Olivine-based marine carbon dioxide removal field trial shows no adverse effects on the benthic community

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Abstract

Marine enhanced rock weathering (mERW) with olivine is an emerging carbon dioxide removal (CDR) strategy, but its ecological impacts remain uncertain. In 2022, a first-of-its-kind mERW with olivine field trial was conducted on a beach in Southampton, New York (USA). Here we report the macrobenthic community responses and trace metal accumulation using a before–after control–impact (BACI) design. Abundance and species richness at olivine-treated sites returned to control levels within ~2 months, while diversity and evenness remained unchanged. Although community composition shifted after placement, these changes were consistent across all treatments, indicating high natural variability or cumulative nourishment effect rather than an olivine-specific effect. Multivariate analyses revealed community reassembly not captured by standard metrics. Concentrations of olivine-associated metals (Ni, Cr, Co, Mn) were comparable across treatments over ~1 year, with no evidence of accumulation. Despite environmental heterogeneity, our results provide the first field evidence that mERW, when deployed under these conditions, does not cause detectable adverse effects on benthic communities over seasonal timescales.

Keywords: marine enhanced rock weathering, ocean alkalinity enhancement, carbon dioxide removal, macrobenthos, beach nourishment, sediment impacts, ecological recovery, trace metals

Introduction

Limiting global warming to below 2°C will require both rapid emissions reductions and large-scale carbon dioxide removal (CDR), potentially reaching 10 Gt CO_2 yr^{-1} by mid-century and 20 Gt CO_2 yr^{-1} by the end of the century[1,2]. Marine enhanced rock weathering (mERW), a form of ocean alkalinity enhancement (OAE), is an emerging CDR strategy[3–6]. By adding alkaline minerals such as olivine to marine environments, mERW accelerates natural weathering processes, increasing seawater alkalinity and enhancing atmospheric CO_2 uptake. Olivine is of particular interest due to its rapid weathering rate, favorable CO_2 sequestration efficiency, and global abundance[3], with estimated removal potentials of 0.3–10 Gt CO_2 yr^{-1} [7,8].

Despite its potential, the environmental impacts of mERW remain poorly constrained and are largely based on laboratory and modelling studies[3]. Field-based evidence is critically needed to assess ecological risks under realistic conditions[9,10]. mERW could be deployed in many settings, but research has focused on coastal zones, from beaches to continental shelves, where strong hydrodynamics and well-mixed waters may speed mineral dissolution and air–sea CO_2 exchange. Furthermore, coastal environments are already frequently disturbed by sediment additions for the purposes of coastal protection. Beach nourishment is widely used to mitigate coastal erosion, with approximately 28 Mm^3 of sand placed annually in the United States[11], 10–15 Mm^3 yr^{-1} in the Netherlands[12], and 49 Mm^3 historically in Australia[13]. Although effective for shoreline stabilization, nourishment can disrupt macrobenthic communities through burial and habitat alteration, with recovery depending on sediment characteristics, seasonality, and species traits[14–16]. Similar impacts may occur with mERW deployment. Laboratory studies have reported reduced burrowing and adverse biological effects under elevated olivine sand exposure conditions[17–19], although these may not reflect natural environments. In addition to physical disturbance (burial and smothering), olivine dissolution releases alkalinity, nutrients and trace metals[20–23]. Increased alkalinity can help counter ocean acidification, potentially affecting calcifying organisms either positively, negatively or not at all, depending on a given species' calcification mechanisms[24]. Releasing nutrients like silica, may favor diatoms, altering phytoplankton communities, the biological pump, and marine carbon cycling, with possible impacts on higher trophic levels[9,25,26] . Finally, olivine contains trace metals such as nickel (Ni), cobalt (Co), and chromium (Cr), which at high concentrations could pose toxic risks to marine life[20,22,23]. Importantly, these effects have only been demonstrated in controlled laboratory settings and have not yet been tested under natural field conditions, where environmental complexity may substantially alter outcomes.

A first-of-its-kind field trial of mERW was conducted in Southampton, New York (USA), where ~650 tonnes of olivine sand were applied to a beach following placement of 13,500 tonnes of dredged sand, and a subsequent environmental impact study was undertaken to evaluate ecosystem responses under natural field conditions. Macrobenthic communities and sediment characteristics across seven longshore transects spanning four treatment areas (Control West, Olivine Nourished, Control Nourished, and Control East) were assessed (Fig. 1). Each transect comprised one shoreface and three offshore stations (~40 m, ~100 m and ~160 m). Sampling was conducted before (May–June 2022) and repeatedly after beach nourishment and olivine placement (August–October 2022 and June–October 2023), enabling a Before–After Control–Impact (BACI) analysis over more than one year. Trace metal concentrations in macrobenthos were additionally measured prior to intervention and at two post-intervention time points.

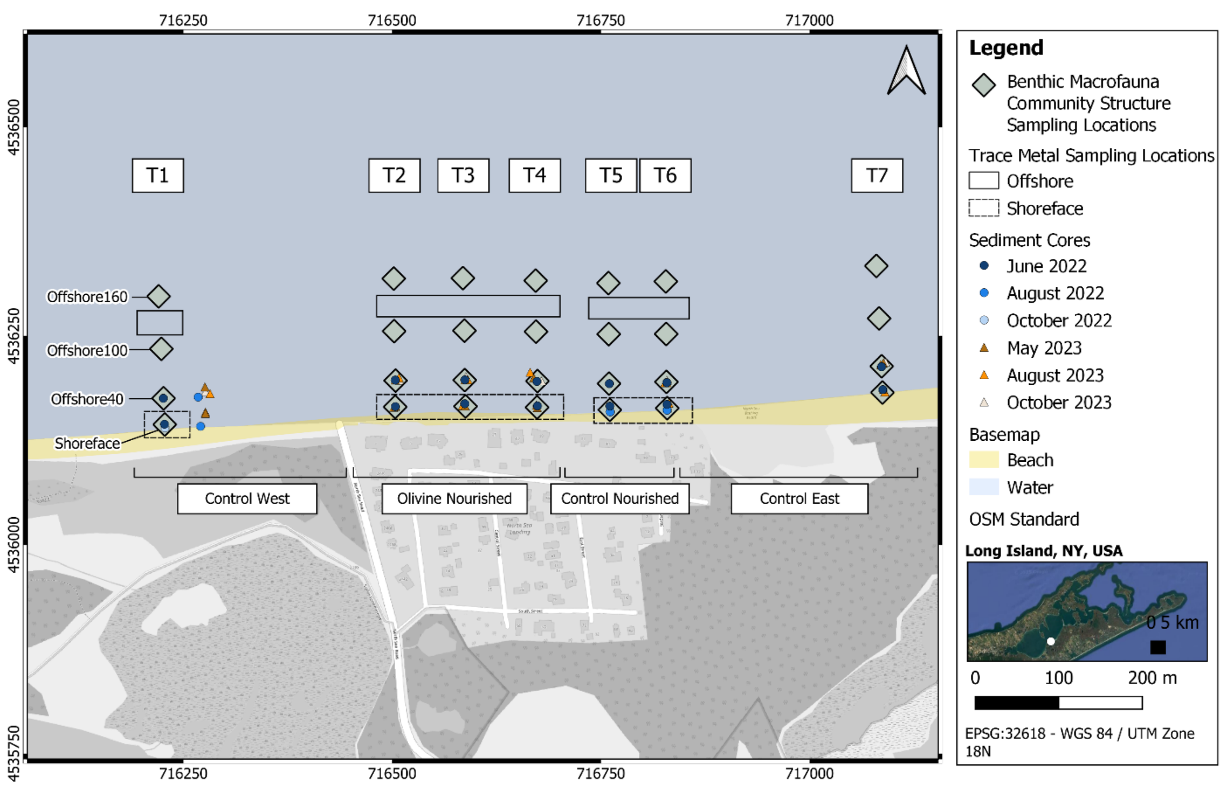

Fig. 1 Study area in Peconic Bay, Long Island, NY, USA.

