portable meter. The  $\text{pH}_T$  (total scale)  
162 and temperatures were measured daily (2-3 hours after the onset of the light period) using a pH meter (914  
163 pH/Conductometer Metrohm). We recorded voltages and temperature from the pH meter and calibrated the  $\text{pH}_T$  at original  
164 temperature at sampled time using the certified reference material (CRM) Tris buffer following the method described in  
165 SOP6a by Dickson et al. (2007). Briefly, the standard buffer’s pH and voltage at different temperature gradients were  
166 recorded, and temperature vs. voltage polynomial regression data were generated for calculating calibrated pH values ( $\text{pH}_T$ )  
167 (refer to Eq. 3 in SOP6a of Dickson et al. (2007)). The regression could then be used to obtain a CRM pH value for each  
168 temperature and to calibrate the pH measured in the microcosms to the total pH scale.

169

170 Total alkalinity was sampled every four days. It was measured in duplicate using a Metrohm 862 Compact Titrosampler  
171 coupled with an Aquatrode Plus with PT1000 temperature sensor following the SOP3b open-cell titration protocol  
172 described in Dickson et al. (2007). Filtered TA samples were stored at 8 °C for a maximum of 23 days before measurement.  
173 Titration curves were evaluated using the “calculate” script within PyCO2sys by Humphreys et al. (2022). The carbon  
174 chemistry equilibrium was calculated with the R package “seacarb” Gattuso et al. (2023) from  $pH_T$ , TA, phosphate, silicate,  
175 temperature, and salinities using stoichiometric equilibrium constants from Lueker et al. (2000). Dissolved macronutrients  
176 were measured every second day using standard spectrophotometric methods developed by Hansen and Koroleff (1999)  
177 on the day the samples were taken from the microcosms.

178

179 Dissolved trace metal concentrations were measured four times during the experiment: a few hours before olivine and slag  
180 were added, a few hours after these minerals were added on day 2, near the middle of the experiment on day 13, and at the  
181 end of the experiment on day 22. Sixty mL of seawater was collected using an acid-washed 60 mL syringe, and the seawater  
182 was filtered through 25 mm diameter 0.2  $\mu\text{m}$  pore size polycarbonate filters. Unfortunately, we did not notice that 0.2  $\mu\text{m}$   
183 pore size nylon filters (acid washed) were used during sampling on days 1 and 2 so we refiltered these seawater samples  
184 again using 0.2  $\mu\text{m}$  pore size polycarbonate filters after one month. All seawater samples were diluted approximately 20-  
185 fold by weight using Milli-Q water (18.2  $\text{M}\Omega\cdot\text{cm}$  grade) and acidified using 1 % ultrapure HCl. These samples were  
186 analysed using Sector Field Inductively Coupled Plasma Mass Spectrometry (SF-ICP-MS) employing multiple resolution  
187 settings to overcome major spectral interferences. Due to the presence of abundant major metal ions in our samples, such  
188 as Na and Mg, natural open-ocean seawater from the Southern Ocean with very low trace metal concentrations was diluted  
189 20 times with Milli-Q water and used as a representative blank. The same Southern Ocean seawater was enriched with  
190 different gradients of trace metal standards to calculate the samples’ trace metal concentrations. Five of the total 36 samples  
191 had abnormal trace metal concentrations, and 2 of them were from day 1. We considered values as outliers using the  
192 interquartile range (IQR) criterion on pre-addition data, and if values are more than 10 times higher than replicates, they  
193 are also considered as outliers. These samples containing outliers were excluded from the data analysis (Table S1.). The  
194 major likely source of these metal contaminations is sampling in the temperature control room, where precautions were  
195 insufficiently implemented.

196

## 197 **2.5 Particulate matter and plankton community analysis**

198 Chlorophyll *a* was sampled every second day by filtering the seawater through glass fibre filters (GF/F, pore size = 0.7  $\mu\text{m}$ ,  
199 diameter = 25 mm), and filters were stored in 15 mL polypropylene tubes wrapped with aluminium foil and stored at -80 °C  
200 for 50-70 days before measurement. Each filter was immersed in 10 mL 100 % methanol for 18-20 h to extract chlorophyll  
201 from phytoplankton and these samples were analysed on a Turner fluorometer (Model 10-AU) following the method  
202 described by Evans et al. (1987).

203

204 Phytoplankton flow cytometry samples were fixed with 40  $\mu\text{L}$  of a mixture of formaldehyde-hexamine (18 %:10 % v/w)  
205 added to 1400  $\mu\text{L}$  of seawater sample. All bacteria samples (700  $\mu\text{L}$ ) were fixed with 14  $\mu\text{L}$  glutaraldehyde (Electron-  
206 microscope grade, 25 %). After mixing samples with fixatives, samples were stored for 25 minutes at 10 °C, then flash-  
207 frozen in liquid nitrogen, and stored at -80 °C until measurement 83-86 days later. Directly before the measurement,  
208 samples were thawed at 37 °C. Bacteria samples were stained with SYBR green I (diluted in dimethylsulfoxide) at a final

209 ratio of 1:10000 (SYBR Green I: sample).

210

211 A Cytex Aurora flow cytometer (Cytex Biosciences) was used to quantify the abundance of fluorescing particles such as  
212 phytoplankton or stained bacteria. Phytoplankton groups were distinguished based on their fluorescence signal intensity of  
213 different laser excitation/emission wavelength combinations and forward scatter (FSC). The yellow-green laser (centre  
214 wavelength: 577 nm), in combination with FSC signal strength, was used to separate cyanobacteria and cryptophytes from  
215 other phytoplankton. The violet laser (centre wavelength: 664 nm) in combination with FSC was used to distinguish  
216 picoeukaryotes, nanoeukaryotes, and microphytoplankton. The blue laser (centre wavelength: 508 nm) in combination with  
217 FSC was used to distinguish bacteria from other living (i.e., DNA-containing) particles (Fig. S. 1).

218

219 The biovolume of each classified flow cytometry phytoplankton type was calculated using the equation:

220

$$221 \text{ Biovolume} = \text{Cell number count} \times \left(\frac{\text{FSC}}{10248}\right)^{2.14} \quad (4)$$

222

223 where biovolume is the biovolume of the phytoplankton ( $\mu\text{m}^3$ ), cell number is the cell count per mL of sample, and the  
224 FSC is the forward scatter signal value from the flow cytometry. This equation is calculated based on the relationship  
225 between biovolume and FSC for different phytoplankton species (Selfe, 2022). The biovolume of each phytoplankton type  
226 was then divided by the total biovolume of all phytoplankton type to calculate the biovolume proportion of each  
227 phytoplankton type (Biovolume prop.). This derived value was used to estimate the phytoplankton composition in each  
228 microcosm.

229

230 Phytoplankton photosynthetic performance was estimated from the rapid light curves measured with an FRRf (FastOcean  
231 Sensor FRRf3, Chelsea Instruments Group) every second day following the protocol adapted from Schallenberg et al.  
232 (2020). Samples were kept in the dark for 20 minutes before the measurement and then added to the FRR fluorometry  
233 cuvette, which was temperature-controlled at 13.5 °C. Filtered natural seawater was used for blank correction. A channel  
234 with three light wavelengths (450, 530, and 624 nm) was used in each acquisition sequence. At least 10 acquisitions were  
235 measured for each sample. The maximum electron transport rate ( $\text{ETR}_{\text{max}}$ ), initial slope of the rapid light curve ( $\alpha$ ), and the  
236 light-saturation parameter ( $E_k$ ) were calculated using the equation described by Platt et al. (1980) without photoinhibition:

237

$$238 \text{ ETR} = \text{ETR}_{\text{max}} \left[1 - e^{-\frac{\alpha E}{\text{ETR}_{\text{max}}}}\right] \quad (5)$$

239

240 These parameters together with the maximum quantum yield of PSII ( $F_v/F_m$ ) were used to compare the photosynthetic  
241 performance of the phytoplankton communities in different microcosms.

242

243 Seawater was sampled before the treatment and at the end of the experiment for particulate trace metal concentrations.  
244 Samples of 100 mL were filtered through an acid-cleaned polycarbonate filter (25 mm diameter, 0.8  $\mu\text{m}$  pore size) and  
245 placed in an acid-cleaned polypropylene filter holder in a trace metal-clean laminar flow bench. The filters were washed  
246 with the EDTA-oxalate reagent (1.4 mL) twice (8 min total) and rinsed with chelexed NaCl solution (0.6 mol L<sup>-1</sup> with 2.38  
247 mmol L<sup>-1</sup> of HCO<sub>3</sub><sup>-</sup>, pH=8.2) 10 times (1.5 mL aliquots) (Tovar-Sanchez et al., 2003; Tang and Morel, 2006). Filters were  
248 stored in acid-washed well plates at -20 °C before analysis. The digestion process followed the method reported by Bowie

249 et al. (2010). Briefly, all samples and triplicate certified reference materials plankton standards (50 mg/vial) were digested  
250 in a mixture of strong ultrapure acids (750  $\mu\text{L}$  12 mol  $\text{L}^{-1}$  HCl, 250  $\mu\text{L}$  40 % HF, 250  $\mu\text{L}$  14 mol  $\text{L}^{-1}$   $\text{HNO}_3$ ) in 15 mL Teflon  
251 perfluoroalkoxy (PFA) vials on a 95 °C hot plate for 12 h in a fume hood. They were then dry evaporated for 4 h and re-  
252 suspended in 10 % v-v ultrapure  $\text{HNO}_3$ . All prepared solutions had indium as internal standard added to a final  
253 concentration of 10  $\mu\text{g L}^{-1}$ . Three pre-mixed multi-element standard solutions (MISA) were prepared as external calibration  
254 standards.

