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

Jiaying A. Guo[1,2], Robert F. Strzepek[2], Kerrie M. Swadling[1,2], Ashley T. Townsend[3], Lennart T. Bach[1]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, 7000 Australia

[2]Australian Antarctic Program Partnership (AAPP), Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, 7000 Australia

[3]Central Science Laboratory, University of Tasmania, Sandy Bay, Tasmania, 7005 Australia

*Correspondence to*: Jiaying A. Guo (Jiaying.guo@utas.edu.au)

**Abstract.** Ocean alkalinity enhancement (OAE) aims to increase atmospheric $CO_2$ 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 $CO_2$ in seawater as bicarbonate. However, $CO_2$ 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 $Mg_2SiO_4$) or steel slag (mainly CaO and $Ca(OH)_2$) as alkalinity sources. Three microcosms were left unperturbed and served as a control, three were enriched with olivine powder (1.9 g $L^{-1}$), and three with steel slag powder (0.038 g $L^{-1}$). Olivine and steel slag powders were of similar grain size. Olivine was added in a higher amount than the steel slag with the aim to compensate for the lower efficiency of olivine to deliver alkalinity over the 3-week experiment. Phytoplankton and zooplankton community responses as well as some biogeochemical parameters were monitored. Olivine and steel slag additions increased total alkalinity by 29 µmol $kg^{-1}$ and 361 µmol $kg^{-1}$ respectively, which corresponds to a theoretical increase of 0.9 % and 14.8 % of the seawater storage capacity for atmospheric $CO_2$. Olivine and steel slag released silicate nutrients into the seawater, 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 $L^{-1}$) in the treatments and the control. The slag addition increased dissolved manganese concentrations (771 nmol $L^{-1}$), while olivine increased dissolved nickel concentrations (37 nmol $L^{-1}$). 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. The abundance of larger phytoplankton (~>20 µm) decreased much more in the control than in the treatments after day 10. Furthermore, the maximum quantum yields of photosystem II ($F_v/F_m$) 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 *Oikopleura* sp. in the olivine treatment. Overall, the steel slag used here ~~is was much~~ more efficient for $CO_2$ removal with OAE than the olivine over the 3-week timescale of the experiment. Furthermore, ~~and appears~~ the steel slag appeared to induce less change in the plankton community than the olivine when ~~relating~~ comparing the $CO_2$ removal potential of both minerals with ~~to~~ the level of environmental impact ~~that was observed~~

37 ~~here~~ they caused.

## 1 Introduction

39 Keeping global warming below 2 °C requires immediate emissions reduction. Additionally, between 450-1100 Gigatonnes

40 of carbon dioxide ($CO_2$) need to be removed from the atmosphere by 2100 (Smith et al., 2023). This could be achieved

41 with a portfolio of terrestrial and marine Carbon Dioxide Removal (CDR) methods. Ocean alkalinity enhancement (OAE)

42 is a marine CDR method that could theoretically contribute significantly to the global CDR portfolio (Ilyina et al., 2013;

43 Feng et al., 2017; Lenton et al., 2018).

45 Alkalinity is generated naturally when rock weathers and it has control on the ocean's chemical capacity to store $CO_2$

46 (Schuiling and Krijgsman, 2006). Natural rock weathering is currently responsible for about 0.5 Gt of atmospheric $CO_2$

47 sequestration every year (Renforth and Henderson, 2017). The idea behind OAE is to accelerate natural rock weathering

48 by extracting calcium- or magnesium-rich rocks, such as olivine, pulverizing them, and spreading them onto the sea surface

49 to increase chemical weathering rates (Hartmann et al., 2013). The weathering (i.e., dissolution) of these alkaline minerals

50 will consume protons ($H^+$), which shifts the carbonate chemistry equilibrium in seawater from $CO_2$ towards increasing

51 bicarbonate ($HCO_3^-$) and carbonate ion ($CO_3^{2-}$) concentrations:

53 $$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+ \tag{1}$$
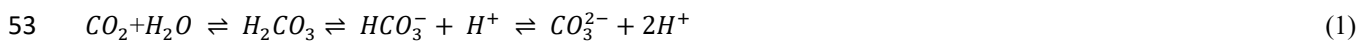
55 thereby making new space for atmospheric $CO_2$ to be dissolved in seawater and permanently stored. Previous model studies

56 have shown that OAE can mitigate climate change significantly by increasing the oceanic uptake of $CO_2$ from the

57 atmosphere (Kohler et al., 2010; Paquay and Zeebe, 2013; Keller et al., 2014; Lenton et al., 2018). For example, the study

58 by Burt et al. (2021) suggested that the total global mean dissolved inorganic carbon (DIC) inventories would increase by

59 156 GtC after total alkalinity is enhanced at a rate of 0.25 Pmol year$^{-1}$ in 75-year simulations.

61 There are a variety of alkaline minerals that could be used for OAE. A widely considered naturally occurring mineral is

62 forsterite, a ($Mg_2SiO_4$)-rich olivine. This type of olivine is abundant in ultramafic rock such as dunite, constituting at least

63 88 % of the rock composition (Ackerman et al., 2009; Su et al., 2016). Olivine occurs in the Earth's crust but is more

64 abundant in the upper mantle. There are at least several billion tons of olivine resources on Earth (Caserini et al., 2022).

65 However, the extraction of olivine in 2017 was only around 8.4 Mt year$^{-1}$ (Reichl et al., 2018), which is about two orders

66 of magnitude below the mass needed for climate-relevant OAE with olivine (Caserini et al., 2022). The net reaction for

67 $CO_2$ sequestration with $Mg_2SiO_4$ is:

69 $$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4 \tag{2}$$

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

72 manufacturing, high-purity calcium oxide (CaO) is used to improve the quality of the steel through accumulation of

73 unwanted materials such as sulphur and phosphorus. Steel slag mainly contains CaO, $SiO_2$, $Al_2O_3$, $Fe_2O_3$, MgO, and MnO

74 (Kourounis et al., 2007), and the chemical composition can vary depending on the manufacturing process (Wang et al.,

2011). Due to the presence of CaO and potentially other alkaline components, steel slag can increase alkalinity when dissolved in seawater. The chemical reaction for $CO_2$ sequestration with CaO is:

$$CaO + H_2O \rightarrow Ca(OH)_2 \text{ and } Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO^- \tag{3}$$
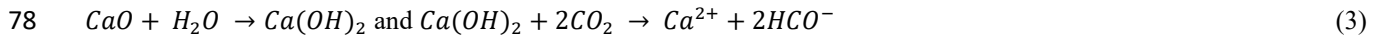
Some of the steel slag that is produced during steel manufacturing is further used (e.g., for road construction and civil engineering) but in some countries like China, 70.5 % of steel slag is left unused and stored in dumps (Guo et al., 2018). In 2016, more than 300 million tons of steel slag was not used effectively, thereby occupying the land and raising environmental concerns (Guo et al., 2018). The effective alkaline composition, availability, and relatively low cost of the raw materials make olivine and steel slag potential source materials for OAE.

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

Here, we describe a microcosm experiment with coastal Tasmanian plankton communities that was used to investigate: (1) how effectively OAE via the application of finely ground olivine and steel slag could sequester atmospheric $CO_2$, and (2) if /how olivine and steel slag additions affect various components of the plankton community.