Results and Discussion

Sediment dynamics and olivine distribution

Sediment characteristics varied significantly across the spatial extent of the study area. The Shoreface station exhibited the highest and most variable gravel content, indicating a heterogeneous habitat likely to influence macrobenthic communities (Fig. S1). Olivine remained largely confined to the Shoreface, with no detection at Offshore stations, suggesting limited cross-shore transport (Fig. S2). Control East consistently exhibited negligible olivine (<1%), confirming its role as a reference site.

Temporal changes in olivine distribution indicated active sediment transport processes, including longshore movement and burial–re-exposure cycles typical of energetic shoreface environments, e.g. olivine content at the Olivine Nourished treatment in August 2022 ranged from 14–35%, by October 2022 it decreased to 7–10%, by May 2023 it dropped to 1% but in October 2023 it rebounded to 30–75% (Fig. S2). These dynamics highlight the importance of accounting for spatial and temporal heterogeneity when interpreting ecological responses of mERW projects.

Abundance, species richness, and recovery

Macrobenthic abundance and species richness showed no consistent olivine-specific effects and were instead primarily driven by natural variability and prior beach nourishment. Abundance and species richness are widely used in beach nourishment monitoring because they are simple, cost-effective, and sensitive indicators of ecosystem status. Accordingly, they form a standard component of environmental assessments in countries such as the United States and across Europe, including the Netherlands and Spain[27,28].

Before–after–control–impact (BACI) analysis revealed significant effects of Treatment, Time, and their interaction on macrobenthic abundance at the Shoreface station only ($p < 0.05$, Table S1). Pairwise comparisons indicated significant differences among all treatments prior to olivine placement (Fig. 2, Table S1; $p < 0.05$). At that time, mean abundance at the Shoreface was lowest at Olivine Nourished (989.2 ± 479.6 ind. 0.04 m^{-2}) and Control Nourished (1180.3 ± 701.9 ind. 0.04 m^{-2}), and highest at Control East (3480.0 ± 755.2 ind. 0.04 m^{-2}). Additional significant differences were observed between Control East and Olivine Nourished after placement, as well as within Control East between pre- and post-placement periods. Following placement, abundance at Olivine Nourished increased to 2259.8 ± 1365.1 ind. 0.04 m^{-2}, similarly at Control Nourished (1675.7 ± 918.0 ind. 0.04 m^{-2}) and exceeding Control East (1035.7 ± 531.2 ind. 0.04 m^{-2}). Notably, the largest changes in abundance before and after placement occurred at the Control East treatment, which was not directly affected by beach nourishment or olivine placement. The initially higher abundance at Control East declined after placement (Fig. 2), underscoring the importance of natural spatial variability in structuring benthic communities.

Species richness per sample varied significantly before versus after olivine placement at the Shoreface and Offshore40 stations only (BACI analysis, $p < 0.05$; Table S1, Fig. 3). No significant differences were detected among treatments. When pooling across treatments, species richness was higher before placement at the Shoreface (27.2 ± 9.1) than after (21.9 ± 5.5; Fig. 3). A similar pattern was observed at the Offshore40 stations, with values decreasing from 29.2 ± 7.5 before to 24.7 ± 4.5 after placement. In contrast, diversity indices, including Shannon diversity and Pielou's evenness, showed no significant changes over time or among treatments (Fig. S5, S6, Table S1).

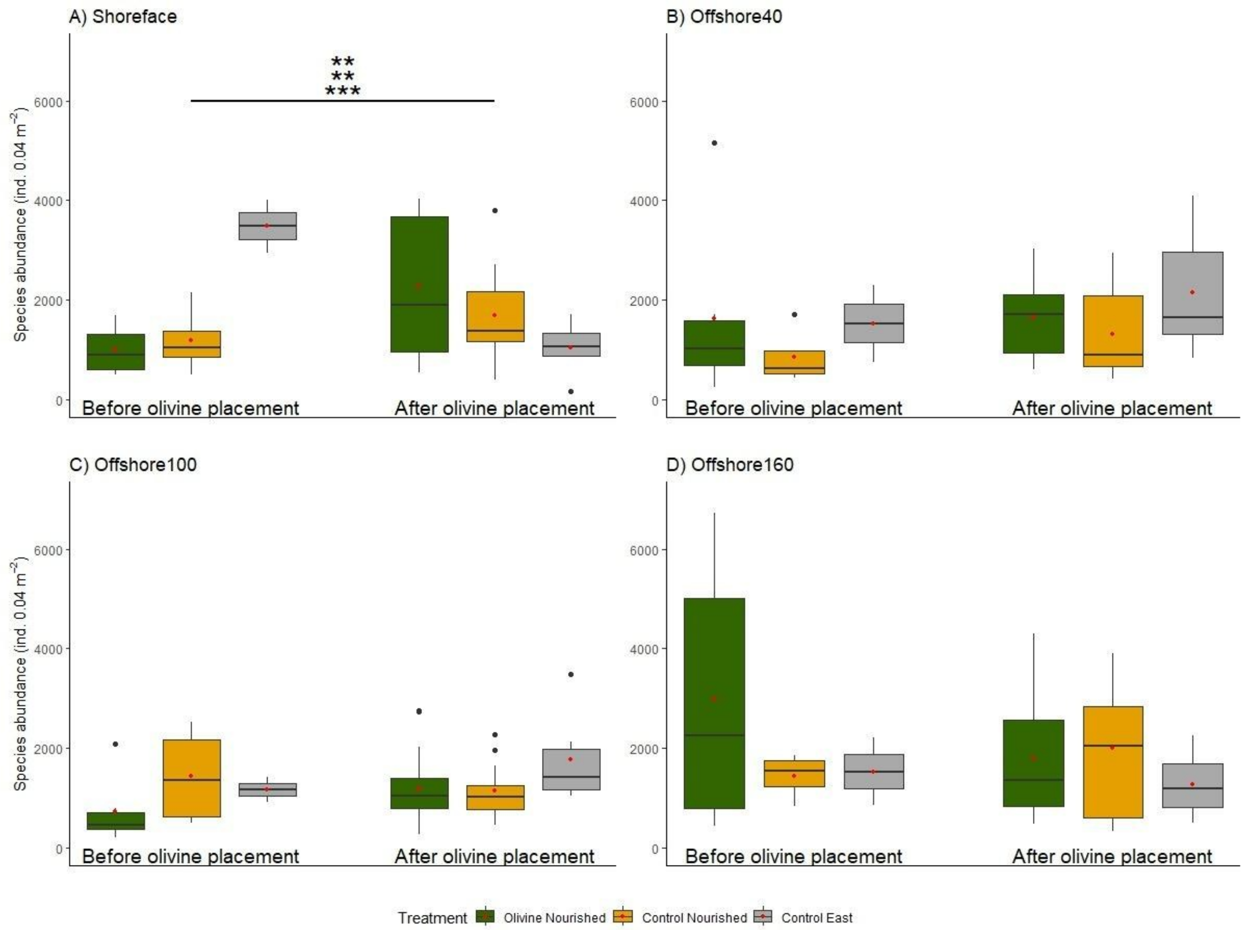

Fig. 2 Macrobenthos abundance (indv. 0.04m^2) at three treatments, before/after olivine placement at A) Shoreface, B) Offshore40, C) Offshore100, and D) Offshore160 stations. The asterisk ** indicates significant general linear mixed model (GLMM) results for the Time and Treatment factor at p<0.01 and their interaction *** at p<0.001 which was identified for intertidal station only.