255

256 Particulate organic carbon (POC) was sampled by filtering 100 mL of seawater from each microcosm. Glass fibre filters  
257 (Whatman GF/F, pore size = 0.7  $\mu\text{m}$ , diameter = 13 mm) were pre-combusted at 400 °C for 6 h. Filters were stored at -20 °C  
258 before measurement. Samples were treated via fuming with 2N HCl to remove carbonates overnight and dried in the oven  
259 for 4h. Finally, filters were folded into silver cups and stored in a desiccator until analysis. Samples were analysed for  
260 carbon with a Thermo Finnigan EA 1112 Series Flash Elemental Analyser (CSL, University of Tasmania).

261

262 Biogenic silica (BSi) concentrations were analysed every 4 days by filtering 100 mL of seawater from each microcosm.  
263 Mixed Cellulose Ester (MCE) membrane filters (diameter = 25 mm, pore size = 0.8  $\mu\text{m}$ ) were used for BSi samples. BSi  
264 filters were placed in a plastic petri dish and stored at -20 °C before measurement. Filters were processed using the hot  
265 NaOH digestion method of Nelson et al. (1989). The final solution was measured using the same process as the dissolved  
266 silicate (see section 2.4).

267

268 A self-made plastic zooplankton net (20 mm height and 15 mm width) with a 210  $\mu\text{m}$  mesh size was acid-washed first and  
269 then used to collect zooplankton from microcosms before mineral addition on day 2, near the middle (day 13), and at the  
270 end of the experiment (day 23). Samples were stored in 10 % formalin seawater solutions and kept at room temperature  
271 until measurements. Zooplankton were quantified and identified under a Leica M165C microscope fitted with a Canon 5D  
272 camera. The number of zooplankton from one mini-trawl in each collection was converted to the unit of individual  $\text{L}^{-1}$  and  
273 used for data analysis. The diversity of zooplankton communities was estimated with the Shannon Diversity Index (H)  
274 calculated as:

275

$$276 \quad H = -\sum(pi \times \ln(pi)) \quad (6)$$

277

278 where pi is the proportion of the entire zooplankton community made up of individual species abundance, and ln is the  
279 natural logarithm.

280

281

## 282 **2.6 Statistic analysis**

283 R studio was used for data analyses. Generalized additive models (GAMs) from the package “mgcv” were fitted to the data  
284 to predict the changes over time. The GAMs all shared the same equations:

285

$$286 \quad Y = s(\text{Day}), \quad (7)$$

287



288 in which Y presents the dependent variable and s(Day) is the smooth term of the day of the experiment. Another GAM was  
289 used to detect significant differences between treatments and the control:

290

$$291 \quad Y = Treatment + s(Day) + s(Day, by = oTreatment) \quad (8)$$

292

293 In this equation, the variable “Treatment” includes three conditions: “Control”, “Slag” and “Olivine”; while “oTreatment”  
294 is the ordered factor of the variable “Treatment” which allowed us to compare the GAMs smooth terms from different  
295 treatments and the control (Simpson, 2017).

296

297 When comparing GAMs, P-means represent the p-value obtained from comparing two GAMs, such as the control and the  
298 olivine treatment. If P-means is below 0.05, it indicates that the mean values of the two GAMs exhibit significant  
299 differences over the course of the experiment. Conversely, if P-means is equal to or greater than 0.05, it suggests that the  
300 two GAMs have similar mean values. In contrast, P-smooths represents the p-value derived from comparing the smooth  
301 terms of two GAMs. If P-smooths is below 0.05, it indicates that the two GAMs demonstrate significantly different trends  
302 in their change over time.

303

304 For the analysis of trace metal concentrations and zooplankton abundance, Generalized Linear Models (GLMs) from the  
305 'stats' package were fitted to the data to determine significant differences between treatments and the control. The selection  
306 of specific GLMs was based on the distribution of the raw data. One GLM equation is

307

$$308 \quad Y = Treatment + \frac{Day}{22} + \left(\frac{Day}{22}\right)^2 \quad (9)$$

309

310 with family = Gamma, where Y represents the measured parameter (abundance of a zooplankton species and dissolved  
311 trace metal concentrations); treatment is the conditions (“Control”, “Slag” and “Olivine”); and Day represents the day of  
312 the experiment. The other GLM equation,

313

$$314 \quad Y = Treatment + Day \quad (10)$$

315

316 with family = Gaussian, was employed for particulate trace metal data and the Shannon Diversity Index. To compare the  
317 contribution of the three treatments on the measured parameters, Tukey's significant difference test was conducted on the  
318 GLMs using the 'glht' function.

319

### 320 **3. Results**

#### 321 **3.1 Elemental composition and grain size of the finely-ground minerals**

322 SEM analysis revealed the approximate elemental composition of olivine and slag powder (Table 1). Based on this analysis  
323 the olivine composition resembles the Mg-rich olivine mineral “forsterite” (Mg<sub>2</sub>SiO<sub>4</sub>). The particle size spectrum of olivine  
324 powder is shown in detail in Fig. S2. Roughly 69 % of the olivine particles, when measured by volume, fell within the

325 diameter range of 35 - 300  $\mu\text{m}$ . Additionally, SEM analysis revealed high levels of Ca and O in the slag, indicative of the  
 326 considerable  $\text{Ca}(\text{OH})_2$  and  $\text{CaO}$  content of the powder (Table 1; please note that H cannot be measured with the applied  
 327 method). The particle size measurement (Fig. S2) showed that 78 % of the ground slag particles were between 35 - 300  
 328  $\mu\text{m}$ .

329

330 **Table 1.** The weight percentage of elements from two minerals. Unit: wt %.

Element	O	Ca	Mn	Si	Mg	Fe	Al	Ti	Cr	Ni
Olivine	39.9	0.4		19.9	26.4	13.0	1.0			0.8
Steel slag	41.9	36.0	7.0	6.5	4.3	3.7	3.4	1.7	1.6	

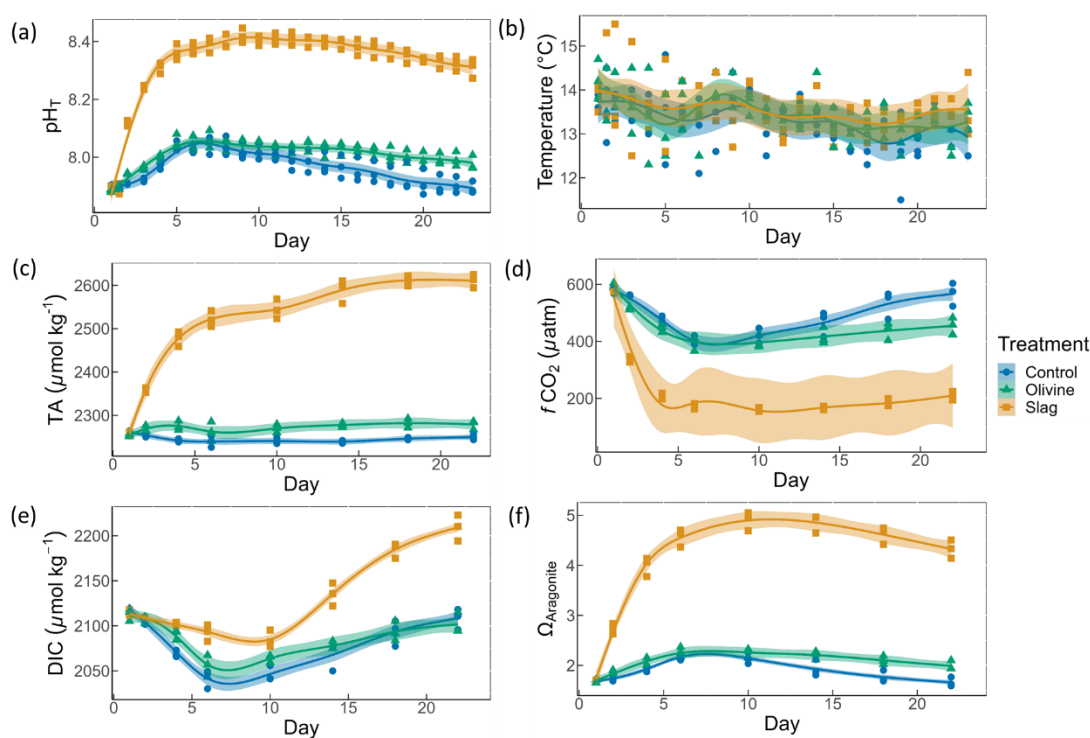
331

332

### 333 3.2 Physical and chemical conditions over the course of the experiment.

334 On day 2 of the experiment, when olivine particles were introduced into the microcosms, the smallest fraction of the powder  
 335 remained suspended, causing the seawater to become highly turbid for several days. The resulting milky appearance of the  
 336 seawater eventually faded over a period of approximately five days, and by day 5, the turbidity had visually become like  
 337 the slag treatment and the control. This effect was not anticipated, and as a result, we decided to investigate its impact on  
 338 light intensity. To do so, a test was conducted after the main experiment in which olivine powder was added to a microcosm  
 339 identical to those used in the experiment, and light intensity was measured daily at a depth of 0.15 m. The results showed  
 340 that the addition of olivine caused an initial reduction in light intensity of 18.5 % at 15 mins after addition, which declined  
 341 to 7.4 %, 3.7 %, 3.7 % and 0 % after 1, 2, 3, and 4 days, respectively. These findings indicate that olivine additions can  
 342 significantly affect the light environment in the microcosms, whereas no such effect was observed in the slag treatment.