## 2 Methodology

### 2.1 Microcosm setup
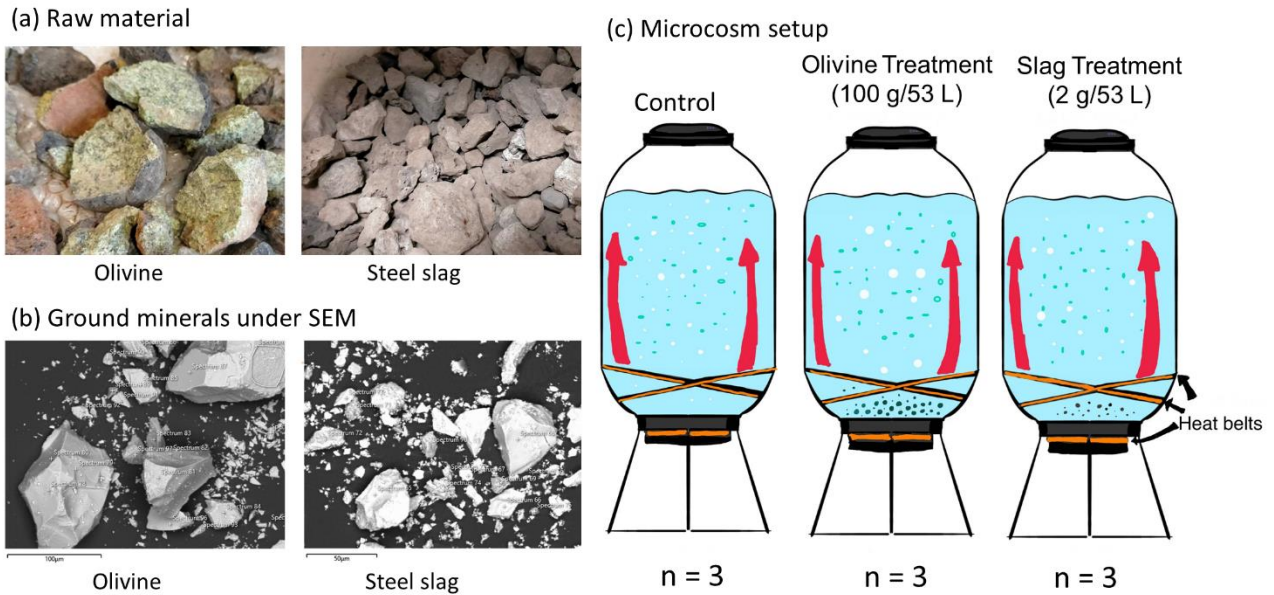


**Fig. 1.** Experimental design and alkalinity sources. (a) Raw materials used as alkalinity sources: olivine (left) and steel slag (right). Olivine and steel slag were originally larger than 20 mm. (b) Ground minerals observed with a scanning electron microscope (SEM). (c) Microcosm setup: each microcosm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

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

4

131 intensity for each microcosm throughout the experiment. Treatments were established 24 hours after collecting the seawater.

132 The total alkalinity released per amount of mineral powder added was much higher for the slag powder than the olivine

133 powder in our preliminary test trials. So, three microcosms were enriched with 100 g of olivine powder, three microcosms

134 with 2 g of steel slag powder, while the remaining three microcosms were left unperturbed and served as controls.

135

136

## 2.2 Preparation of olivine and steel slag powder

138 The olivine rocks were provided by Moyne Shire Council who sourced the mineral from a quarry in Mortlake, Victoria,

139 Australia. The Basic Oxygen Slag (hereafter referred to as "slag") was provided by Bradley Mansell who sourced the

140 material from Liberty Primary Steel Whyalla Steelworks in Whyalla, South Australia, Australia. Upon delivery, the olivine

141 rocks were 40-80 mm in diameter, and slag aggregates were 20-50 mm in diameter. These were crushed to smaller than 10

142 mm pieces using a hydraulic crusher. The crushed material was further ground with a ring mill with a chrome milling pot.

143 Afterwards, finely-ground samples were sieved to get samples with 150 ~ 250 µm grain size. The sieved olivine and slag

144 grains were inspected for their appearance and elemental composition using a Hitachi SU-70 analytical field emission

145 scanning electron microscope (SEM), and energy dispersive spectrometers (Central Science Laboratory (CSL), University

146 of Tasmania). Grain size spectra were determined with a Sympatec QICPIC particle size analyser LIXCELL (CSL,

147 University of Tasmania).

148

## 2.3 Seawater sampling

150 Seawater was transferred with a peristaltic pump from the microcosms at a depth of about 0.15 m into 1 L acid-washed

151 sampling bottles (LDPE) using an acid-washed silicon tube. Seawater in these bottles was then subsampled for dissolved

152 trace metal samples, filtrations, Fast Repetition Rate fluorometry (FRRf), and flow cytometry analysis. Samples for

153 nutrients and total alkalinity (TA) were transferred using the same pump but through a silicone tube into 80 mL HDPE

154 bottles. Total alkalinity and macronutrient samples were filtered during this process through a 0.2 µm nylon filter attached

155 to the silicone tube to remove all particles and organisms > 0.2 µm.

156

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

158 Salinity was measured before and at the end of the experiment using a HACH HQ40d portable meter. The $pH_T$ (total scale)

159 and temperatures were measured daily (2-3 hours after the onset of the light period) using a pH meter (914

160 pH/Conductometer Metrohm). We recorded voltages and temperature from the pH meter and calibrated the $pH_T$ at original

161 temperature at sampled time using the certified reference material (CRM) Tris buffer following the method described in

162 SOP6a by Dickson et al. (2007). Briefly, the standard buffer's pH and voltage at different temperature gradients were

163 recorded, and temperature vs. voltage polynomial regression data were generated for calculating calibrated pH values ($pH_T$)

164 (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

165 temperature and to calibrate the pH measured in the microcosms to the total pH scale.

166

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

176  Dissolved trace metal concentrations were measured four times during the experiment: a few hours before olivine and slag
177  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
178  end of the experiment on day 22. Sixty mL of seawater was collected using an acid-washed 60 mL syringe, and the seawater
179  was filtered through 25 mm diameter 0.2 µm pore size polycarbonate filters. Unfortunately, we did not notice that 0.2 µm
180  pore size nylon filters (acid washed) were used during sampling on days 1 and 2 so we refiltered these seawater samples
181  again using 0.2 µm pore size polycarbonate filters after one month. All seawater samples were diluted approximately 20-
182  fold by weight using Milli-Q water (18.2 MΩ·cm grade) and acidified using 1 % ultrapure HCl. These samples were
183  analysed using Sector Field Inductively Coupled Plasma Mass Spectrometry (SF-ICP-MS) employing multiple resolution
184  settings to overcome major spectral interferences. Due to the presence of abundant major metal ions in our samples, such
185  as Na and Mg, natural open-ocean seawater from the Southern Ocean with very low trace metal concentrations was diluted
186  20 times with Milli-Q water and used as a representative blank. The same Southern Ocean seawater was enriched with
187  different gradients of trace metal standards to calculate the samples' trace metal concentrations. Five of the total 36 samples
188  had abnormal trace metal concentrations, and 2 of them were from day 1. We considered values as outliers using the
189  interquartile range (IQR) criterion on pre-addition data, and if values are more than 10 times higher than replicates, they
190  are also considered as outliers. These samples containing outliers were excluded from the data analysis (Table S1.). The
191  major likely source of these metal contaminations is sampling in the temperature control room, where precautions were
192  insufficiently implemented.