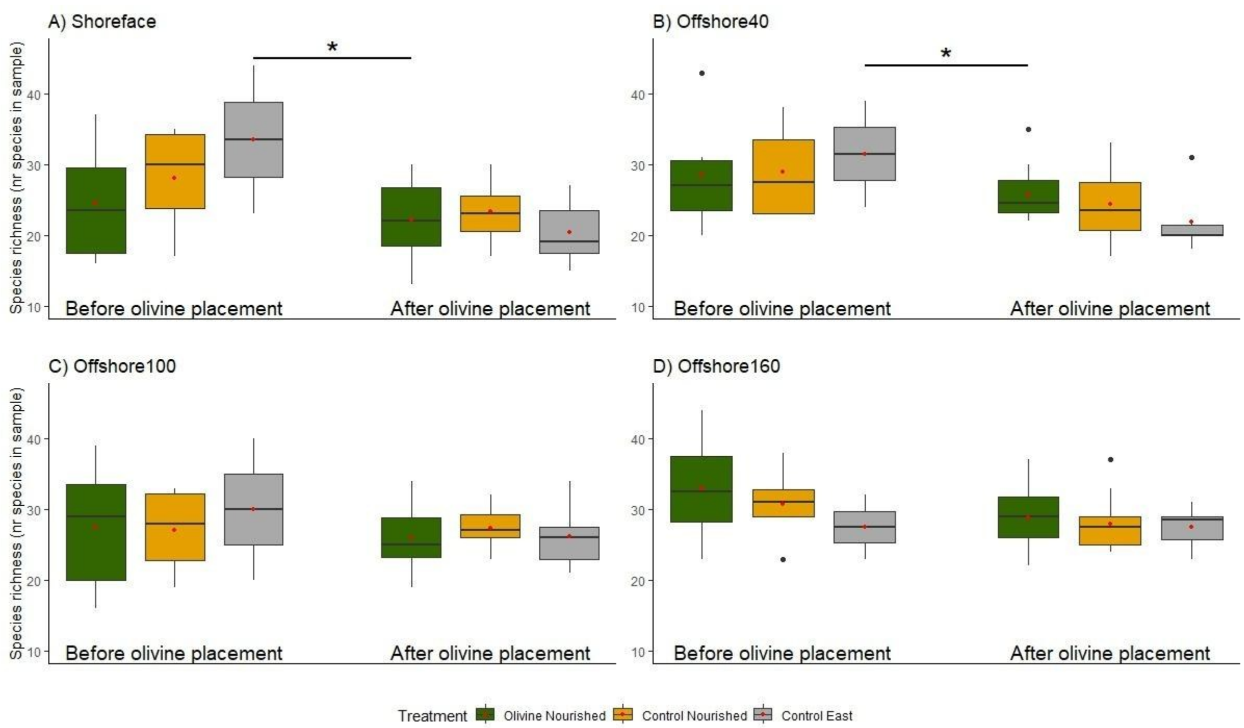

Fig. 3 Species richness (number of species per sample) at three treatments, before/after olivine placement at A) Shoreface, B) Offshore40, C) Offshore100, and D) Offshore160 stations. The asterisk * indicates significant general linear mixed model (GLMM) results for the Time factor at $p<0.05$.

Abundance and species richness at Olivine Nourished returned to baseline levels within ~2 months (Fig. S3, S4, Table S2). For example, mean abundance at the Olivine Nourished Shoreface station was 908.3 ± 452.1 ind. 0.04 m^{-2} (May 2022) and 1070.0 ± 592.6 ind. 0.04 m^{-2} (June 2022), compared to 1039.7 ± 398.2 ind. 0.04 m^{-2} in August 2022. Similarly, species richness reached 26.0 ± 4.6 species per sample two months post-placement, comparable to pre-deployment values, and remained stable one year later (22.0 ± 5.6 to 29.7 ± 5.0 species per sample, Fig. S4).

Overall, abundance and species richness values were at the upper range reported for Peconic Bay mean values. Abundance typically ranges from 134 to 292 individuals per 0.04 m^2, and species richness ranges from 3 to 48 per sample[29], further emphasizing the high baseline variability of the system. Rapid recolonization and similar recovery trajectories between olivine and control treatments suggest that olivine placement effects were comparable to those of conventional beach nourishment.

Community composition

Although macrobenthos abundance and diversity are widely used in nourishment monitoring, they can overlook community-level changes detectable only with multivariate approaches[30]. Here, community composition varied with seasonality, sediment disturbance (olivine and nourishment), and grain size. After accounting for season, redundancy analysis showed significant BACI interactions at all stations (Table S3), with most pairwise comparisons also significant except for a few Offshore160 and Shoreface contrasts. The fraction of variance attributed to season increased from Shoreface (17%) to Offshore160 (27.4%), while the fraction of variance explained by the BACI interactions was stable between Shoreface to Offshore100 (17.1 – 17.9%) and declined at Offshore160 (12.9%) (Table S4). Environmental variables explained an additional 0–17% after season and BACI interactions were removed. % gravel was significant in the Shoreface station, while water depth and grab penetration depth explained variation at the other stations (Table S5), although not always significant. Overall, the combination of season, BACI interactions and continuous environmental variables explained between 39.7 to 55.3% of the total variation in the community structure.

Although macrobenthos abundance and biodiversity recovered rapidly, community composition shifted following placement. No distinct olivine-specific effect was detected, as BACI responses were consistent across all treatments, including controls, indicating that high natural variability obscured any clear olivine signal. Sediment transport was likely less pronounced at the Control East site, suggesting that observed compositional changes primarily reflect natural variability, although cumulative effects of repeated nourishment cannot be excluded. Disturbance and recovery dynamics in nourished systems are well documented, with recovery times ranging from months to years[31], and discrepancies between univariate and multivariate responses are common[32]. The limited use of multivariate approaches has been identified as a key limitation in detecting subtle ecological change[27]. Nourishment influences benthic communities both directly, through burial, and indirectly via altered hydrodynamics and sediment characteristics[30], with repeated interventions potentially driving longer-term shifts[32]. Given the semi-enclosed nature of the study system and prior sand additions in 2020 and 2022, nourished sites may still have been undergoing recovery during the study period.

Sediment grain size, particularly % gravel, was a significant factor influencing macrobenthos community structure at the Shoreface (Fig. 4). Although % olivine was also selected in the model it was not significant after Bonferroni correction (Table S5), despite associations with post-placement conditions (After*OlN and After*CN, Fig. 4). Sediment grain size is a well-established determinant of benthic community composition and diversity[33]. In this study the Shoreface consistently exhibited the highest %gravel across all treatments, with high spatiotemporal variability among treatments but no statistically significant change before and after olivine placement at any treatment (Fig. S1, Table S1, Table S9), indicating that olivine did not substantially alter sediment characteristics. Cross-shore spatial variability was also evident, and the Control East Offshore40 station had elevated % gravel relative to Olivine Nourished. These observations may result from natural variability at the site, as well as the potentially unequilibrated nature of the system due to repeated nourishment activities and complicates attribution of community responses to specific drivers. Nonetheless, sediment grain size distribution, as well as the volume and method of material placement, should be carefully considered when applying olivine in mERW interventions.

Opportunistic early colonizers can rapidly recolonize disturbed habitats, potentially masking longer-term changes in community composition and function. As a result, apparent post-placement recovery in abundance may not reflect a full return to pre-disturbance conditions. In this study, higher abundances of the early colonizer *Capitella* spp. were observed across all treatments, but only at Offshore100 stations that were not directly affected by placement (Fig. S7.1). Several taxa increased following placement in both Olivine Nourished and Control Nourished treatments, including cirratulid polychaetes (all stations, Fig. S7.2 – S7.5), the cumacean *O. smithi* (except Offshore100, Fig. S7.6 – S7.8), the bivalve *G. gemma* (Offshore40, Fig. S7.9), and *Nucula* spp. (Offshore160, Fig. 7.10). In contrast, the gastropod *H. solitaria* (Shoreface, Offshore40, Fig. S7.10 – S7.12) and *Lyonsia* spp. (Offshore100, Fig. 7.13) declined. Comparable shifts were not observed at Control East. No species emerged as a significant positive indicator of post-placement conditions across treatments (Tables S6.1 to S6.4), whereas the polychaete *Pollycirrus eximius* was the only significant negative indicator at the Shoreface for After*Olivine Nourished ($p = 0.004$). Together, these patterns suggest that community changes were driven primarily by broader nourishment disturbance (sand and olivine) rather than olivine placement alone.