343



344

345 **Fig. 2.** Carbonate chemistry conditions. The temporal development of (a)  $\text{pH}_T$ , (b) temperature, (c) total alkalinity (TA), (d)  $\text{CO}_2$  fugacity

346 ( $f\text{CO}_2$ ) computed at *in situ* temperature and atmospheric pressure, (e) dissolved inorganic carbon (DIC), and (f) aragonite saturation state  
347 ( $\Omega_{\text{aragonite}}$ ). The dots represent the raw data ( $n=3$  for each treatment per sampling time), and the fitted curve is the generalized additive  
348 model (GAM). The shading represents the 95 % confidence interval of the fitted GAM.

349

350 The  $\text{pH}_T$  of all microcosms increased from day 1 to day 5 (Fig. 2a). This was due to photosynthetic  $\text{CO}_2$  drawdown in the  
351 control or photosynthetic  $\text{CO}_2$  drawdown in combination with alkalinity release from minerals in the treatments. During  
352 the peak of the bloom,  $\text{pH}_T$  was  $8.037 \pm 0.010$  in the control (average values  $\pm$  standard error),  $8.054 \pm 0.014$  in the olivine  
353 treatment and  $8.411 \pm 0.015$  in the slag treatment. The  $\text{pH}_T$  was significantly higher in the slag than the olivine treatment  
354 and the control throughout the experiment (control and olivine  $\text{pH}_T$  were not significantly different). The final  $\text{pH}_T$  of the  
355 control, olivine, and slag treatments were  $7.893 \pm 0.012$ ,  $7.978 \pm 0.015$ , and  $8.309 \pm 0.019$ , respectively. The temperature  
356 inside of the microcosms varied between replicates, which may have added noise in the biological response data. However,  
357 on average there was no statistically significant difference between control/treatments during the experiment.

358

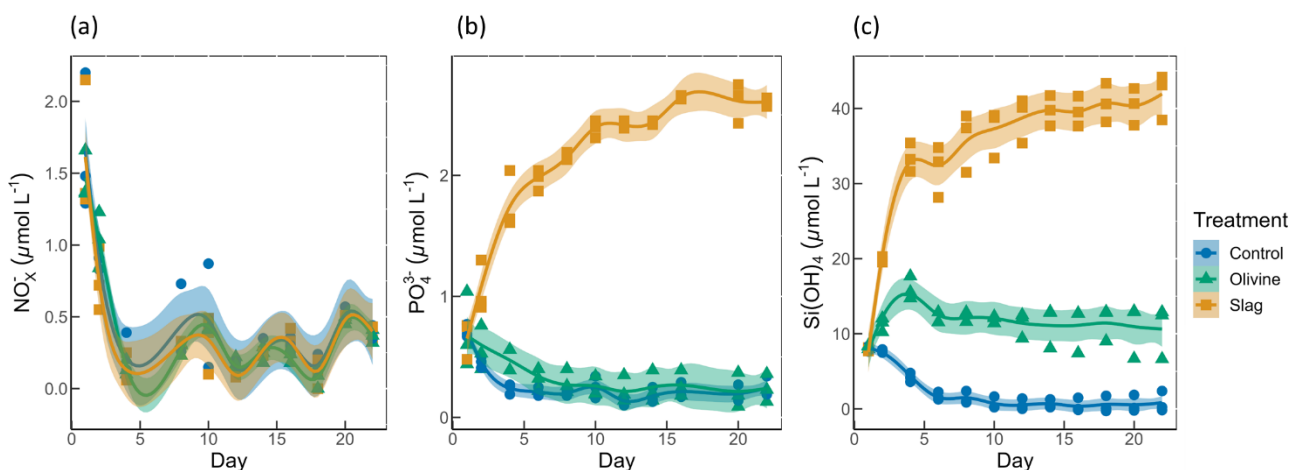
359 In our data analysis, all the fitted GAMs from the treatments and the control exhibited significant differences in  $\text{pH}_T$  from  
360 each other, as evidenced by the p-values of both P-means and P-smooths being smaller than 0.001. For detailed results of  
361 the GAM p-values, please refer to Table S2.

362

363 Total alkalinity increased marginally from  $2255 \pm 2$  to  $2262 \pm 13 \mu\text{mol kg}^{-1}$  within the first 6 days after olivine addition  
364 while it increased more substantially from  $2259 \pm 1$  to  $2522 \pm 11 \mu\text{mol kg}^{-1}$  in the same time span in the slag treatment (Fig.  
365 2c). The TA in the control decreased from  $2261 \pm 2 \mu\text{mol kg}^{-1}$  to  $2240 \pm 7 \mu\text{mol kg}^{-1}$  from day 1 to day 6 but remained  
366 stable thereafter. The TA reached  $2279 \pm 6 \mu\text{mol kg}^{-1}$  in the olivine treatment and  $2611 \pm 9 \mu\text{mol kg}^{-1}$  in the slag treatment  
367 on day 22. The slag treatment reached a significantly higher TA than the olivine treatment and the control (P-smooths <  
368 0.001). The mean TA from GAM in olivine treatment was higher than the control (P-means < 0.001).

369

370 The  $\text{CO}_2$  fugacity ( $f\text{CO}_2$ ) computed at *in situ* temperature and atmospheric pressure decreased continuously in the first 6  
371 days in all microcosms (Fig. 2d). Then it increased again in the control and olivine treatments while staying lower in the  
372 slag treatment (P-means and P-smooths  $\leq 0.001$  between either treatment or the control). Dissolved inorganic carbon (Fig.  
373 2e) and the aragonite saturation state ( $\Omega_{\text{aragonite}}$ ; Fig. 2f) revealed a similar trend over the course of the experiment in the  
374 control and the olivine treatment. In contrast, the slag treatment had higher DIC and  $\Omega_{\text{aragonite}}$  values throughout the  
375 experiment (P-means < 0.001).



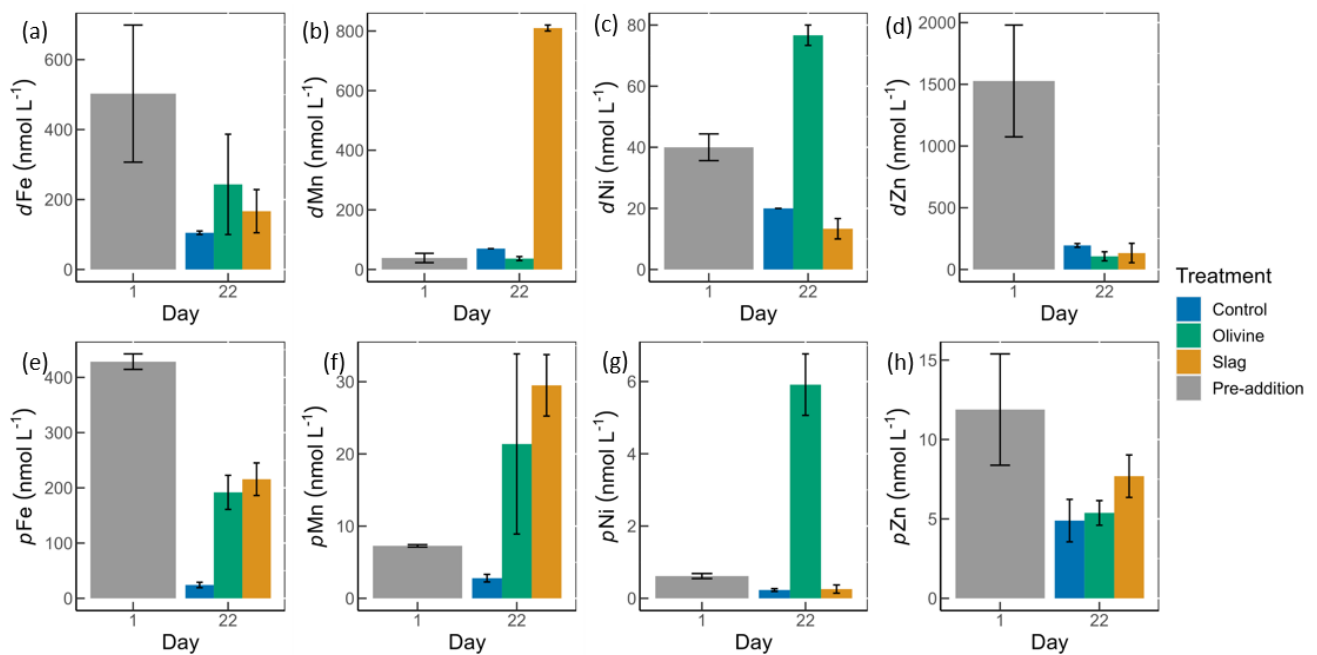
376

377 **Fig. 3.** Macronutrients concentrations over the course of the study. (a) Nitrate and nitrite concentrations. (b) Phosphate concentrations.  
 378 (c) Silicic acid concentrations. The dots represent the raw data ( $n=3$  for each treatment per collection), and the fitted curve is the  
 379 generalized additive model.

380

381 Initial nitrate and nitrite ( $\text{NO}_x^-$ ), phosphate ( $\text{PO}_4^{3-}$ ), and silicic acid ( $\text{Si}(\text{OH})_4$ ) concentrations were  $1.58 \pm 0.12$ ,  $0.69 \pm 0.59$ ,  
 382 and  $8.04 \pm 0.10 \mu\text{mol L}^{-1}$ , respectively (Fig. 3).  $\text{NO}_x^-$  declined rapidly in all microcosms once the experiment had  
 383 commenced to values below  $0.5 \mu\text{mol L}^{-1}$  and no significant difference was detected between treatments and control ( $P$ -  
 384 smooths  $>0.05$ ; Fig. 3a). In both the olivine treatment and the control, the  $\text{PO}_4^{3-}$  concentration decreased in the first six  
 385 days (Fig. 3b). In the slag treatment,  $\text{PO}_4^{3-}$  increased to a maximum of  $2.65 \pm 0.01 \mu\text{mol L}^{-1}$ , which was significantly higher  
 386 than in the olivine treatment and the control ( $P$ -means  $<0.001$ ). The  $\text{Si}(\text{OH})_4$  concentration increased to a maximum of  
 387  $15.99 \pm 0.87 \mu\text{mol L}^{-1}$  in the olivine treatment, increased to a maximum of  $41.92 \pm 1.75 \mu\text{mol L}^{-1}$  in the slag treatment, but  
 388 decreased below the detection limit in the control (Fig. 3c). Significant differences were observed in the development of  
 389  $\text{Si}(\text{OH})_4$  between all treatments and the control (Table S2).