194  **2.5 Particulate matter and plankton community analysis**

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

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

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

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

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

218
$$Biovolume = Cell\ number\ count \times (\frac{FSC}{10248})^{2.14} \qquad (4)$$

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

227 Phytoplankton photosynthetic performance was estimated from the rapid light curves measured with an FRRf (FastOcean
228 Sensor FRRf3, Chelsea Instruments Group) every second day following the protocol adapted from Schallenberg et al.
229 (2020). Samples were kept in the dark for 20 minutes before the measurement and then added to the FRR fluorometry
230 cuvette, which was temperature-controlled at 13.5 °C. Filtered natural seawater was used for blank correction. A channel
231 with three light wavelengths (450, 530, and 624 nm) was used in each acquisition sequence. At least 10 acquisitions were
232 measured for each sample. The maximum electron transport rate ($ETR_{max}$), initial slope of the rapid light curve ($\alpha$), and the
233 light-saturation parameter ($E_k$) were calculated using the equation described by Platt et al. (1980) without photoinhibition:

235
$$ETR = ETR_{max} \left[1 - e^{-\frac{\alpha E}{ETR_{max}}}\right] \qquad (5)$$

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

240 Seawater was sampled before the treatment and at the end of the experiment for particulate trace metal concentrations.
241 Samples of 100 mL were filtered through an acid-cleaned polycarbonate filter (25 mm diameter, 0.8 $\mu m$ pore size) and
242 placed in an acid-cleaned polypropylene filter holder in a trace metal-clean laminar flow bench. The filters were washed
243 with the EDTA-oxalate reagent (1.4 mL) twice (8 min total) and rinsed with chelexed NaCl solution (0.6 mol L$^{-1}$ with 2.38
244 mmol L$^{-1}$ of HCO$_3^-$, pH=8.2) 10 times (1.5 mL aliquots) (Tovar-Sanchez et al., 2003; Tang and Morel, 2006). Filters were
245 stored in acid-washed well plates at -20 °C before analysis. The digestion process followed the method reported by Bowie

246 et al. (2010). Briefly, all samples and triplicate certified reference materials plankton standards (50 mg/vial) were digested

247 in a mixture of strong ultrapure acids (750 μL 12 mol $L^{-1}$ HCl, 250 μL 40 % HF, 250 μL 14 mol $L^{-1}$ HNO₃) in 15 mL Teflon

248 perfluoroalkoxy (PFA) vials on a 95 ℃ hot plate for 12 h in a fume hood. They were then dry evaporated for 4 h and re-

249 suspended in 10 % v-v ultrapure $HNO_3$. All prepared solutions had indium as internal standard added to a final

250 concentration of 10 μg $L^{-1}$. Three pre-mixed multi-element standard solutions (MISA) were prepared as external calibration

251 standards.


253 Particulate organic carbon (POC) was sampled by filtering 100 mL of seawater from each microcosm. Glass fibre filters

254 (Whatman GF/F, pore size =0.7 μm, diameter =13 mm) were pre-combusted at 400 ℃ for 6 h. Filters were stored at -20 ℃

255 before measurement. Samples were treated via fuming with 2N HCl to remove carbonates overnight and dried in the oven

256 for 4h. Finally, filters were folded into silver cups and stored in a desiccator until analysis. Samples were analysed for

257 carbon with a Thermo Finnigan EA 1112 Series Flash Elemental Analyser (CSL, University of Tasmania).


259 Biogenic silica (BSi) concentrations were analysed every 4 days by filtering 100 mL of seawater from each microcosm.

260 Mixed Cellulose Ester (MCE) membrane filters (diameter = 25 mm, pore size = 0.8 μm) were used for BSi samples. BSi

261 filters were placed in a plastic petri dish and stored at -20 ℃ before measurement. Filters were processed using the hot

262 NaOH digestion method of Nelson et al. (1989). The final solution was measured using the same process as the dissolved

263 silicate (see section 2.4).


265 A self-made plastic zooplankton net (20 mm height and 15 mm width) with a 210 μm mesh size was acid-washed first and

266 then used to collect zooplankton from microcosms before mineral addition on day 2, near the middle (day 13), and at the

267 end of the experiment (day 23). Samples were stored in 10 % formalin seawater solutions and kept at room temperature

268 until measurements. Zooplankton were quantified and identified under a Leica M165C microscope fitted with a Canon 5D

269 camera. The number of zooplankton from one mini-trawl in each collection was converted to the unit of individual $L^{-1}$ and

270 used for data analysis. The diversity of zooplankton communities was estimated with the Shannon Diversity Index (H)

271 calculated as:


273 $$H = -\sum(pi \times \ln(pi)) \tag{6}$$


275 where pi is the proportion of the entire zooplankton community made up of individual species abundance, and ln is the

276 natural logarithm.



279 **2.6 Statistic analysis**

280 R studio was used for data analyses. Generalized additive models (GAMs) from the package "mgcv" were fitted to the data

281 to predict the changes over time. The GAMs all shared the same equations:


283 $$Y = s(Day), \tag{7}$$

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

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

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

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

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

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

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

$$Y = Treatment + Day$$ (10)

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


## 3. Results

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

SEM analysis revealed the approximate elemental composition of olivine and slag powder (Table 1). Based on this analysis the olivine composition resembles the Mg-rich olivine mineral "forsterite" ($Mg_2SiO_4$). The particle size spectrum of olivine powder is shown in detail in Fig. S2. Roughly 69 % of the olivine particles, when measured by volume, fell within the

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

327 **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 | |

330 **3.2  Physical and chemical conditions over the course of the experiment.**

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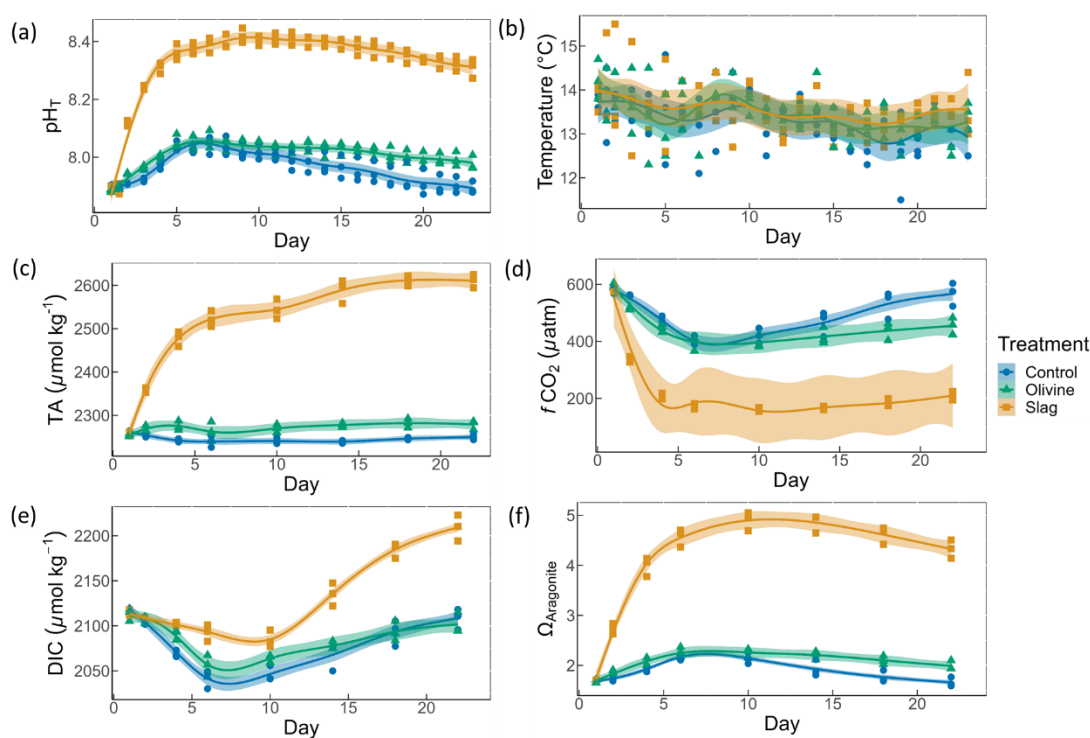