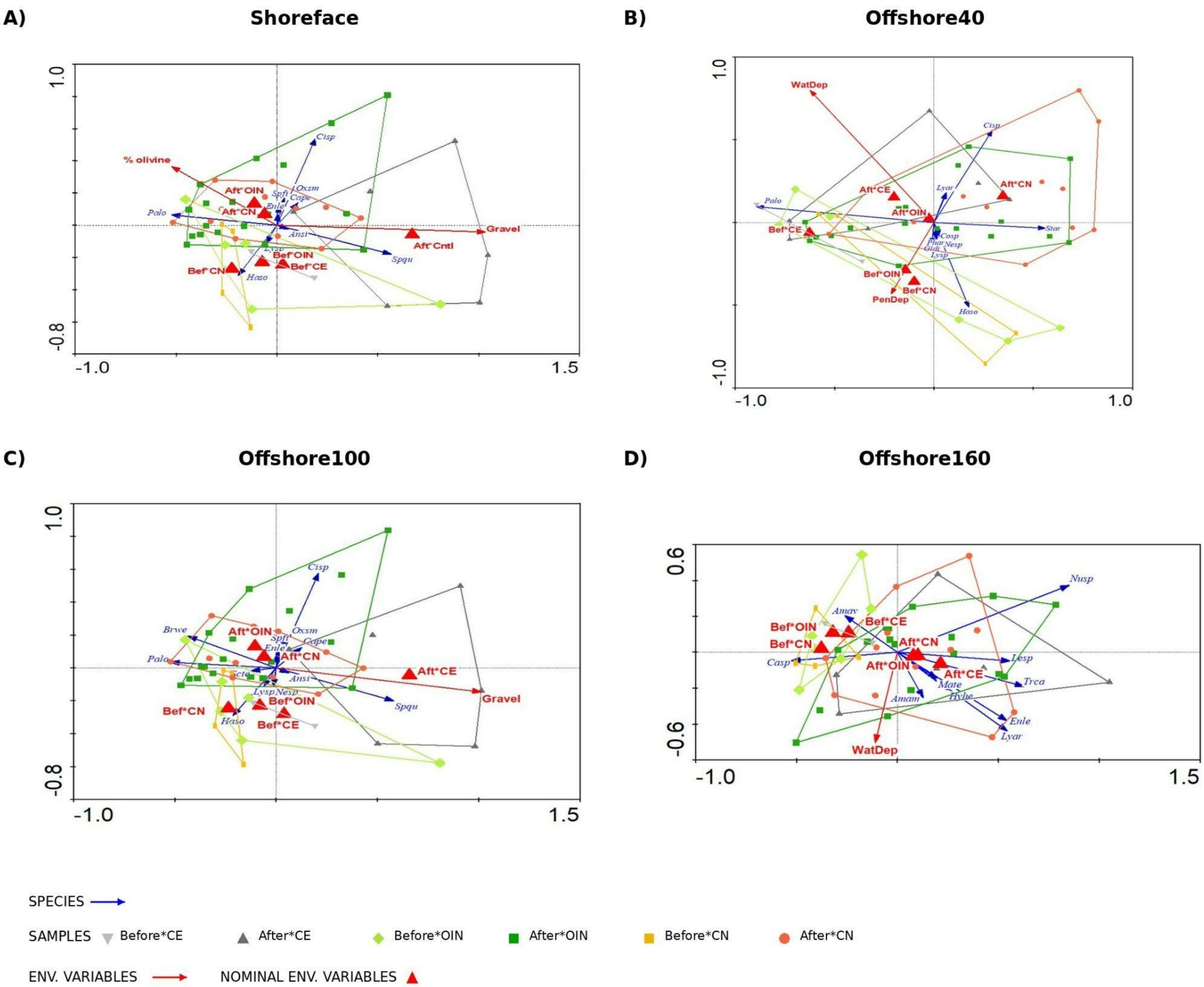

Fig. 4 Redundancy Analysis (RDA) triplot of community structure at A) Shoreface, B) Offshore40, C) Offshore100, and D) Offshore160. The effects of season were removed before analysis. Only the first two RDA axes are plotted. The points are sample scores derived from Hellinger transformed species scores. Envelopes drawn around points designate BACI groups. Red triangles represent the categorical BACI explanatory variables and are located at the centroid of the samples belonging to that group. The blue arrows represent species and the red arrows represent environmental gradients, i.e., the direction of steepest increase for the species or quantitative environmental variable. The origin is the variable mean and decreasing values extend in the opposite direction to the head of the arrow. Only the significant quantitative environmental

variables are plotted. The number of species plotted was reduced for clarity. Abbreviations: CE-Control East, OlN - Olivine Nourished, CN- Control Nourished.

Trace metal accumulation

Trace metal concentrations in macrobenthos remained low across all treatments and time points, with no evidence of accumulation following olivine placement (Fig. 5, Table S8, p>0.05). Ni concentrations remained below 1 µg g ww^{-1}, while Cr concentrations were consistently below 0.6 µg g ww^{-1}. Co concentrations were also low (<0.5 µg g ww^{-1}), with temporal variation likely reflecting seasonal effects (Table S8, p<0.05, Fig. 5).