390



391

392

393 **Fig. 4.** Dissolved and particulate trace metal concentrations in microcosm seawater. (a)-(d) are dissolved trace metal concentrations, and  
 394 (e)-(h) are total particulate trace metal concentrations. The error bars represent the standard error from measured samples. The pre-  
 395 addition data shown in (a)-(d) represent the average of 7 microcosms before addition of slag or olivine. The data for the control on day  
 396 22 in (a)-(d) and for the pre-addition on day 1 in (e)-(h) were based on two of three microcosm replicates. The remaining data were based  
 397 on all three microcosm replicates.

398

399 The dissolved trace metal concentrations measured from microcosms are presented in Fig. S3. While the mass of olivine  
 400 added to the microcosms was 50-fold greater (100 g vs 2 g), it's noteworthy that the variation in dissolved trace metal  
 401 concentrations between the two treatments were much smaller than 50 folds. After 21 days of experiment, the treatments  
 402 showed an increase in dissolved Al concentrations from  $920 \pm 286$  to  $970 \pm 228 \text{ nmol L}^{-1}$  in olivine treatment, and from  
 403  $920 \pm 286$  to  $1093 \pm 77 \text{ nmol L}^{-1}$  in slag treatment, while in the control dissolved Al decreased to  $230 \pm 10 \text{ nmol L}^{-1}$  (Fig.

404 S3). The fitted GLMs were compared, and the p-value revealed how much influence a treatment had on the dissolved metal  
405 concentrations (Table S3). The results indicate that the slag and olivine additions led to significantly higher Al  
406 concentrations than in the control (p-values < 0.05), but no significant difference was found between the two treatments  
407 (p-value = 0.189). The Cu concentration in the olivine on day 22 was significantly higher than the slag treatment and the  
408 control (p-value < 0.05) (Fig. S3). The addition of olivine and slag released some dissolved Fe, but overall, the concentration  
409 of Fe did not differ significantly between treatments (Fig. 4a, Table S3). The slag released a substantial amount of dissolved  
410 Mn (maximum  $810 \pm 10 \text{ nmol L}^{-1}$  on day 22) (Fig. 4b), leading to significantly higher concentrations than in the olivine  
411 treatment and the control (p-values < 0.001). A significant amount of dissolved Ni (maximum  $77 \pm 3 \text{ nmol L}^{-1}$  on day 22)  
412 was released from the olivine powder (p-values < 0.001) (Fig. 4c). The initial concentration of dissolved Zn in seawater  
413 was much higher than on day 22 in all microcosms, and no significant difference in Zn concentrations was found between  
414 the treatments and the control.

415

416 Particulate concentrations of some trace metals also differed between treatments. The total particulate Fe decreased in all  
417 microcosms on day 22 comparing with the pre-addition level, but both mineral addition treatments had higher particulate  
418 Fe concentrations than the control (Fig. 4e). The addition of slag elevated particulate Mn concentrations to a level higher  
419 than the pre-addition and the control on day 22 (Fig. 4f), while the addition of olivine increased the particulate Ni  
420 concentrations to a level higher than the slag, the control, and the pre-addition (Fig. 4g). The particulate Zn concentrations  
421 in general decreased by the end of the experiment (Fig. 4h), and no significant differences were found between the  
422 treatments and the control.

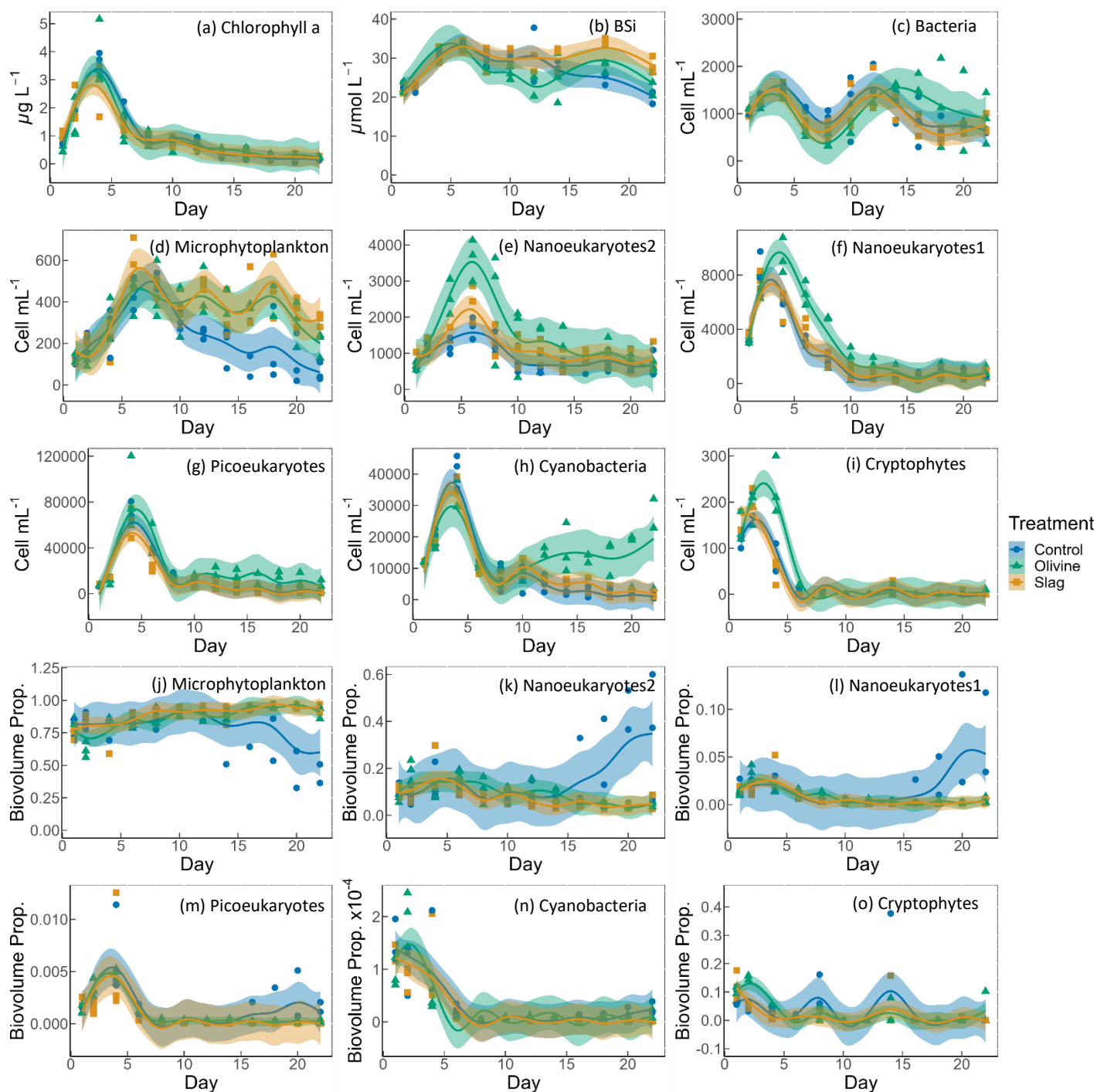
423

424 The POC on day 1 and day 22 from all microcosms were very similar,  $10.99 \pm 0.58$  and  $11.03 \pm 0.41 \text{ } \mu\text{mol L}^{-1}$  respectively  
425 (Fig. S4) so the metal:POC results were consistent with the particulate trace metal results (Fig. 4 e-h). In general, the non-  
426 surface metal:POC are positively correlated with the total metal:POC ratios (Fig. S5). The ratio of non-surface to total  
427 particulate trace metal concentrations is summarized in Table S5. Both non-surface and total Fe concentrations decreased  
428 in microcosms on day 22 compared with the pre-addition level. Iron:POC ratios were significantly higher in the treatments  
429 than in the control on day 22 (p-values < 0.05. Table S3), and there was no significant difference between mineral addition  
430 treatments. The non-surface to total Fe:POC ratios were > 0.94 in all microcosms on both day 1 and day 22. The total and  
431 non-surface Mn:POC ratio was the highest in the slag treatment. These ratios were higher than the pre-addition level and  
432 the control at the end of the experiment. The total particulate Ni concentrations in the olivine treatment were significantly  
433 higher than before olivine addition. The olivine treatment led to a >22-fold higher Ni:POC ratio compared to the other two  
434 treatments (p-value < 0.001).

435

436

437



439  
 440 **Fig. 5.** Temporal development of chlorophyll a concentration (chl-a), BSi, and different eukaryotic and bacterial plankton groups as  
 441 determined with flow cytometry. (a) chlorophyll a; (b) BSi; cell concentrations of (c) heterotrophic bacteria, (d) microphytoplankton, (e)  
 442 nanoeukaryotes2, (f) nanoeukaryotes1 (g) picoeukaryotes, (h) cyanobacteria, and (i) cryptophytes; biovolume proportion of (j)  
 443 microphytoplankton, (k) nanoeukaryotes2, (l) nanoeukaryotes1 (m) picoeukaryotes, (n) cyanobacteria, and (o) cryptophytes. The figure  
 444 data points represent the raw data, and the fitted curve is the generalized additive model. The shaded area represents the 95 % confidence  
 445 interval.