342 **Fig. 2**. Carbonate chemistry conditions. The temporal development of (a) pH$_T$, (b) temperature, (c) total alkalinity (TA), (d) CO$_2$ fugacity

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

The pH$_T$ of all microcosms increased from day 1 to day 5 (Fig. 2a). This was due to photosynthetic CO$_2$ drawdown in the control or photosynthetic CO$_2$ drawdown in combination with alkalinity release from minerals in the treatments. During the peak of the bloom, pH$_T$ was $8.037 \pm 0.010$ in the control (average values $\pm$ standard error), $8.054 \pm 0.014$ in the olivine treatment and $8.411 \pm 0.015$ in the slag treatment. The pH$_T$ was significantly higher in the slag than the olivine treatment and the control throughout the experiment (control and olivine pH$_T$ were not significantly different). The pH$_T$ on day 23 of the 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 inside of the microcosms varied between replicates, which may have added noise in the biological response data. However, on average there was no statistically significant difference between control/treatments during the experiment.

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

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

The CO$_2$ fugacity ($f$CO$_2$) computed at *in situ* temperature and atmospheric pressure decreased continuously in the first 6 days in all microcosms (Fig. 2d). Then it increased again in the control and olivine treatments while staying lower in the slag treatment (P-means and P-smooths $\leq$ 0.001 between either treatment or the control). Dissolved inorganic carbon (Fig. 2e) and the aragonite saturation state ($\Omega_{aragonite}$; Fig. 2f) revealed a similar trend over the course of the experiment in the control and the olivine treatment. In contrast, the slag treatment had higher DIC and $\Omega_{aragonite}$ values throughout the experiment (P-means < 0.001).
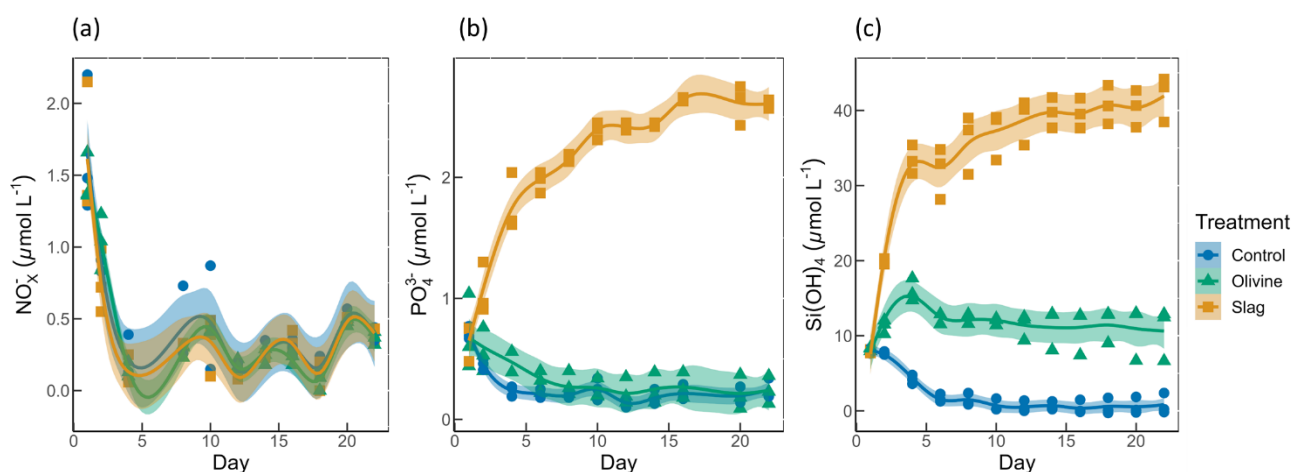
374 **Fig. 3.** Macronutrients concentrations over the course of the study. (a) Nitrate and nitrite concentrations. (b) Phosphate concentrations.

375 (c) Silicic acid concentrations. The dots represent the raw data (n=3 for each treatment per collection), and the fitted curve is the

376 generalized additive model.

377

378 Initial nitrate and nitrite ($NO_x^-$), phosphate ($PO_4^{3-}$), and silicic acid ($Si(OH)_4$) concentrations were $1.58 \pm 0.12$, $0.69 \pm 0.59$,

379 and $8.04 \pm 0.10$ µmol $L^{-1}$, respectively (Fig. 3). $NO_x^-$ declined rapidly in all microcosms once the experiment had

380 commenced to values below 0.5 µmol $L^{-1}$ and no significant difference was detected between treatments and control (P-

381 smooths >0.05; Fig. 3a). In both the olivine treatment and the control, the $PO_4^{3-}$ concentration decreased in the first six

382 days (Fig. 3b). In the slag treatment, $PO_4^{3-}$ increased to a maximum of $2.65 \pm 0.01$ µmol $L^{-1}$, which was significantly higher

383 than in the olivine treatment and the control (P-means <0.001). The $Si(OH)_4$ concentration increased to a maximum of

384 $15.99 \pm 0.87$ µmol $L^{-1}$ in the olivine treatment, increased to a maximum of $41.92 \pm 1.75$ µmol $L^{-1}$ in the slag treatment, but

385 decreased below the detection limit in the control (Fig. 3c). Significant differences were observed in the development of

386 $Si(OH)_4$ between all treatments and the control (Table S2).

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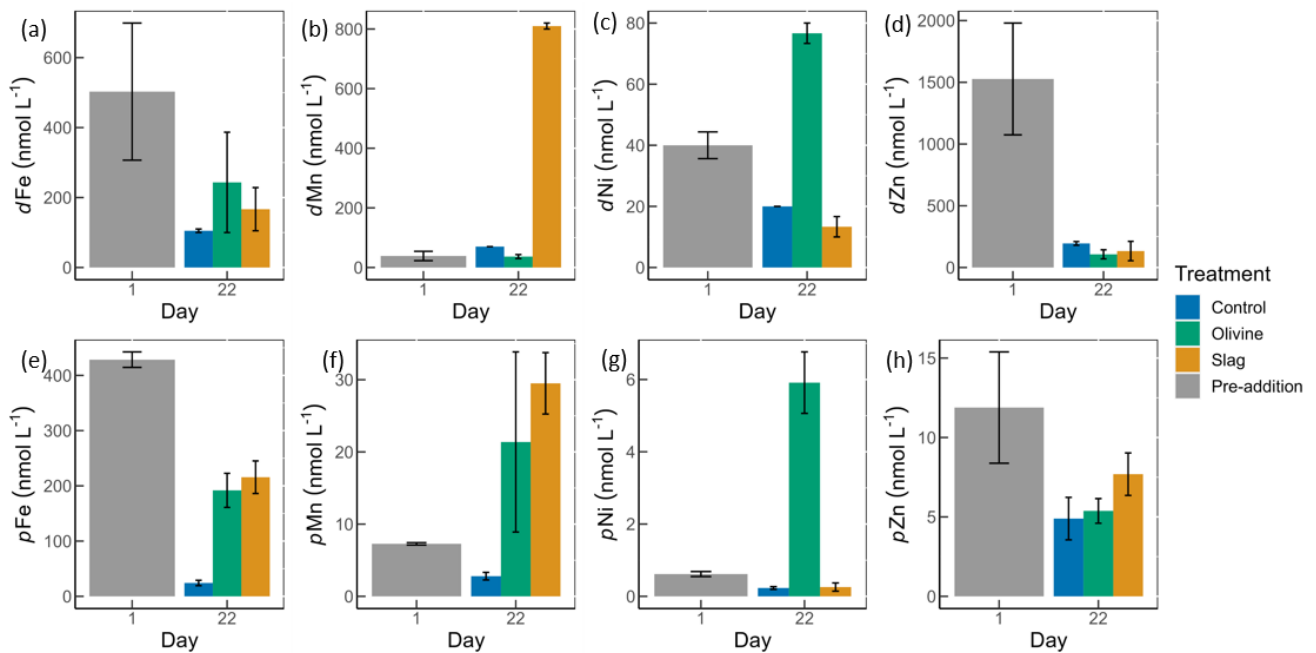