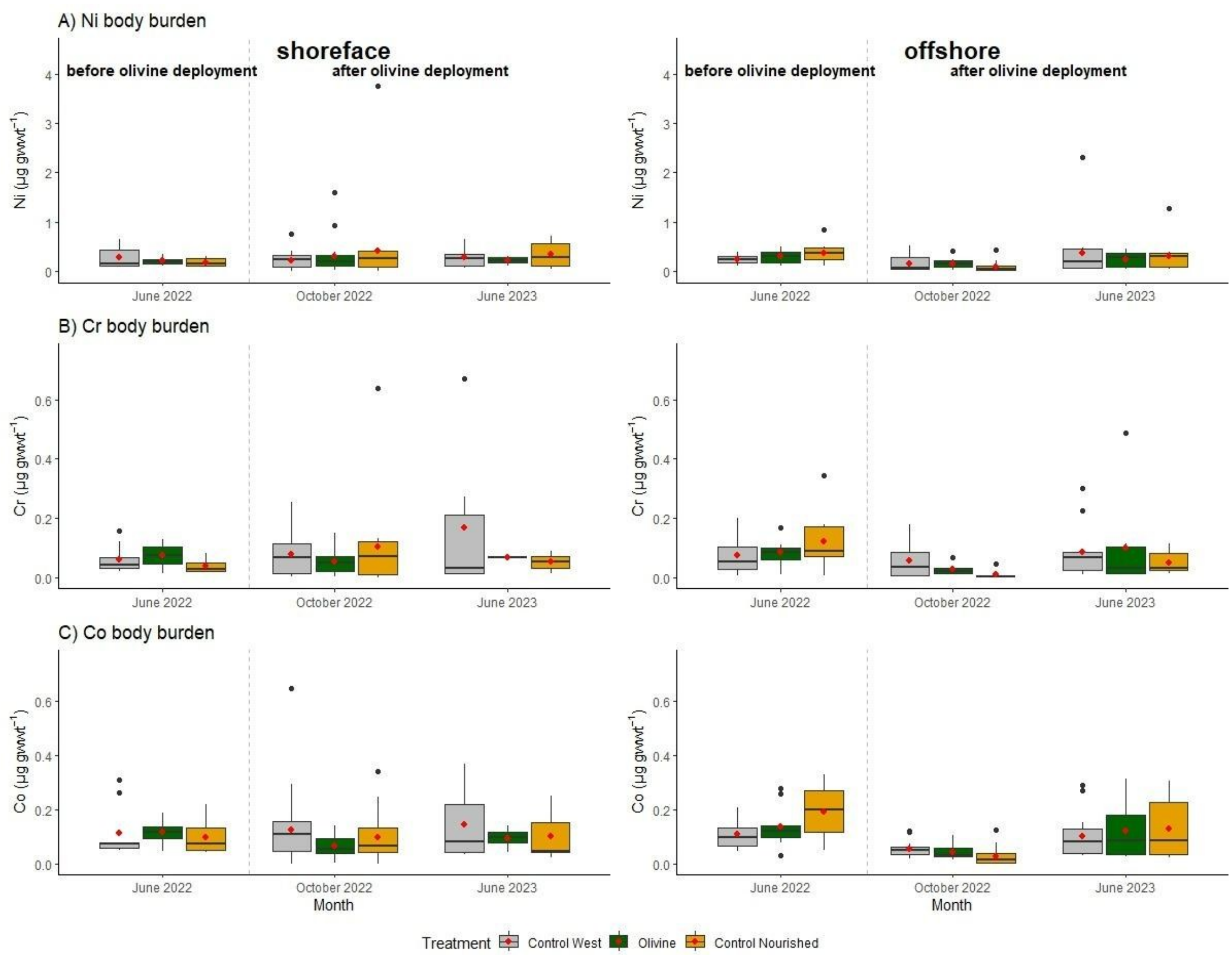

Fig. 5 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at Shoreface and Offshore locations A) Ni body burden, B) Cr body burden, C) Co body burden.

A significant difference in Fe concentrations was observed at Offshore stations in October 2022 ($p < 0.05$; Table S8, Fig. S8), with lower values at Olivine Nourished (44.1 ± 44.7 µg g ww^{-1}) compared to Control West (81.6 ± 82.8 µg g ww^{-1}). In addition, Mn concentrations in invertebrate tissues increased significantly across all treatments in October 2022 (33.1 ± 47.81 µg g ww^{-1}) relative to June 2022 (19.4 ± 34.35 µg g ww^{-1}; $p < 0.05$; Table S8, Fig. S9). This pattern likely reflects the strong redox sensitivity and mobility of Mn in coastal sediments. Additional trace metals not directly associated with olivine were measured in macrobenthic tissues and some of them showed significant differences at Offshore stations, however they exhibited lower concentrations in October 2022 compared to June 2022 and 2023, indicating seasonal variability as the primary driver (Fig. S8–S13, Table S8).

Bioaccumulation of olivine-derived metals in marine invertebrates has previously been demonstrated in laboratory studies, showing significant uptake of Ni and/or Cr[17,18]. For example, Flipkens et al.2023[17] reported high accumulation of Ni (29.3–45.8 µg g ww^{-1}) and Cr (2.08–6.8 µg g ww^{-1}) in amphipods after 35 days of exposure to fine-grained olivine, likely due to enhanced metal release and particle ingestion. In contrast, Jankowska et al. 2024[18] found much lower Ni levels (3.5–4.2 µg g ww^{-1}) in depurated invertebrates exposed to olivine sand for 28 days. Although this study represents the first field application of olivine for carbon removal, an earlier field experiment in Kirkebukten Port, Bergen (Norway), assessed its potential for pollutant adsorption by placing a 30 cm olivine layer on the seafloor and exposing mussels for 12 weeks[34]. Mussels contained 0.1–0.2 µg Ni g ww^{-1}, while naturally occurring mussels sampled four years later contained 0.3–0.7 µg Ni g ww^{-1} [35](converted from dw using a factor of 5[36]), indicating limited long-term bioavailability under natural conditions. Similarly, here we found no evidence of Ni accumulation attributable to olivine, and metal concentrations across all taxa were lower than those reported in laboratory studies (mean Ni at Olivine Nourished post-placement: Polychaeta 0.25 ± 0.37, Decapoda 0.37 ± 0.11, Amphipoda 0.07 ± 0.07, Gastropoda 0.43 ± 0.94, Bivalvia 0.21 ± 0.16 µg g ww^{-1}). These results suggest that laboratory experiments may overestimate bioaccumulation potential, likely due to closed-system conditions with limited water exchange. In contrast, natural environments appear to limit metal bioavailability likely through processes such as sedimentation and dispersal of olivine grains, reduced exposure of benthic fauna, and the tendency of trace metals to adsorb onto particles or precipitate as secondary mineral phases.

Conclusions and Implications

This study provides the first field-based evidence that mERW with olivine causes no adverse effects on macrobenthic communities over seasonal timescales. Changes in abundance, diversity, and community composition were not distinguishable from natural variability or conventional beach nourishment impacts, and no bioaccumulation of olivine-derived trace metals was observed.

Sediment grain size influenced community composition at some stations, consistent with previous nourishment studies[37], and highlights the importance of matching olivine sand to native sediment characteristics. This supports the applicability of existing regulatory frameworks for guiding mERW implementation[38].

The study also underscores key considerations for future mERW trials. Pre-existing disturbances at the study site limited attribution of observed effects, emphasizing the need for stable baselines. Future work should examine a broader range of coastal settings, where hydrodynamics and sediment regimes differ. Finally, our results reinforce the importance of multivariate approaches to detect community-level changes not captured by standard metrics such as abundance and species richness[27].

Materials and methods

Field trial description and site characteristics

The field trial took place at the North Sea Beach Colony (NSBC), located on the southern coastline of Little Peconic Bay in Southampton, New York, USA (40.947886°, -72.427809°; EPSG:4326). Little Peconic Bay is a component of the Peconic Bay tidal estuary system, which lies between eastern Long Island's northern and southern forks and is divided from the Atlantic Ocean by a network of islands, sounds, and tidal channels. Tidal forces dominate the area's hydrodynamic conditions, with a tidal range of 0.87 m[39], and the region experiences pronounced, localized tidal currents. The bay is sheltered from larger waves and swells from the Atlantic Ocean by islands such as Shelter Island and Gardiners Island. Wind-driven waves in the area are typically short-period and low-amplitude, carrying enough erosive force to affect the beaches. Water temperatures exhibit seasonal fluctuations, reaching a maximum of 25°C in July and dropping to 3.9°C in January, as recorded by the Shelter Island USGS Station (01304650)[40]. The NSBC beach undergoes regular beach nourishment using material dredged from the neighboring North Sea Harbor Inlet. Therefore, the benthic communities at the study site are under a near-constant process of rebuilding and recolonizing their population. Earlier beach nourishment projects included a placement of dredged material in December 2020 and again in June 2022, just weeks prior to the mERW field trial (July 2022). The June 2022 beach nourishment occurred from June 8th to 27th and featured the placement of 13,500 tonnes of dredged sand along the ~400 m coastline in front of the NSBC. Following this, the mERW field trial was deployed between July 5th to 8th, 2022, and ~650 tonnes of olivine sand was placed on top of a ~270 m long section of the nourished beach in the intertidal zone (Fig. 1). To the west of the NSBC beachfront, the land above the mean high tide line is a nature reserve and as such, this section of coastline has not experienced historical beach nourishment, nor did it directly receive beach nourishment or olivine during this study. The coastline to the east and west of the NSBC beachfront however separates NSBC from the North Sea Harbor Inlet, and so although it also has not undergone historical beach nourishment, it experiences significant disruption from heavy machinery and pipelines during NSBC nourishment projects and receives nourishment sand through hydrodynamic activity.