447 The chl-a concentration in all microcosms increased from day 1 to day 4 from 1  $\mu\text{g L}^{-1}$  to 3-4  $\mu\text{g L}^{-1}$  (Fig. 5a). The chl-a  
448 concentration then decreased rapidly from day 4 to day 8, then continued to decrease, though more slowly, to  $<0.3 \mu\text{g L}^{-1}$   
449 until the end of the experiment. The GAMs of chl-a did not show any difference between treatments and the control (both  
450 P-means and P-smooths  $>0.05$ , see Table S2).

451

452 The BSi concentration increased from day 1 to day 6 in all microcosms (Fig. 5b). In the olivine treatments, BSi  
453 concentrations decreased slightly after the peak until day 12 but then increased again. In the slag treatment, BSi  
454 concentrations remained relatively stable after the initial phytoplankton bloom. In contrast, BSi concentration decreased  
455 continuously in the control after the initial peak. Olivine particles suspended in seawater after the mineral addition (see  
456 section 3.2) partially ended up on BSi filters during filtration. This led to extremely high BSi measurements on days 2 and  
457 4 that were removed from Fig. 5b. Without these outliers, the mean of fitted BSi GAM in the olivine treatment was lower  
458 than the control and the slag treatment (Table S2), and the slag had the highest average BSi over the course of the  
459 experiment. Overall, the BSi trends in the two treatments were similar (P-smooths = 0.269), and both were significantly  
460 different from the control (P-smooths  $<0.05$ ).

461

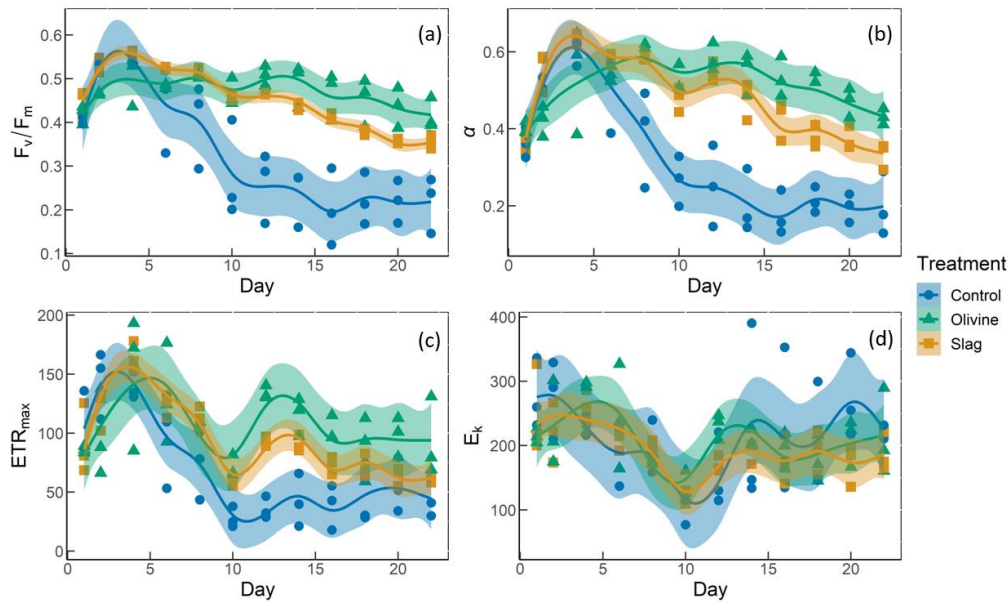
462 The development of the phytoplankton community composition showed significant differences between the treatments and  
463 the control. In general, most phytoplankton groups exhibited similar patterns to chl-a, with peak cell numbers occurring on  
464 day 4 (Fig. 5f-i) apart from microphytoplankton and nanoeukaryotes2 which had the peak delayed for 1-2 days (Fig. 5d-  
465 e). Please be aware that flow cytometers may not capture some large and chain-forming phytoplankton. After reaching  
466 peak values during the bloom, phytoplankton abundance generally decreased steadily. Microphytoplankton displayed  
467 similar trends to the results for BSi. Before day 10, all microcosms had similar microphytoplankton abundances (Fig. 5d).  
468 However, in the control, microphytoplankton abundance declined continuously and at a faster rate compared to the two  
469 treatments (P-smooths values  $<0.03$ ). From day 2 to day 6, the abundance of nanoeukaryotes1, nanoeukaryotes2,  
470 picoeukaryotes, and cryophytes was higher in the olivine treatment compared to the slag treatment and the control. After  
471 day 8, their abundance in the olivine treatment decreased to a similar level as the slag treatment and the control. Notably,  
472 there were few significant differences observed between the slag treatment and the control in terms of the abundances of  
473 nanoeukaryotes1, nanoeukaryotes2, picoeukaryotes, cyanobacteria, and cryptophytes throughout the experiment. In the  
474 olivine treatment, cyanobacteria experienced a second bloom after day 10, which was significantly different from the other  
475 two groups (P-smooths  $<0.01$ ). Heterotrophic bacteria exhibited an increase and decline pattern following the  
476 phytoplankton bloom until day 8 (Fig. 5c). Subsequently, bacteria abundance increased again, reaching a second peak  
477 during days 12-14, followed by a decline until the end of the experiment. The decline in bacteria abundance was slower in  
478 the olivine treatment, although no significant differences were detected between treatments (Table S2).

479

480 Among all the microcosms, microphytoplankton consistently accounted for the largest proportion of biovolume. From the  
481 perspective of biovolume proportion, the mineral addition mainly influenced the microphytoplankton and nanoeukaryotes.  
482 The control had similar phytoplankton biovolume distribution as the treatments from day 1 to day 15, but after that the  
483 proportion of microphytoplankton biovolume decreased to a level significantly lower than the treatments. In the control  
484 treatment, the proportion of nanoeukaryotes' biovolume increased as the proportion of microphytoplankton decreased. The  
485 biovolume of picoeukaryotes, cyanobacteria and cryptophytes increased during the phytoplankton bloom and then  
486 decreased drastically after the bloom. There were no significant differences in biovolume proportion observed for

487 picoeukaryotes, cyanobacteria and cryptophytes between the treatments and the control.

488



489

490 **Fig. 6.** The photosynthetic performance of the phytoplankton community. (a)  $F_v/F_m$ , the maximum quantum yield of photosynthesis II.  
491 (b)  $\alpha$ , the initial slope of the rapid light curves. (c)  $ETR_{max}$  is the maximum electron transport rate, the maximum potential photosynthetic  
492 rate. (d)  $E_k$  is light-saturation parameter, Unit:  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ .

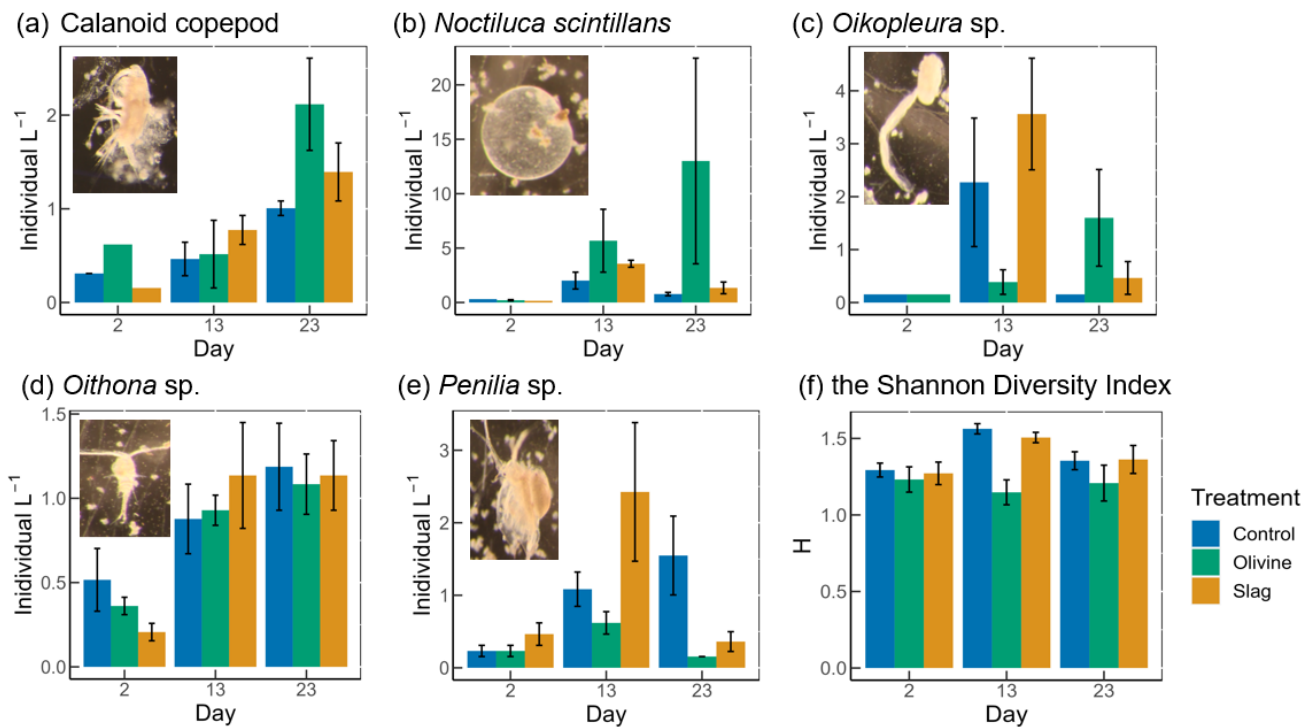
493

494 The temporal development of  $F_v/F_m$ ,  $\alpha$ ,  $ETR_{max}$ , and  $E_k$  is illustrated in Fig. 6. The  $F_v/F_m$  values of the phytoplankton  
495 community were approximately  $0.42 \pm 0.01$  and increased to levels  $> 0.5$  during the peak of the phytoplankton bloom on  
496 day 4 (Fig. 6a). Following the bloom,  $F_v/F_m$  values dropped below 0.3 in the control. However, the decline in  $F_v/F_m$  after  
497 the bloom was less pronounced in the two mineral addition treatments with the olivine treatment maintaining higher  $F_v/F_m$   
498 values than the slag treatment (P-smooths  $< 0.05$ ). At the end of the experiment,  $F_v/F_m$  was  $0.22 \pm 0.04$  in the control,  $0.35$   
499  $\pm 0.01$  in the slag treatment, and  $0.42 \pm 0.02$  in the olivine treatment. The temporal development of  $\alpha$  aligned with the  
500 patterns observed for  $F_v/F_m$  (compare Fig. 6a and 6b). The maximum values of  $ETR_{max}$  were observed on day 4 in the  
501 control and the slag treatment, while in the olivine treatment, it occurred on day 5 (Fig. 6c). Subsequently,  $ETR_{max}$   
502 continuously decreased until day 10 and then stabilized until the end of the experiment. However,  $ETR_{max}$  exhibited a  
503 subsequent increase in the mineral treatments around day 12. The  $ETR_{max}$  values were higher in the mineral treatments  
504 compared to the control group (P-means  $< 0.001$ , Table S2). The parameter  $E_k$  decreased from  $246 \pm 17 \mu\text{mol photons m}^{-2}$   
505  $\text{s}^{-1}$  on day 1 to  $121 \pm 7 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  on day 10, and then it increased again to approximately  $200 \mu\text{mol photons m}^{-2}$   
506  $\text{s}^{-1}$  by the end of the experiment (Fig. 6d). The change in  $E_k$  did not exhibit significant differences between the treatments  
507 and the control (both P-means and P-smooths  $> 0.05$ ).

508

509





510

511 **Fig. 7.** The dominant zooplankton abundance and community diversity from different treatments. Abundance of dominant zooplankton  
 512 in microcosms: (a) calanoid copepod; (b) *Noctiluca scintillans*; (c) *Oikopleura* sp.; (d) *Oithona* sp.; (e) *Penilia* sp.; and (f) the Shannon  
 513 diversity index (H) of different treatments and the control. Error bars represent the standard error calculated from three microcosm  
 514 replicates. Photographs of each zooplankton group are shown on the corresponding graphs.

515

516 Thirteen zooplankton taxonomic groups were identified in the microcosms. The dominant taxa were the appendicularian  
 517 *Oikopleura* sp., the cyclopoid copepod *Oithona* sp., the cladoceran *Penilia* sp., the heterotrophic dinoflagellate *Noctiluca*  
 518 *scintillans* and several calanoid copepods including *Acartia* sp., *Paracalanus* sp. and *Gladioferens* sp. The larvae and eggs  
 519 of *Oikopleura*, *Penilia* and copepod were also observed under the microscope. In general, higher zooplankton numbers  
 520 were observed after the bloom on day 13 (Fig. 7). The abundance of calanoid copepods and *Oithona* sp. increased after  
 521 day 2 (Fig. 7a, d), and there was no significant difference between treatments and the control (p-values >0.05, Table S4).  
 522 The abundance of *N. scintillans* increased significantly more in the olivine treatment than in the control and the slag  
 523 treatment, with highest abundance of  $13 \pm 9$  individual  $L^{-1}$  observed in the olivine treatment on the last day (Fig. 7b). The  
 524 abundance of *Oikopleura* in the control and the slag treatment was higher than the olivine treatment on day 13 but was  
 525 higher in the olivine treatment on day 22 (Fig. 7c). A higher abundance of *Penilia* sp. was found in the slag treatment on  
 526 day 13 and in the control on day 23 (Fig. 7e). Due to the patchy distribution of zooplankton, these data have large standard  
 527 errors and only the differences in the numbers of *N. scintillans* in the olivine treatment were statistically significantly  
 528 different from the slag treatment and the control (p-value <0.05, Table S4).

529

530 Considering the control and slag treatment, the Shannon Diversity Index (H) increased from day 2 to day 13 and declined  
 531 on day 23, while in the olivine treatment, H was lower on day 13 than on day 2 and day 23 (Fig. 7f). The GLMs revealed  
 532 that the olivine treatment had significantly lower H on day 13 than the control and the slag treatment (p-values <0.001).  
 533 There were no significant differences in H between the control and the slag treatment (Table S4). The addition of olivine  
 534 decreased the zooplankton community's diversity. This is mainly driven by distinct trends observed in the abundance of  
 535 *Oikopleura* sp., *Penilia* sp., and *N. scintillans* (Fig. 7).

536

## 537 **4. Discussion**

### 538 **4.1 CO<sub>2</sub> removal potential of slag and olivine**

539 The slag powder created significantly higher CO<sub>2</sub> removal potential than the olivine powder over the course of the study.  
540 Ca(OH)<sub>2</sub> and CaO in slag and Mg<sub>2</sub>SiO<sub>4</sub> in olivine are likely to be the main functional minerals driving the measured  
541 alkalinity enhancement. Total alkalinity increased by 361 μmol kg<sup>-1</sup> in the slag treatment while it increased by only 29  
542 μmol kg<sup>-1</sup> in the olivine treatment, equivalent to a potential increase in marine inorganic carbon by 14.7 and 0.9% within  
543 3 weeks of their application. When normalizing these alkalinity increases to the same material weight, 1 g of slag would  
544 release 9626 μmol TA while 1 g of olivine would release 16 μmol TA. Thus, over 3 weeks of experimental incubation, slag  
545 is ~600-fold more efficient in releasing alkalinity for particles of this size class (please note that particle size spectra of  
546 olivine and slag were similar but not identical; Fig. S1). We can also use these values to make a rough estimate of how  
547 much CO<sub>2</sub> these two minerals could potentially sequester. One mole of alkalinity from olivine and slag can sequester  
548 approximately 0.85 mole of CO<sub>2</sub>. Thus, one tonne of slag and olivine powder as used here could sequester 360 and 0.6 kg,  
549 respectively, within 3 weeks. It is likely that optimization of particle size and application method may lead to higher  
550 efficiencies. Nevertheless, the slag showed potential as an OAE source mineral, even when applied as relatively coarse  
551 powder in this experiment.

552

### 553 **4.2 Environmental implications of slag and olivine additions**

554 The amount of olivine and slag powder added to the treatments differed significantly (100 g of olivine powder were added  
555 while only 2 g of slag powder were added to the 53 L microcosms). Our rationale for these different mass additions was to  
556 yield somewhat similar amounts of detectable alkalinity enhancement in the dissolved phase, since we already knew from  
557 tests before the experiment that slag elevates alkalinity faster than olivine. However, olivine was less efficient in releasing  
558 alkalinity than we had anticipated so that even a 50-fold higher addition of olivine (in mass) did not compensate for this  
559 difference. As such, our experiments are associated with an “apples and oranges issue” in that our perturbation with  
560 minerals and associated OAE differs. We argue that an adjusted addition of minerals depending on the alkalinity  
561 enhancement rate would be consistent with what OAE practitioners may do under real-world conditions. Presumably, OAE  
562 deployments may have to adjust the amounts of minerals to detect alkalinity enhancement in the dissolved phase for  
563 verification purposes. Nevertheless, to account for the “apples and oranges issue”, the following discussion mainly relates  
564 the observed environmental effects with the alkalinity enhancement achieved over the course of the study.

#### 565 **4.2.1. OAE effects on phytoplankton physiology and community**

566 Previous research has hypothesised that OAE-induced changes in seawater carbonate chemistry could delay phytoplankton  
567 bloom formation due to reductions in seawater *p*CO<sub>2</sub> in the aftermath of an OAE deployment (Bach et al., 2019). The build-  
568 up of chlorophyll *a* concentration as observed here was indistinguishable between treatments and the control, suggesting  
569 no effect of slag- or olivine-based OAE on phytoplankton bloom dynamics under these experimental settings. A lack of  
570 bloom delay due to carbonate chemistry is unsurprising for the olivine treatment where the release of alkalinity was small

571 (29  $\mu\text{mol kg}^{-1}$  alkalinity release), but somewhat more surprising in the slag treatment where alkalinity was quite rapidly  
572 increased by 361  $\mu\text{mol kg}^{-1}$ . However, the release was still lower than in a very similar study by Ferderer et al., (2022)  
573 where alkalinity was increased by 500  $\mu\text{mol kg}^{-1}$  using sodium hydroxide and even there they did not observe a bloom  
574 delay. Based on this very limited evidence, it seems that bloom delays do not occur consistently under OAE within this  
575 alkalinity range.