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389

390 **Fig. 4.** Dissolved and particulate trace metal concentrations in microcosm seawater. (a)-(d) are dissolved trace metal concentrations, and

391 (e)-(h) are total particulate trace metal concentrations. The error bars represent the standard error from measured samples. The pre-

392 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

393 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

394 on all three microcosm replicates.

395

396 The dissolved trace metal concentrations measured from microcosms are presented in Fig. S3. While the mass of olivine

397 added to the microcosms was 50-fold greater than in steel slag (100 g vs 2 g), it's noteworthy that the variation in dissolved

398 trace metal concentrations between the two treatments were much smaller than 50 folds. After 21 days of experiment, the

399 treatments showed an increase in dissolved Al concentrations from $920 \pm 286$ to $970 \pm 228$ nmol $L^{-1}$ in olivine treatment,

400 and from $920 \pm 286$ to $1093 \pm 77$ nmol $L^{-1}$ in slag treatment, while in the control dissolved Al decreased to $230 \pm 10$ nmol

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

412

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

420

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

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## 3.3 Development and physiology of the plankton community
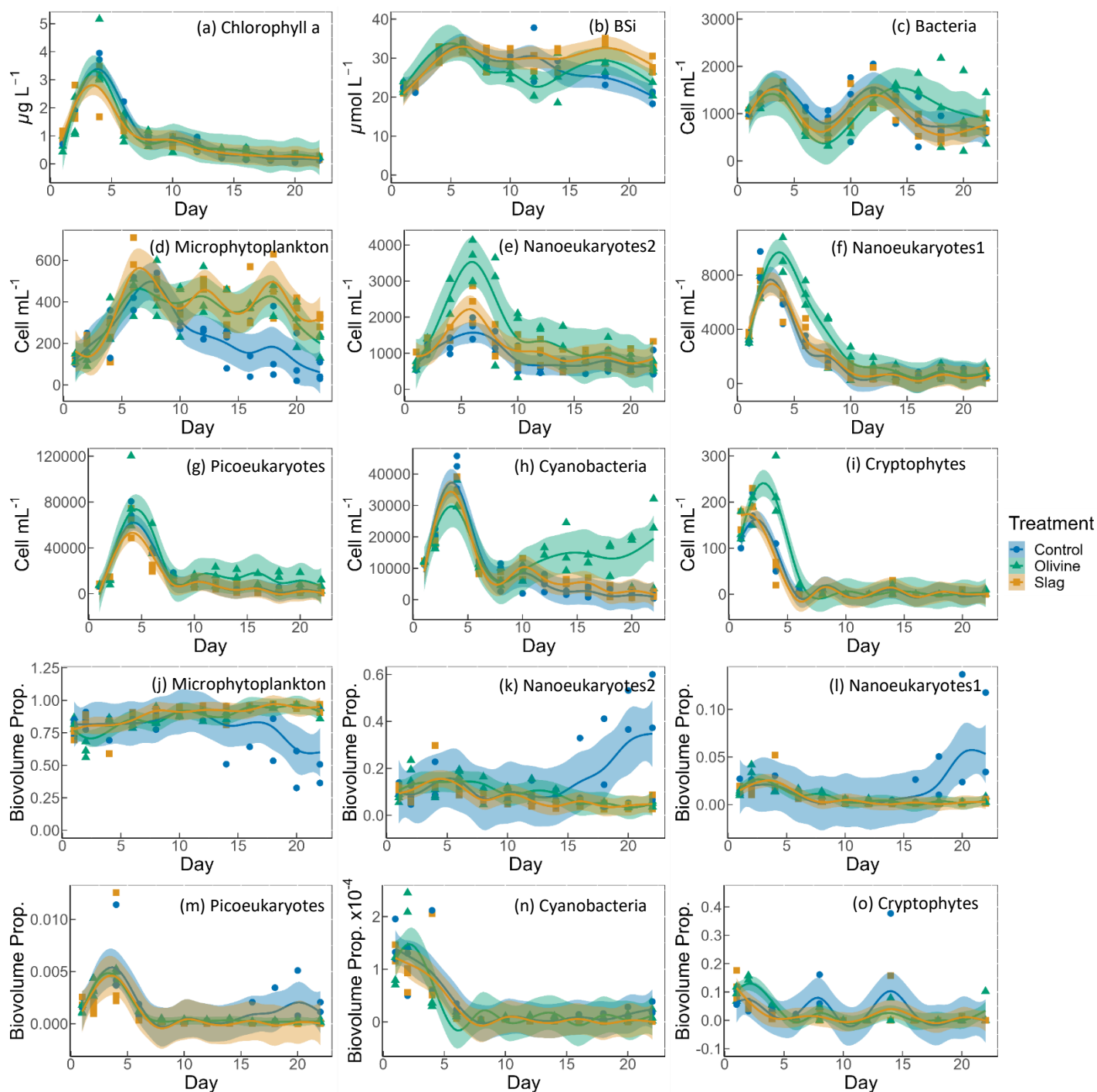


**Fig. 5.** Temporal development of chlorophyll a concentration (chl-a), BSi, and different eukaryotic and bacterial plankton groups as determined with flow cytometry. (a) chlorophyll a; (b) BSi; cell concentrations of (c) heterotrophic bacteria, (d) microphytoplankton, (e) nanoeukaryotes2, (f) nanoeukaryotes1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

444   The chl-a concentration in all microcosms increased from day 1 to day 4 from 1 µg L$^{-1}$ to 3-4 µg L$^{-1}$ (Fig. 5a). The chl-a

445   concentration then decreased rapidly from day 4 to day 8, then continued to decrease, though more slowly, to <0.3 µg L$^{-1}$

446   until the end of the experiment. The GAMs of chl-a did not show any difference between treatments and the control (both

447   P-means and P-smooths >0.05, see Table S2).

449   The BSi concentration increased from day 1 to day 6 in all microcosms (Fig. 5b). In the olivine treatments, BSi

450   concentrations decreased slightly after the peak until day 12 but then increased again. In the slag treatment, BSi

451   concentrations remained relatively stable after the initial phytoplankton bloom. In contrast, BSi concentration decreased

452   continuously in the control after the initial peak. Olivine particles suspended in seawater after the mineral addition (see

453   section 3.2) partially ended up on BSi filters during filtration. This led to extremely high BSi measurements on days 2 and

454   4 that were removed from Fig. 5b. Without these outliers, the mean of fitted BSi GAM in the olivine treatment was lower

455   than the control and the slag treatment (Table S2), and the slag treatment had the highest average BSi over the course of

456   the experiment. Overall, the BSi trends in the two treatments were similar (P-smooths = 0.269), and both were significantly

457   different from the control (P-smooths <0.05).