The material used in the trial was a harzburgite and had a mineralogical composition of 85 wt% forsteritic olivine, 6.7 wt% orthopyroxene, 5.2% chlorite, 2.2% serpentine and 0.9% talc, as determined by XRD (Detailed method, S2.1). However, the field trial feedstock is hereafter referred to by its primary mineral, olivine. The feedstock had a median grain size of 0.49 mm (D50) and contained 0.5% fines (<0.0625 mm). Following placement, the olivine was reworked by wave and tidal energy continuously, and the project was monitored as detailed in the following sections (Fig. S2).

For the present study, seven longshore transects (T1 - T7), representing four treatment areas (Control West, Olivine Nourished, Control Nourished, Control East) were chosen to monitor macrobenthos community and sediment characteristics (Fig. 1). The Control West treatment represents native coastline that has never been nourished and sits seaward of a nature preserve. The Control East treatment represents native coastline, never nourished but subjected to recurring heavy machinery. The Control Nourished treatment represents coastline that has been heavily nourished with dredged sand, both historically and immediately prior to the mERW field trial. Finally, the Olivine Nourished treatment represents coastline that has been heavily nourished with dredged sand, both historically and immediately prior to the mERW field trial, and then additionally subject to olivine placement. Each transect consisted of four stations, one Shoreface station and three Offshore stations (~40m, ~100m, and ~160m offshore) (Fig. 1). 10 sediment grabs for macrobenthos trace metals analysis were collected across larger areas representing either the Shoreface and Offshore100 and 160 areas, and at the Control West, Olivine Nourished and Control Nourished treatments (Fig. 1). Control East was not sampled for macrobenthos trace metal analysis due to logistical reasons.

Sampling and laboratory analysis

Macrobenthos community

Macrobenthos sampling occurred twice (May and June 2022) before the June beach nourishment and July olivine placement, and six times after (August, September, October 2022, June, August, and October 2023), covering over a one-year post-nourishment timeline to allow for Before and After Control Impact (BACI) analysis[41]. Samples were collected using a 0.04 m^2 van Veen grab. The grab penetration depth was recorded. The sediment was sieved through a 0.5 mm sieve to separate macrobenthos individuals from the sediment. Samples were preserved with 10%

buffered formalin, stained with rose bengal, and they were later transferred to 70% ethyl alcohol. In the laboratory, all macrofaunal individuals were identified to the species level or the lowest possible taxonomic level and counted.

Macrobenthos trace metals

Macrobenthos sampling for trace metals was conducted in June 2022, prior to beach nourishment and olivine placement, as well as twice afterward (October 2022 and June 2023). Samples were collected as described above, and sediments were sieved through a 1-mm non-metallic sieve. Live specimens were sorted with non-metallic tweezers and maintained in aerated seawater for 48 hours to allow clearance of gut contents. Specimens were then grouped by major taxa, rinsed, and processed by separating soft tissues from shells. Wet weights were recorded, and samples were analyzed for trace metals using ICP-MS at Dartmouth College Trace Element Analysis Resource.

Samples were acid digested prior analysis and all necessary data was recorded gravimetrically. Between 0.1 - 0.2 g of sample were weighed into 15 ml polypropylene centrifuge tubes (VWR trace metal free) and 1 ml of 9:1 HNO_3:HCl was added. The samples were left for 16 hrs to 'cold digest' and 100 ul of H_2O_2 was added to each sample. Samples were acid digested using a MAR6 microwave digestion unit with a 15 minute ramp to 105 C and a 45 minute hold. After cooling, nine ml of deionized water was added and the final sample digest weight recorded. Blanks, standard reference materials and sample duplicates were prepared at a frequency of 1 each per 20 samples.

The samples were analyzed for 22 analytes by triple quadrupole ICP-MS (Agilent 8900, Wilmington, DE). The elements measured and their associated ICP-QQQ gas mode were: Helium (collision mode): B, Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Hg, Tl, Pb, U and additionally in oxygen (reaction) mode: V, As, Se, Cd; O_2-mode provides greater sensitivity and/or better interference removal for these analytes. The ICP-MS was optimized prior to each analysis and calibrated with a seven-point calibration prepared by serial dilution of NIST traceable single and multi-element stocks. A second source calibration check was used to initially and continually validate the calibration accuracy at a frequency of every 10 samples. Proficiency test USGS water samples which report most of the elements in the analyte list, and for which consensus values exist, was used as an additional quality control check. The standard reference materials used were Mussel Tissue NIST 2976 and Oyster Tissue NIST 1566b.

Sediment grain size

A sediment subsample (~36 g) was collected from each macrobenthos community structure grab for grain size analysis. Grain-size distribution was determined following Folk, 1974[42]. Samples were partitioned into three size-fractions by adding 50 ml of a 1% Calgon solution, mixing to disaggregate the particles in the sample, and wet sieving with distilled water through a combination of 2 mm and 63 μm sieves. The >2 mm (representing % gravel) and 2 mm-63 μm (representing % sand) fractions were placed in a drying oven at 60°C for at least 48 hours to dry and then weighed. Water containing the <63 μm fraction (representing % mud, i.e., silt + clay) was brought up to 1000 ml total volume in a graduated cylinder, mixed thoroughly, and subsampled with a 20 ml pipette at a depth of 20 cm, 20 seconds after mixing. Pipette samples were placed in a drying oven at 60°C for at least 48 hours to dry and then weighed. Mud weight estimates included a correction for the amount of Calgon added to the samples.

Sediment mineralogy

The mineralogical composition of the feedstock was determined by X-ray diffraction (XRD) at QMineral (Leuven, Belgium) using a Bruker D8 Advance with an XE-T detector and Cu-Kα radiation. Data interpretation was conducted using in-house software.

To quantify the % olivine content of sediment at the project site through time, six sediment core surveys were conducted throughout the study (June 7th, August 16th, October 18th, 2022, and May 24th, August 16th, and October 11th, 2023). Sediment cores were collected near the macrobenthos Shoreface and Offshore40 stations (Fig. 1). Each core was ~20 cm in depth and sub-sampled at depth horizons of 0-1, 1-3, 3-5, 5-10, and 10+ cm using an incremental sediment core extruder. For this study, only the 3-5 cm sediment layer was analyzed for % olivine content as this depth was most representative of the penetration depth of macrobenthos grabs. Sediment samples were stored in Whirlpak bags. Following collection, sediments were dried at 60°C and sieved to separate the >2 mm fraction. The < 2 mm fraction was sub-sampled to approximately 10 g using a sample splitter. The samples were analyzed in-house using a Bruker Tracer 5G handheld XRF analyzer, an energy-dispersive X-ray fluorescence (EDXRF) device. % olivine content of sediments was determined using a calibration curve derived from standards with known olivine and Ni concentrations (see Supplement S2 for detailed methodology).