576

577 The nutrient data show that the phytoplankton community was most likely N-limited after day 4 so that the release of  
578  $\text{Si(OH)}_4$  from olivine and  $\text{Si(OH)}_4$  and  $\text{PO}_4^{3-}$  from slag did not stimulate a further increase in chlorophyll-*a* concentration  
579 in the treatments. The development of BSi concentrations is indicative of the prevalence of diatoms in the microcosms but  
580 differences between treatments and the control were small. The release of  $\text{Si(OH)}_4$  through olivine and slag will most likely  
581 benefit diatoms but this fertilization effect did not manifest in this specific experiment because N was limiting diatom  
582 growth. However, when new N is supplied then diatoms will likely take a bigger share of the limiting N pool when olivine  
583 or slag are used for OAE, as has been shown in  $\text{Si(OH)}_4$  manipulation experiments in and outside the context of OAE  
584 research (Egge and Jacobsen, 1997; Ferderer et al., 2023). As such, diatoms are likely to benefit from olivine and slag  
585 applications. In the case of slag, the release of  $\text{PO}_4^{3-}$  will likely be another driver that affects plankton productivity and  
586 community composition. As for  $\text{Si(OH)}_4$ , however, the effect of additional  $\text{PO}_4^{3-}$  did likely not materialise in this  
587 experiment because  $\text{PO}_4^{3-}$  was not limiting over the course of the study. However, in ecosystems where  $\text{PO}_4^{3-}$  is a limiting  
588 resource, the application of slag could enhance productivity with associated benefits for higher trophic levels. In contrast,  
589 excessive applications of slag and concomitant  $\text{PO}_4^{3-}$  release could also pose a risk of eutrophication. Future studies may  
590 need to investigate what the most sustainable dose of OAE via olivine and/or slag applications could be and the suitable  
591 regions for application.

592

593 The flow cytometry results further revealed the change in phytoplankton community composition. Both the olivine and  
594 slag treatments sustained higher microphytoplankton abundances after the peak of the phytoplankton bloom. This trend is  
595 consistent with higher  $F_v/F_m$  values in the treatments than in the control so that it is tempting to assume that  
596 photophysiological fitness gain measured with the FRRf led to higher competitiveness of microphytoplankton in the  
597 community. Indeed, calculations of the contribution of different phytoplankton groups to total biovolume based on flow  
598 cytometry indicate that microphytoplankton were predominantly contributing to the phytoplankton community biovolume  
599 so that the responses measured by the FRRf were probably to a large extent driven by this group.

600

601 Apart from the increased microphytoplankton abundance, for the slag treatment, other phytoplankton groups distinguished  
602 with flow cytometry did not deviate considerably from the control. The olivine addition, however, triggered more  
603 pronounced shifts in the phytoplankton community. In particular, the nanoeukaryotes (roughly between 2-20  $\mu\text{m}$ ),  
604 picoeukaryotes and the cryptophytes showed relatively higher abundance during the peak of the phytoplankton bloom, and  
605 the abundance of cyanobacteria was higher after the bloom. We speculate that this shift following olivine treatment may  
606 be attributable to a top-down effect from the decrease in zooplankton grazing effects in microcosms, which will be  
607 discussed in section 4.2.2.

608

609 The measurement of photophysiological parameters revealed that the phytoplankton had generally better photosynthetic  
610 performance in the slag and olivine treatments than in the control, especially after the phytoplankton bloom. During the

611 first 5 days, the changes in phytoplankton photosynthetic performance were indistinguishable between the control and the  
612 slag treatment, while the values of  $\alpha$ ,  $ETR_{max}$  and  $F_v/F_m$  were lower in olivine treatment. At this time all microcosms had  
613 similar health because of the relatively high  $NO_x^-$  concentrations and Fe supply (around  $500 \text{ nmol L}^{-1}$ ), but the suspended  
614 particles in the olivine treatment may have led to artifacts in the measuring of photophysiology by FRRf. Scattering and/or  
615 absorption of light by suspended olivine particles is the most parsimonious explanation for the simultaneous depression in  
616  $\alpha$ ,  $ETR_{max}$  and  $F_v/F_m$ . After day 5, the  $F_v/F_m$ ,  $\alpha$  and  $ETR_{max}$  values decreased significantly faster in the control than in the  
617 treatments, and to values lower than the initial condition. A decrease of  $F_v/F_m$  is commonly associated with physiological  
618 stress, such as nutrient limitation, and high light stress (Bhagooli, et al., 2021), with Fe limitation causing a more  
619 pronounced decline in  $F_v/F_m$  than nitrogen limitation (Gorbunov, et al., 2021). The  $ETR_{max}$ , which represents the maximum  
620 electron transport rate, has also been shown to be negatively affected when phytoplankton experience nitrogen or Fe  
621 limitation (Kolber et al., 1994; Gorbunov & Falkowski 2021). Furthermore, the change in photosynthesis performance  
622 after day 10 was suspected to be driven by the microphytoplankton because the decrease of  $F_v/F_m$ ,  $\alpha$ , and  $ETR_{max}$  in the  
623 control was coupled with the decrease in microphytoplankton abundance while the other phytoplankton groups were in  
624 low abundance as in the mineral addition treatments, and the microphytoplankton contributed significantly (75 %) to  
625 community biovolume. All microcosms were similarly  $NO_x^-$  limited from day 5 onward (Fig. 3) so that N-limitation is  
626 unlikely to explain different trends in photophysiological parameters between the control and OAE treatments. Trace metals,  
627 especially Fe, released through slag and olivine additions could potentially explain these differences.

628  
629 Several of the trace metals released from slag and olivine are required for photosynthesis. For example, Fe is required for  
630 many proteins functioning in photosynthesis, such as cytochromes, ferredoxin, and superoxide dismutase (SOD) (Twining  
631 and Baines, 2013), and the addition of Fe can stimulate the growth of phytoplankton (Sunda and Huntsman, 1997) and  
632 increase  $F_v/F_m$  (Behrenfeld et al., 2006). The dissolved and particulate Fe concentrations were higher in mineral addition  
633 treatments than in the control indicating potentially more Fe available to sustain phytoplankton photosynthesis. While this  
634 explanation is intriguing for the observed trends in photophysiology, it remains unclear why such strong differences  
635 occurred between mineral addition and control treatments despite dissolved Fe concentrations of  $\sim 500 \text{ nmol L}^{-1}$  at the end  
636 of the experiment in the control. In Fe-limited ocean regions, dissolved Fe is at least two orders of magnitude lower, and  
637 the enhancement of Fe to  $\sim 1.5 \text{ nmol L}^{-1}$  can induce major phytoplankton blooms and relieve photophysiological stress (De  
638 Baar et al., 2005). It is possible that these coastal phytoplankton species have higher Fe requirements than those from the  
639 open ocean where Fe is limiting (Strzepek and Harrison, 2004). We speculate that when Fe was consumed during the  
640 phytoplankton bloom, bioavailable Fe was much lower in the control, and may have been insufficient to meet the cellular  
641 requirements of coastal phytoplankton. Our findings therefore suggest that Fe perturbations is not only relevant for lower  
642 Fe open ocean regions but could also be relevant for coastal ocean locations.

643  
644 Alternatively, the addition of Mn, Ni and other trace metals from mineral addition may have benefited photosynthesis.  
645 Manganese is required for the water-splitting reaction of photosystem II (Armstrong, 2008), and both Mn and Ni are  
646 common bioactive trace metals for SODs in marine phytoplankton. The noxious superoxide anion radical ( $O_2^-$ ) generated  
647 from aerobic respiration and oxygenic photosynthesis could be harmful to phytoplankton physiology, and SOD removes  
648  $O_2^-$ , thus improving photosynthesis (Wafar et al., 1995; Wolfe-Simon et al., 2005). This is consistent with our  
649 photosynthetic measurements. Interestingly, although the amounts and types of trace metals released from the slag and  
650 olivine powders were different, they led to relatively similar  $F_v/F_m$  values with only slightly higher  $F_v/F_m$  in the olivine

651 than the slag treatment from days 10-21. Over this time, these trace metal additions could have fertilized different  
652 phytoplankton species (Pausch et al., 2019; Balaguer et al., 2022; Guo et al., 2022) possibly because different  
653 phytoplankton could have different trace metal requirements, such as for SOD. For example, cyanobacteria have NiSOD,  
654 diatoms have MnSOD, dinoflagellates have both FeSOD and MnSOD (Wolfe-Simon et al., 2005). Another explanation is  
655 that phytoplankton in the control were limited by bicarbonate while the treatments had sufficient bicarbonate from added  
656 minerals. However, we were unable to determine the species-level changes in the phytoplankton community, and hence  
657 whether these trace metals, individually or combined, could account for the observed phytoplankton community  
658 photosynthetic performance.

659

#### 660 **4.2.2. OAE impacts on the zooplankton community**

661 Slag-based OAE did not significantly influence the zooplankton community composition while olivine-based OAE induced  
662 some statistically significant effects, including a lower Shannon diversity. The increase in *N. scintillans* abundance and the  
663 decrease in *Penilia* sp. and *Oikopleura* sp. in the olivine treatment indicate that the zooplankton response to OAE can vary  
664 among different zooplankton types.

665

666 The observed lower abundance of *Oikopleura* sp. on day 13 in the olivine treatment may indicate a temporary suppression  
667 or a slower growth rate of this zooplankton species in response to the olivine addition. This could be attributed to the  
668 potential effects of olivine on the availability of essential nutrients or changes in the physicochemical environment of the  
669 water. However, the subsequent increase in *Oikopleura* sp. abundance by day 22 suggests that the growth of this species  
670 may have recovered or accelerated in the olivine treatment, leading to a higher abundance compared to the slag treatment  
671 and the control on day 22. As discussed in section 4.2.1, reduced *Oikopleura* sp. abundance was unlikely due to reduced  
672 food availability since phytoplankton within the preferred edible size spectrum, such as cyanobacteria and nanoeukaryotes,  
673 were even more abundant in the olivine treatment. Instead, we hypothesize it to be an effect of the suspended olivine  
674 particles that occurred for approximately the first 5 days of the study that were so plentiful that they turned the enclosed  
675 seawater milky and may have clogged the mucous feeding mesh of *Oikopleura* sp. (Lombard et al., 2011).