459   The development of the phytoplankton community composition showed significant differences between the treatments and

460   the control. In general, most phytoplankton groups exhibited similar patterns to chl-a, with peak cell numbers occurring on

461   day 4 (Fig. 5f-i) apart from microphytoplankton and nanoeukaryotes2 which had the peak delayed for 1-2 days (Fig. 5d-

462   e). Please be aware that flow cytometers may not capture some large and chain-forming phytoplankton. After reaching

463   peak values during the bloom, phytoplankton abundance generally decreased steadily. Microphytoplankton displayed

464   similar trends to the results for BSi. Before day 10, all microcosms had similar microphytoplankton abundances (Fig. 5d).

465   However, in the control, microphytoplankton abundance declined continuously and at a faster rate compared to the two

466   treatments (P-smooths values <0.03). From day 2 to day 6, the abundance of nanoeukaryotes1, nanoeukaryotes2,

467   picoeukaryotes, and cryophytes was higher in the olivine treatment compared to the slag treatment and the control. After

468   day 8, their abundance in the olivine treatment decreased to a similar level as the slag treatment and the control. Notably,

469   there were few significant differences observed between the slag treatment and the control in terms of the abundances of

470   nanoeukaryotes1, nanoeukaryotes2, picoeukaryotes, cyanobacteria, and cryptophytes throughout the experiment. In the

471   olivine treatment, cyanobacteria experienced a second bloom after day 10, which was significantly different from the other

472   two groups (P-smooths <0.01). Heterotrophic bacteria exhibited an increase and decline pattern following the

473   phytoplankton bloom until day 8 (Fig. 5c). Subsequently, bacteria abundance increased again, reaching a second peak

474   during days 12-14, followed by a decline until the end of the experiment. The decline in bacteria abundance was slower in

475   the olivine treatment, although no significant differences were detected between treatments (Table S2).

477   Among all the microcosms, microphytoplankton consistently accounted for the largest proportion of biovolume. From the

478   perspective of biovolume proportion, the mineral addition mainly influenced the microphytoplankton and nanoeukaryotes.

479   The control had similar phytoplankton biovolume distribution as the treatments from day 1 to day 15, but after that the

480   proportion of microphytoplankton biovolume decreased to a level significantly lower than the treatments. In the control

481   treatment, the proportion of nanoeukaryotes' biovolume increased as the proportion of microphytoplankton decreased. The

482   biovolume of picoeukaryotes, cyanobacteria and cryptophytes increased during the phytoplankton bloom and then

483   decreased drastically after the bloom. There were no significant differences in biovolume proportion observed for

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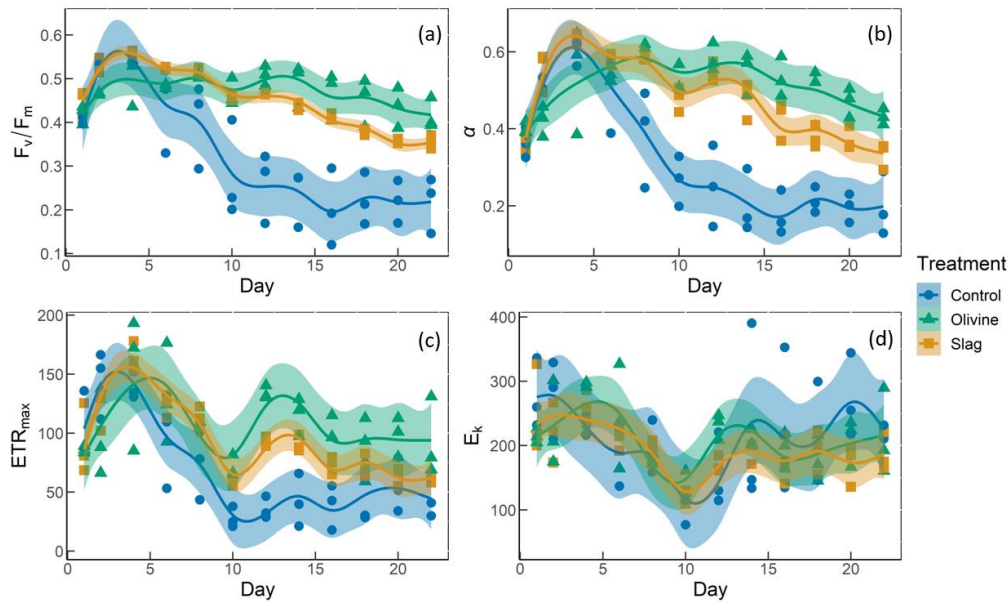


**Fig. 6.** The photosynthetic performance of the phytoplankton community. (a) $F_v/F_m$, the maximum quantum yield of photosynthesis II. (b) $\alpha$, the initial slope of the rapid light curves. (c) $ETR_{max}$ is the maximum electron transport rate, the maximum potential photosynthetic rate. (d) $E_k$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

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 community were approximately $0.42 \pm 0.01$ and increased to levels $> 0.5$ during the peak of the phytoplankton bloom on 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 the bloom was less pronounced in the two mineral addition treatments with the olivine treatment maintaining higher $F_v/F_m$ 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, $0.35 \pm 0.01$ in the slag treatment, and $0.42 \pm 0.02$ in the olivine treatment. The temporal development of $\alpha$ aligned with the 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 control and the slag treatment, while in the olivine treatment, it occurred on day 5 (Fig. 6c). Subsequently, $ETR_{max}$ continuously decreased until day 10 and then stabilized until the end of the experiment. However, $ETR_{max}$ exhibited a subsequent increase in the mineral treatments around day 12. The $ETR_{max}$ values were higher in the mineral treatments compared to the control group (P-means <0.001, Table S2). The parameter $E_k$ decreased from $246 \pm 17$ $\mu$mol photons $m^{-2}$ $s^{-1}$ on day 1 to $121 \pm 7$ $\mu$mol photons $m^{-2}$ $s^{-1}$ on day 10, and then it increased again to approximately 200 $\mu$mol photons $m^{-2}$ $s^{-1}$ by the end of the experiment (Fig. 6d). The change in $E_k$ did not exhibit significant differences between the treatments and the control (both P-means and P-smooths >0.05).
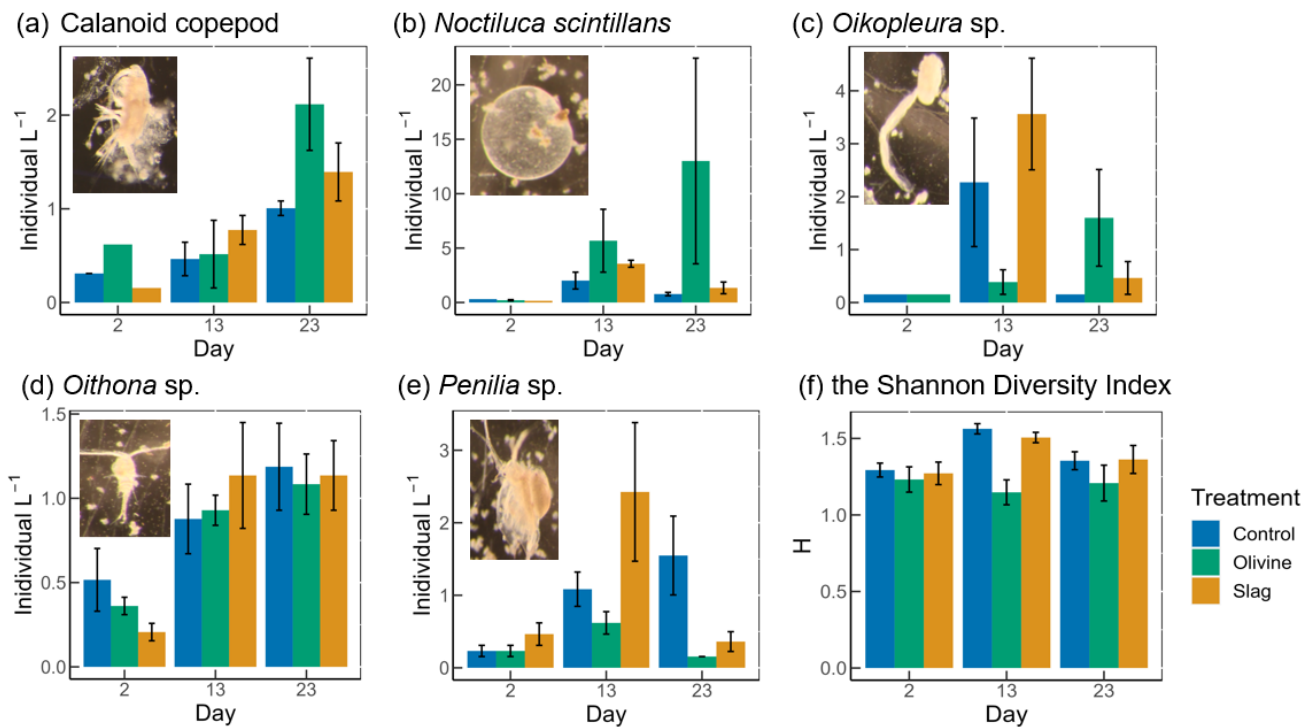
**Fig. 7.** The dominant zooplankton abundance and community diversity from different treatments. Abundance of dominant zooplankton in microcosms: (a) calanoid copepod; (b) *Noctiluca scintillans*; (c) *Oikopleura* sp.; (d) *Oithona* sp.; (e) *Penilia* sp.; and (f) the Shannon diversity index (H) of different treatments and the control. Error bars represent the standard error calculated from three microcosm replicates. Photographs of each zooplankton group are shown on the corresponding graphs.

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

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

533

## 4. Discussion

### 4.1 CO$_2$ removal potential of slag and olivine

The slag powder used here (i.e. Basic Oxygen Slag from Whyalla, Australia) created significantly higher CO$_2$ removal potential than the olivine powder used here (i.e. olivine from Mortlake, Australia) over the course of the study. Ca(OH)$_2$ and CaO in slag and Mg$_2$SiO$_4$ in olivine are likely to be the main functional minerals driving the measured alkalinity enhancement. Total alkalinity increased by 361 μmol kg$^{-1}$ in the slag treatment while it increased by only 29 μmol kg$^{-1}$ in the olivine treatment, equivalent to a potential increase in marine inorganic carbon by 14.7 and 0.9% within 3 weeks of their application. When normalizing these alkalinity increases to the same material weight, 1 g of slag would release 9626 μmol TA while 1 g of olivine would release 16 μmol TA. Thus, over 3 weeks of experimental incubation, slag is ~600-fold more efficient in releasing alkalinity for particles of this size class (please note that particle size spectra of olivine and slag were similar but not identical; Fig. S1). We can also use these values to make a rough estimate of how much CO$_2$ these two minerals could potentially sequester. One mole of alkalinity from olivine and slag can sequester approximately 0.85 mole of CO$_2$. Thus, one tonne of slag and olivine powder as used here could sequester 360 and 0.6 kg CO$_2$, respectively, within 3 weeks. Please note, however, that the amount of olivine added to the experiments (1.9 g L$^{-1}$) contains substantially more alkalinity in solid phase than the slag and that this alkalinity could be released over longer timescales so that the CDR efficiency of olivine could increase more substantially than slag over time. Furthermore, it is likely that optimization of particle size and application method may lead to higher efficiencies of the slag but especially of the olivine with its inherently slower dissolution rate. Last, it needs to be emphasized that other types or sources of slag and olivine may have slightly different composures so that the CDR potentials estimated here, and the associated environmental implications discussed below may vary accordingly.

### 4.2 Environmental implications of slag and olivine additions

The amount of olivine and slag powder added to the treatments differed significantly (100 g of olivine powder were added while only 2 g of slag powder were added to the 53 L microcosms). Our rationale for these different mass additions was to yield somewhat similar amounts of detectable alkalinity enhancement in the dissolved phase, since we already knew from tests before the experiment that slag elevates alkalinity faster than olivine. However, olivine was less efficient in releasing alkalinity than we had anticipated so that even a 50-fold higher addition of olivine (in mass) did not compensate for this difference. As such, our experiments are associated with an "apples and oranges issue" in that our perturbation with minerals and associated OAE differs. To account for this, the following discussion mainly relates the observed environmental effects with the alkalinity enhancement achieved over the course of the study.

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

Previous research has hypothesised that OAE-induced changes in seawater carbonate chemistry could delay phytoplankton bloom formation due to reductions in seawater $p$CO$_2$ in the aftermath of an OAE deployment (Bach et al., 2019). The build-up of chlorophyll $a$ concentration as observed here was indistinguishable between treatments and the control, suggesting

568  no effect of slag- or olivine-based OAE on phytoplankton bloom dynamics under these experimental settings. A lack of

569  bloom delay due to carbonate chemistry is unsurprising for the olivine treatment where the release of alkalinity was small

570  (29 $\mu$mol kg$^{-1}$ alkalinity release), but somewhat more surprising in the slag treatment where alkalinity was quite rapidly

571  increased by 361 $\mu$mol kg$^{-1}$. However, the release was still lower than in a very similar study by Ferderer et al., (2022)

572  where alkalinity was increased by 500 $\mu$mol kg$^{-1}$ using sodium hydroxide and even there they did not observe a bloom

573  delay. Based on this very limited evidence, it seems that bloom delays do not occur consistently under OAE within the

574  alkalinity ranges tested in this study.

575

576  The nutrient data show that the phytoplankton community was most likely N-limited after day 4 so that the release of

577  $Si(OH)_4$ from olivine and $Si(OH)_4$ and $PO_4^{3-}$ from slag did not stimulate a further increase in chlorophyll-*a* concentration

578  in the treatments. The development of BSi concentrations is indicative of the prevalence of diatoms in the microcosms but

579  differences between treatments and the control were small. The release of $Si(OH)_4$ through olivine and slag will most likely

580  benefit diatoms but this fertilization effect did not manifest in this specific experiment because N was limiting diatom

581  growth. However, when new N is supplied then diatoms will likely take a bigger share of the limiting N pool when olivine

582  or slag are used for OAE, as has been shown in $Si(OH)_4$ manipulation experiments in and outside the context of OAE

583  research (Egge and Jacobsen, 1997; Ferderer et al., 2023). In the case of slag, the release of $PO_4^{3-}$ will likely be another

584  driver that affects plankton productivity and community composition. As for $Si(OH)_4$, however, the effect of additional

585  $PO_4^{3-}$ did likely not materialise in this experiment because $PO_4^{3-}$ was not limiting over the course of the study. However, in

586  ecosystems where $PO_4^{3-}$ is a limiting resource, the application of slag could enhance productivity with associated benefits

587  for higher trophic levels. In contrast, excessive applications of slag and concomitant $PO_4^{3-}$ release could also pose a risk of

588  eutrophication. Future studies may need to investigate what the most sustainable dose of OAE via olivine and/or slag

589  applications could be and the suitable regions for application.