676

677 The abundance of *Penilia* sp. and *Oikopleura* sp. was lower in the olivine treatment than the other two groups throughout  
678 the experiment while the abundance of *N. scintillans* was consistently higher. The second bloom of cyanobacteria in olivine  
679 is likely to be the results of decreased predators, like *Penilia* sp. and *Oikopleura* sp., although the changes in their  
680 abundance were not statistically significant between treatments and the control. We cannot provide a particularly  
681 convincing hypothesis about what specifically drove these differences though it is tempting to speculate that suspended  
682 particles present at the beginning may have played a role also for those organisms since this was the only apparent  
683 systematic difference to the control and slag treatment. The proliferation of *N. scintillans* can be problematic since  
684 heterotrophic dinoflagellate blooms can regulate phytoplankton communities, cause toxicity to aquatic fish, and create a  
685 hypoxic sub-surface zone (Baliarsingh et al., 2016; Zhang et al., 2020; Al-Azri et al., 2007), although a bloom of *N.*  
686 *scintillans* in southeast Australia only induced ichthyotoxicity when the cell concentration reached 2,000,000 cells L<sup>-1</sup>  
687 (Hallegraeff et al., 2019). For comparison, we observed a maximum of 32 cells L<sup>-1</sup> in one microcosm replicate of the olivine  
688 treatment.

689

690 In comparison to olivine, steel slag seemed to have less potential to affect zooplankton community composition. The  
691 abundance of all groups of phytoplankton, apart from microphytoplankton after day 10, was similar in the slag treatment  
692 and the control through the experiment. This is probably because the amount of slag powder added in the treatment was  
693 much less than the olivine powder resulting in fewer physical particle perturbations to zooplankton. In addition, the  
694 chemistry perturbations such as enhanced alkalinity concentration and various dissolved trace metals, especially Mn, from  
695 the slag powder did not seem to have a notable direct influence on zooplankton abundance over the three-week period.  
696 Even though we did not observe drastic changes in zooplankton abundance during the experiment, considering there was  
697 higher microphytoplankton abundance in the slag treatment after day 10, slag powder may benefit some zooplankton  
698 especially those who feed on large phytoplankton on a longer time scale.  
699

#### 700 **4.2.3. Dissolved trace metal accumulation in seawater and its environmental implications**

701 The addition of olivine and slag as OAE source minerals released trace metals into the seawater, predominantly Al, Fe, Ni,  
702 and Cu (olivine) as well as Al, Fe, and Mn (slag). The maximum measured concentrations for dissolved Al, Fe, Ni, Cu, and  
703 Mn were 1093, 253, 77, 27, and 810 nmol L<sup>-1</sup>, respectively. The threshold values for drinking water with health or aesthetic  
704 considerations by the Australian Drinking Water Guidelines for Al, Fe, Ni, Cu, and Mn are 7400, 5360, 340, 15600, and  
705 1800 nmol L<sup>-1</sup>, respectively (NRMMC, 2022). All dissolved trace metal concentrations measured herein are well below  
706 these health and aesthetic threshold values. In natural freshwater sources, the concentrations of Al, Fe, Ni, Cu and Mn are  
707 generally less than 44000, 71400, 510, 156, and 25400 nmol L<sup>-1</sup> (NRMMC, 2022). Although these natural water data were  
708 primarily derived from rivers and streams, they serve as valuable references for evaluating trace metal release in our  
709 experiment. Thus, mineral additions to the microcosms as simulated here did not increase thresholds for any of the  
710 measured trace metals beyond those that are considered safe for drinking water quality, and they were within the trace  
711 metal concentration range in natural water. However, while these guidelines on drinking water provide a good starting point  
712 on how to quantify what OAE perturbation could be considered “safe” and “unsafe” with regards to trace metals, it must  
713 be recognized that seawater is not drinking water and that critical thresholds may be different in the latter.  
714

715 The release of trace metals from OAE materials is considered to have relatively strong effects on biology, particularly in  
716 the open ocean where trace metals usually occur in lower concentrations. For example, oceanic Al, Fe, Ni, and Mn  
717 concentrations are about 2, 0.5, 8, and 0.3 nmol L<sup>-1</sup> (Bruland and Lohan, 2003; Sohrin and Bruland, 2011). Previous  
718 research on OAE-associated trace metal impacts on individual phytoplankton species grown in laboratory environments  
719 has shown that concentration thresholds beyond which trace metal induces negative effects on fitness likely differ between  
720 species (Guo et al., 2022; Hutchins et al., 2023; Xin et al., 2023). Indeed, our experiment with plankton communities  
721 provides further support that several components of the planktonic food web are affected by OAE. However, our experiment  
722 does not allow determining whether observed effects were primarily invoked by carbonate chemistry, macronutrient (P and  
723 Si), or trace metal perturbations. Thus, dedicated experiments isolating the impact of these factors on plankton will be  
724 required in the future.

#### 725 **4.2.4. Particulate trace metal accumulation in seawater and its environmental implications**

726 The Derwent Estuary (where we collected our plankton communities) was highly metal polluted due to industrial practice  
727 (Macleod and Coughanowr, 2019). Both our dissolved and particulate trace metal data indicated high background metal

728 concentrations, especially for Fe and Zn. Furthermore, the metal:POC ratios found here are higher than reported for open  
729 ocean studies or lab cultures. For example, the Fe:POC can vary from 2-136  $\mu\text{mol mol}^{-1}$  depending on the cultured  
730 phytoplankton species and the environmental dissolved Fe concentration (Kulkarni et al., 2006; Sunda and Huntsman,  
731 1995; King et al., 2012; Boyd et al., 2015). In our results the Fe:POC values ranged from 1200 to 39 000  $\mu\text{mol mol}^{-1}$ , which  
732 may be due to the particulate trace metal richness of the Derwent Estuary (control) and/or the addition of lithogenic particles  
733 (slag and olivine treatment). The presence of abiotic particulate metal sources creates challenges to quantify metal quotas  
734 and then to evaluate metal accumulation effects on biological organisms.

735

736 Our study reveals that the added minerals enriched the particulate trace metal pools to various degrees. Consistent with the  
737 dissolved trace metal data, the slag treatment was enriched with particulate Fe and Mn while the olivine treatment was  
738 enriched with particulate Fe and Ni. The enhanced particulate Ni and Mn concentrations were higher than before mineral  
739 additions and the control levels. This is in line with previous research which indicates a positive correlation between  
740 particulate and dissolved trace metal concentrations (Gaulier et al., 2019).

741

742 Based on the amounts released through OAE as simulated herein, it appears that Ni and Mn have the highest potential to  
743 cause toxicity in certain marine organisms (Jakimska et al., 2011). These trace metals have the potential to accumulate in  
744 marine organisms over time (bioaccumulation effects), and their increased concentrations in the food chain can lead to  
745 adverse effects on the health and well-being of organisms at higher trophic levels (biomagnification effects). One crucial  
746 next step will be to investigate whether the enhanced dissolved/particulate trace metal will affect higher trophic levels to  
747 estimate the environmental risks of OAE on other marine organisms.

748

## 749 **5 Conclusions**

750 Our study aimed to assess the environmental impacts of two ground OAE minerals, olivine and steel slag, on coastal  
751 plankton communities. Both minerals released alkalinity, leading to an elevation in  $\text{pH}_T$ . However, the addition of steel  
752 slag exhibited significantly higher efficiency in elevating alkalinity compared to olivine.

753

754 Approximately 1.9 g  $\text{L}^{-1}$  of olivine powder were added in the olivine treatments, leading to a 29  $\mu\text{mol kg}^{-1}$  increase in  
755 alkalinity and increased concentrations of  $\text{Si(OH)}_4$  and trace metals (Fe and Ni). Compared to this relatively modest  
756 increase of alkalinity and associated  $\text{CO}_2$  removal potential, the impacts on the plankton community appeared to be  
757 relatively pronounced. Thus, although our experiment ran for only 3 weeks, and olivine powder may slowly release more  
758 alkalinity, the short-term response monitored here suggests that the immediate climatic benefit is relatively small compared  
759 to a relatively pronounced environmental effect.

760

761 Only 0.038 g  $\text{L}^{-1}$  of slag were added to the treatment but this led to an alkalinity enhancement of 361  $\mu\text{mol kg}^{-1}$  and the  
762 increased concentrations of macronutrients (P and Si) and trace metals (Mn and Fe) additions as well as changes in  
763 carbonate chemistry. Although limited environmental impacts were observed from the slag treatment in our experiment,  
764 some aspects require further study. For example, the pronounced release of P could cause eutrophication and the relatively  
765 rapid increase in pH may be a detrimental aspect if organisms cannot acclimate fast enough. Furthermore, it is essential to

766 consider that the composition of steel slag can vary depending on the source factory (Wang et al., 2011; Proctor et al.,  
767 2000), which may affect the efficiency of carbon removal and change the trace metal perturbation. Nevertheless, just based  
768 on our experiment, the comparison between the immediate climatic benefit and environmental effect appears to be more  
769 favourable for slag than olivine.

770

771 Based on our findings, it can be concluded that steel slag powder exhibited fewer environmental impacts on plankton  
772 communities compared to olivine powder relative to its capacity for alkalinity enhancement. The results highlight the  
773 importance of carefully assessing the environmental consequences of using specific OAE minerals, particularly when  
774 considering their potential effects on plankton communities.

775

776 **Data availability.** Data are available in the Institute for Marine and Antarctic Studies (IMAS) data catalogue, University  
777 of Tasmania (UTAS) (<https://doi.org/10.25959/X6FH-9K15>, Guo, J., & Bach, L. (2023).).

778

779 **Author contributions.** LTB, RFS, KMS and JAG designed the experiments and JAG carried them out. LTB, RFS and  
780 KMS supervised the study. ATT analysed the dissolved/particulate trace metal samples. JAG conducted statistical analyses.  
781 JAG prepared the manuscript with contributions from all authors.

782

783 **Competing interests.** The contact author has declared that none of the authors has any competing interests.

784

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