590

591  The flow cytometry results further revealed the change in phytoplankton community composition. Both the olivine and

592  slag treatments sustained higher microphytoplankton abundances after the peak of the phytoplankton bloom. This trend is

593  consistent with higher $F_v/F_m$ values in the treatments than in the control so that it is tempting to assume that

594  photophysiological fitness gain measured with the FRRf led to higher competitiveness of microphytoplankton in the

595  community. Indeed, calculations of the contribution of different phytoplankton groups to total biovolume based on flow

596  cytometry indicate that microphytoplankton were predominantly contributing to the phytoplankton community biovolume

597  so that the responses measured by the FRRf were probably to a large extent driven by this group.

598

599  Apart from the increased microphytoplankton abundance, for the slag treatment, other phytoplankton groups distinguished

600  with flow cytometry did not deviate considerably from the control. The olivine addition, however, triggered more

601  pronounced shifts in the phytoplankton community. In particular, the nanoeukaryotes (roughly between 2-20 $\mu$m),

602  picoeukaryotes and the cryptophytes showed relatively higher abundance during the peak of the phytoplankton bloom, and

603  the abundance of cyanobacteria was higher after the bloom. We speculate that this shift following olivine treatment may

604  be attributable to a top-down effect from the decrease in zooplankton grazing effects in microcosms, which will be

605  discussed in section 4.2.2.

606

607  The measurement of photophysiological parameters revealed that the phytoplankton had generally better photosynthetic

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

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

Alternatively, the addition of Mn, Ni and other trace metals from mineral addition may have benefited photosynthesis. Manganese is required for the water-splitting reaction of photosystem II (Armstrong, 2008), and both Mn and Ni are common bioactive trace metals for SODs in marine phytoplankton. The noxious superoxide anion radical ($O_2^-$) generated from aerobic respiration and oxygenic photosynthesis could be harmful to phytoplankton physiology, and SOD removes $O_2^-$, thus improving photosynthesis (Wafar et al., 1995; Wolfe-Simon et al., 2005). This is consistent with our photosynthetic measurements. Interestingly, although the amounts and types of trace metals released from the slag and 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 than the slag treatment from days 10-21. Over this time, these trace metal additions could have fertilized different

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

655

### 4.2.2. OAE impacts on the zooplankton community

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

661

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

672

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

684

685  In comparison to olivine, steel slag seemed to have less potential to affect zooplankton community composition. The
686  abundance of all groups of phytoplankton, apart from microphytoplankton after day 10, was similar in the slag treatment

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

694

695 **4.2.3. Dissolved trace metal accumulation in seawater and its environmental implications**

696 The addition of olivine and slag as OAE source minerals released trace metals into the seawater, predominantly Al, Fe, Ni,
697 and Cu (olivine) as well as Al, Fe, and Mn (slag). The maximum measured concentrations for dissolved Al, Fe, Ni, Cu, and
698 Mn were 1093, 253, 77, 27, and 810 nmol $L^{-1}$, respectively. The threshold values for drinking water with health or aesthetic
699 considerations by the Australian Drinking Water Guidelines for Al, Fe, Ni, Cu, and Mn are 7400, 5360, 340, 15600, and
700 1800 nmol $L^{-1}$, respectively (NRMMC, 2022). All dissolved trace metal concentrations measured herein are well below
701 these health and aesthetic threshold values. In natural freshwater sources, the concentrations of Al, Fe, Ni, Cu and Mn are
702 generally less than 44000, 71400, 510, 156, and 25400 nmol $L^{-1}$ (NRMMC, 2022). Although these natural water data were
703 primarily derived from rivers and streams, they serve as valuable references for evaluating trace metal release in our
704 experiment. Thus, mineral additions to the microcosms as simulated here did not increase thresholds for any of the
705 measured trace metals beyond those that are considered safe for drinking water quality, and they were within the trace
706 metal concentration range in natural water. However, while these guidelines on drinking water provide a good starting point
707 on how to quantify what OAE perturbation could be considered "safe" and "unsafe" with regards to trace metals, it must
708 be recognized that seawater is not drinking water and that critical thresholds may be different in the latter.

709

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

720 **4.2.4. Particulate trace metal accumulation in seawater and its environmental implications**

721 The Derwent Estuary (where we collected our plankton communities) was highly metal polluted due to industrial practice
722 (Macleod and Coughanowr, 2019). Both our dissolved and particulate trace metal data indicated high background metal
723 concentrations, especially for Fe and Zn. Furthermore, the metal:POC ratios found here are higher than reported for open
724 ocean studies or lab cultures. For example, the Fe:POC can vary from 2-136 µmol $mol^{-1}$ depending on the cultured

phytoplankton species and the environmental dissolved Fe concentration (Kulkarni et al., 2006; Sunda and Huntsman, 1995; King et al., 2012; Boyd et al., 2015). In our results the Fe:POC values ranged from 1200 to 39 000 $\mu$mol mol$^{-1}$, which may be due to the particulate trace metal richness of the Derwent Estuary (control) and/or the addition of lithogenic particles (slag and olivine treatment). The presence of abiotic particulate metal sources creates challenges to quantify metal quotas and then to evaluate metal accumulation effects on biological organisms.

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

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

## 5 Conclusions

Our study aimed to assess the environmental impacts of two ground OAE minerals, olivine and steel slag, on coastal plankton communities. Both minerals released alkalinity, leading to an elevation in $pH_T$. However, the addition of steel slag exhibited significantly higher efficiency in elevating alkalinity compared to olivine.

Approximately 1.9 g L$^{-1}$ of olivine powder were added in the olivine treatments, leading to a 29 $\mu$mol kg$^{-1}$ increase in alkalinity and increased concentrations of $Si(OH)_4$ and trace metals (Fe and Ni). Compared to this relatively modest increase of alkalinity and associated $CO_2$ removal potential, the impacts on the plankton community appeared to be relatively pronounced. Thus, although our experiment ran for only 3 weeks, and olivine powder may slowly release more alkalinity, the short-term response monitored here suggests that the immediate climatic benefit is relatively small compared to a relatively pronounced environmental effect.

Only 0.038 g L$^{-1}$ of slag were added to the treatment but this led to an alkalinity enhancement of 361 $\mu$mol kg$^{-1}$ and the increased concentrations of macronutrients (P and Si) and trace metals (Mn and Fe) additions as well as changes in carbonate chemistry. Although limited environmental impacts were observed from the slag treatment in our experiment, some aspects require further study. For example, the pronounced release of P could cause eutrophication and the relatively rapid increase in pH may be a detrimental aspect if organisms cannot acclimate fast enough. Furthermore, it is essential to consider that the composition of steel slag can vary depending on the source factory (Wang et al., 2011; Proctor et al., 2000), which may affect the efficiency of carbon removal and change the trace metal perturbation. Nevertheless, just based

763 on our experiment, the comparison between the immediate climatic benefit and environmental effect appears to be more
764 favourable for slag than olivine.

765

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

770

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