Data analysis

Macrobenthos univariate characteristics

Before conducting statistical analysis, the two most abundant taxa (Nematoda, Oligochaeta) were excluded from the dataset (S2.2). Their high abundances tend to overly dominate analyses and obscure the contributions of other species without providing meaningful information about macrofaunal community structure. Due to high variability in Control West baseline data (both univariate and multivariate) that was not observed at other stations, it was determined that Control West was not a suitable control and it was excluded from the final analysis (for detailed explanation, see S2.2). Species richness, defined as the number of taxa in a sample (S), species diversity measured with the Shannon-Wiener diversity index (H), evenness of distribution of individuals among taxa expressed by the Pielou index (J), and abundance were calculated for all macrobenthic samples using the 'vegan' package in R[43,44]. Differences in macrozoobenthic univariate characteristics (abundance, S, J, H) among time and treatments (before-after-control-impact (BACI) analysis) were tested using the generalized linear mixed model (GLMM) based on a normal distribution (all stations except S Offshore100, which needed poisson family application). The model included 2 fixed factors (Time, Treatment) and their interaction (Time x Treatment) and Season as a random factor. The best model was selected according to Akaike's Information Criterion and diagnostic tests such as dispersion, residuals, and Levene tests for heteroscedasticity following DHARMa R package (version 0.4.7). When significant effects were detected by the main test, Tukey pairwise tests were applied at a family error rate of 0.05. All analyses were performed in R using the 'glmmTMB' package, version 4.2.2[45]. Additionally, differences in the above mentioned parameters were tested at the Olivine and Control Nourished treatment with one fixed factor, Month, in order to test for the recolonization time of abundance and species richness recovery. This analysis was done only for the stations that exhibited significant effects on BACI comparison (abundance - Shoreface; species richness - Shoreface and Offshore40). The fixed factor, Month, was tested in a parametric ANOVA test. Post hoc pairwise comparisons were applied following a significant main test result, using Tukey test. All statistical analyses were carried out in R (R version 4.4.1,[46]), and significance was assessed at $\alpha = 0.05$.

Macrobenthos multivariate characteristics

The principal goal of the multivariate analysis was to directly relate benthic community structure and changes in community structure to available explanatory variables that included season, treatment levels (i.e., combinations of the categorical factors Before-After olivine placement and Olivine Nourished-Control Nourished-Control East) and continuous environmental factors of water depth, grab penetration depth, grain size (% gravel, % sand, % silt-clay), and % olivine (Shoreface only). As in the case of the univariate analyses, the Control West transect was removed from this analysis since its species composition was quite different from all the remaining transects. Preliminary analysis of the faunal data by detrended correspondence analysis indicated that the gradient length in species turnover was moderate (< 4SD) and that redundancy analysis (RDA), a linear direct gradient analysis method, could be used[47]. After this preliminary analysis, taxa that occurred in less than 4.5% of samples were deleted, since rare taxa would not contribute much information to community structure[48]. RDA combines ordination of samples of species data with linear regression on the explanatory variables to examine biotic-environmental relationships[49]. RDA is based on Euclidean distance, which is not the most appropriate resemblance measure for species data, since it incorrectly interprets shared species absences between samples as similarities. In order to circumvent this shortcoming, abundance data were Hellinger transformed by taking the square root of relative abundances of each species in a sample[50]. This transformation focuses the analysis on compositional differences, reduces the influence of the most abundant species, and combined with Euclidean distance, has been shown to produce good representations of ecological data[50]. RDA analyses were carried out in Canoco 4.5[47]. As with any linear model analysis, an F-ratio statistic can be used to express how strongly the species data are explained by the explanatory variables[47]. The size of this F statistic is assessed in Canoco by permutation test. In the present study, data were permuted at least 1000 times.

Data analysis of each transect location proceeded in three stages to separate out sources of variation in the species data. Since grab samples were collected over a seventeen-month interval (May 2022 to October 2023), considerable seasonal changes in the benthic community were anticipated. To remove the effect of season in subsequent steps, the first stage in the analysis was to regress the Hellinger transformed faunal data with Spring (May, June), Summer (August, September), and Fall (October) categorical variables. Residuals from this step were then analyzed as a hierarchical split plot Before/After, Control/Impacted (BACI) experiment. Treatment (Olivine Nourished-Control Nourished-Control East) were whole-plots and sampling time relative to beach nourishment were split-plots. The interaction between the two categorical factors was examined by explicitly defining each interaction term as an explanatory variable (Before*Control East, After*Control East, Before*Olivine Nourished, After*Olivine Nourished, Before*Control Nourished, After*Control Nourished). Treatments and sampling time within treatments were permuted, with treatment freely exchanged and with samples freely exchanged between before/after but always remaining as a set within the whole-plot. If an interaction model was not justified from this analysis, the effect of each categorical factor would next be considered separately in an additive model.

As a third stage, residuals from the season and BACI analyses were analyzed by forward selection RDA to identify whether any remaining variation could be explained by water depth, grab penetration depth, grain size (% gravel, % sand, % silt-clay), and % olivine (Shoreface only). Family error rates were corrected by the Bonferroni inequality to determine whether to retain any of these as explanatory variables. The final outcome of all three analysis stages allowed the partitioning of faunal community variance into season, BACI, continuous environmental, and residual variance. Results with this transect included are reported in the Supplement and exclusion did not alter the outcome of the multivariate analyses.

In addition to Hellinger transformed abundance trends identified for individual species in the RDA analysis, differences in individual taxa among BACI groups was carried out using a group-equalized indicator value analysis[51,52]. This method was used to identify those individual taxa that were “indicator species” for specific sample groups. The index value IndVal.g is the product of the specificity, an estimate of the probability that the sample came from a targeted site group given that the species was found, and the fidelity, an estimate of the probability that samples within a targeted site group contain that species. Group equalization accounted for differences in the number of samples among site groups. Targeted site groups may contain samples from a single treatment combination (e.g., After*Olivine Nourished) or multiple combinations (e.g., After*Olivine Nourished & After*Control Nourished). IndVal.g was calculated by the multipatt() function in the indicspecies R library[53]. The IndVal.g reported is the maximum value found over all site groups and site group combinations. Permutation tests with nperm = 9999 were used to test significance. A significant outcome indicated that the species is positively associated with that site group or, in a complementary way, negatively associated if a positive association occurred with the other site groups.

Macrobenthos trace metals

As noted above, due to logistical constraints, only one control treatment (Control West) was sampled for trace metal analysis. While Control West was excluded from the community structure analysis, variability in baseline abundance or species composition is not expected to influence the bioaccumulation results which are presented per major taxa, not species. Differences in macrobenthos tissue metals content were tested using the GLMM model, fitted using a Gamma distribution with a log link to assess the effects of treatment, season, and their interaction. The model included a dispersion structure to account for potential heteroskedasticity among groups. Similarly to macrobenthos univariate characteristics, Akaike's Information Criterion and diagnostic tests following the DHARMa R package and Tukey pairwise tests at a family error rate of 0.05 were used, and all analyses conducted in R with the 'glmmTMB' package[45].

Grain size characteristics

Based on the multivariate analysis, % gravel was the variable responsible for macrobenthos variability (Table S5); therefore, it has been chosen as the most representative descriptor of sediment characteristics for presentation purposes. Differences in % gravel among the three treatments were tested using the GLMM model based on a normal distribution with two fixed factors (Treatment, Time) and their interaction, following the same criteria as described above. Results of other sediment fractions are presented in Table S9.

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References

1. IPCC. Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, Cambridge, Cambridge, UK and New York, NY, USA, 2022).
2. National Academies of Sciences, Engineering, and Medicine. A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration. https://doi.org/10.17226/26278 (2022).
3. Geerts, L. J. J., Hylén, A. & Meysman, F. J. R. Review and syntheses: Ocean alkalinity enhancement and carbon dioxide removal through marine enhanced rock weathering using olivine. Biogeosciences **22**, 355–384 (2025).
4. Campbell, J. S. et al. Geochemical Negative Emissions Technologies: Part I. Review. Frontiers in Climate **4**, (2022).
5. Meysman, F. J. R. & Montserrat, F. Negative CO_2 emissions via enhanced silicate weathering in coastal environments. Biol. Lett. **13**, 20160905 (2017).
6. Renforth, P. & Henderson, G. Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics **55**, 636–674 (2017).
7. Feng, E. Y., Koeve, W., Keller, D. P. & Oschlies, A. Model-Based Assessment of the CO2 Sequestration Potential of Coastal Ocean Alkalinization. Earth's Future **5**, 1252–1266 (2017).

8. Palmiéri, J. & Yool, A. Global-Scale Evaluation of Coastal Ocean Alkalinity Enhancement in a Fully Coupled Earth System Model. Earth's Future **12**, e2023EF004018 (2024).

9. Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S. & Renforth, P. CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. Frontiers in Climate **1**, (2019).

10. Gattuso, J.-P. et al. Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Front. Mar. Sci. **5**, (2018).

11. Elko, N. et al. A century of U.S. beach nourishment. Ocean & Coastal Management **199**, 105406 (2021).

12. Stive, M. J. F. et al. A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. coas **29**, 1001–1008 (2013).

13. Jackson, A., Hill, P. & McGrath, J. A history of the implementation and evolution of sand nourishment methods on the Gold Coast, Australia. in Coasts Ports 418–423 (2013).

14. Schlacher, T. A., Noriega, R., Jones, A. & Dye, T. The effects of beach nourishment on benthic invertebrates in eastern Australia: Impacts and variable recovery. Science of The Total Environment **435–436**, 411–417 (2012).

15. Wilber, D., Clarke, D., Ray, G. & Dolah, R. V. LESSONS LEARNED FROM BIOLOGICAL MONITORING OF BEACH NOURISHMENT PROJECTS. WEDA 262–274 (2010).

16. Wooldridge, T., Henter, H. J. & Kohn, J. R. Effects of beach replenishment on intertidal invertebrates: A 15-month, eight beach study. Estuarine, Coastal and Shelf Science **175**, 24–33 (2016).

17. Flipkens, G. et al. Acute bioaccumulation and chronic toxicity of olivine in the marine amphipod Gammarus locusta. Aquatic Toxicology **262**, 106662 (2023).

18. Jankowska, E., Montserrat, F., Romaniello, S. J., Walworth, N. G. & Andrews, M. G. Metal bioaccumulation and effects of olivine sand exposure on benthic marine invertebrates. Chemosphere **358**, 142195 (2024).

19. Flipkens, G. et al. Olivine avoidance behaviour by marine gastropods (Littorina littorea L.) and amphipods (Gammarus locusta L.) within the context of ocean alkalinity enhancement. Ecotoxicology and Environmental Safety **270**, 115840 (2024).

20. Flipkens, G., Blust, R. & Town, R. M. Deriving Nickel (Ni(II)) and Chromium (Cr(III)) Based Environmentally Safe Olivine Guidelines for Coastal Enhanced Silicate Weathering. Environ. Sci. Technol. **55**, 12362–12371 (2021).

21. Montserrat, F. et al. Olivine Dissolution in Seawater: Implications for CO_2 Sequestration through Enhanced Weathering in Coastal Environments. Environ. Sci. Technol. **51**, 3960–3972 (2017).

22. De Hoog, J. C. M., Gall, L. & Cornell, D. H. Trace-element geochemistry of mantle olivine and application to mantle petrogenesis and geothermobarometry. Chemical Geology **270**, 196–215 (2010).

23. Rimstidt, J. D., Brantley, S. L. & Olsen, A. A. Systematic review of forsterite dissolution rate data. Geochimica et Cosmochimica Acta **99**, 159–178 (2012).

24. Bednaršek, N. et al. Assessment framework to predict sensitivity of marine calcifiers to ocean alkalinity enhancement – identification of biological thresholds and importance of precautionary principle. Biogeosciences **22**, 473–498 (2025).

25. Hutchins, D. A. et al. Responses of globally important phytoplankton groups to olivine dissolution products and implications for carbon dioxide removal via ocean alkalinity enhancement. EGUsphere 1–0 (2023) doi:10.1101/2023.04.08.536121.

26. Hope, J. A., Hewitt, J., Pilditch, C. A., Savage, C. & Thrush, S. F. Effect of Nutrient Enrichment and Turbidity on Interactions Between Microphytobenthos and a Key Bivalve: Implications for Higher Trophic Levels. Front. Mar. Sci. **7**, (2020).

27. Peterson, C. H. & Bishop, M. J. Assessing the environmental impacts of beach nourishment. BioScience **55**, 887–896 (2005).

28. Defeo, O. et al. Threats to sandy beach ecosystems: A review. Estuarine, Coastal and Shelf Science **81**, 1–12 (2009).

29. Cerrato, R. M., Flood, R. D. & Holt, L. C. Benthic Mapping for Habitat Classification in the Peconic Estuary: Phase III Ground Truth Studies. (2010).

30. Staudt, F. et al. The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. J Coast Conserv **25**, 34 (2021).

31. Peterson, C. H., Bishop, M. J., D'Anna, L. M. & Johnson, G. A. Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments. Sci Total Environ **487**, 481–492 (2014).

32. Leewis, L., van Bodegom, P. M., Rozema, J. & Janssen, G. M. Does beach nourishment have long-term effects on intertidal macroinvertebrate species abundance? Estuarine, Coastal and Shelf Science **113**, 172–181 (2012).

33. Chauvel, N. et al. Sediment grain size and benthic community structure in the eastern English Channel: Species-dependent responses and environmental influence. Mar Pollut Bull **200**, 116042 (2024).

34. Gjesdal, A. & Solheimslid, S. O. Environmental Condition in Kirkebukten. Monitoring Results 2015. 36 (2016).

35. Sæterdal Bøyum, M. & Ane Moe, G. Environmental Condition in Kirkebukten Monitoring Results 2019. 54 (2020).

36. Rainbow, P. S. & Phillips, D. J. H. Cosmopolitan biomonitors of trace metals. Marine Pollution Bulletin **26**, 593–601 (1993).

37. Colosio, F., Abbiati, M. & Airoldi, L. Effects of beach nourishment on sediments and benthic assemblages. Marine Pollution Bulletin **54**, 1197–1206 (2007).

38. Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024).

39. NOAA. Datums for 8512735, South Jamesport NY. (2011).

40. USGS. Surface Water data for USA: USGS Surface-Water Monthly Statistics. (2024).

41. Seger, K. D., Sousa-Lima, R., Schmitter-Soto, J. J. & Urban, E. R. Editorial: Before-After Control-Impact (BACI) Studies in the Ocean. Front. Mar. Sci. **8**, (2021).

42. Folk, R.L. (1974) Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, 170 p. - References - Scientific Research Publishing. https://www.scirp.org/reference/referencespapers?referenceid=1471425.

43. Oksanen, J. et al. vegan: Community Ecology Package. (2026).

44. De Smet, B. et al. The Community Structure of Deep-Sea Macrofauna Associated with Polymetallic Nodules in the Eastern Part of the Clarion-Clipperton Fracture Zone. Front. Mar. Sci. **4**, (2017).

45. Brooks, M. E. et al. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. The R Journal **9**, 378–400 (2017).

46. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna (2024).

47. ter Braak, C. J. F. & Šmilauer, P. CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (Version 4.5). (2002).

48. McCune, B. & Grace, J. Analysis of Ecological Communities. MjM Software Design (2003).

49. Jongman, R. H. G., Braak, C. J. F. T. & Tongeren, O. F. R. van. Data Analysis in Community and Landscape Ecology. (Cambridge University Press, Cambridge, 1995). doi:10.1017/CBO9780511525575.

50. Legendre, P. & Gallagher, E. D. Ecologically meaningful transformations for ordination of species data. Oecologia **129**, 271–280 (2001).

51. Dufrêne, M. & Legendre, P. Species Assemblages and Indicator Species:the Need for a Flexible Asymmetrical Approach. Ecological Monographs **67**, 345–366 (1997).

52. Improving indicator species analysis by combining groups of sites - De Cáceres - 2010 - Oikos - Wiley Online Library. https://nsojournals.onlinelibrary.wiley.com/doi/10.1111/j.1600-0706.2010.18334.x.

53. Cáceres, M. D. & Legendre, P. Associations between species and groups of sites: indices and statistical inference. Ecology **90**, 3566–3574 (2009).

Supplementary materials

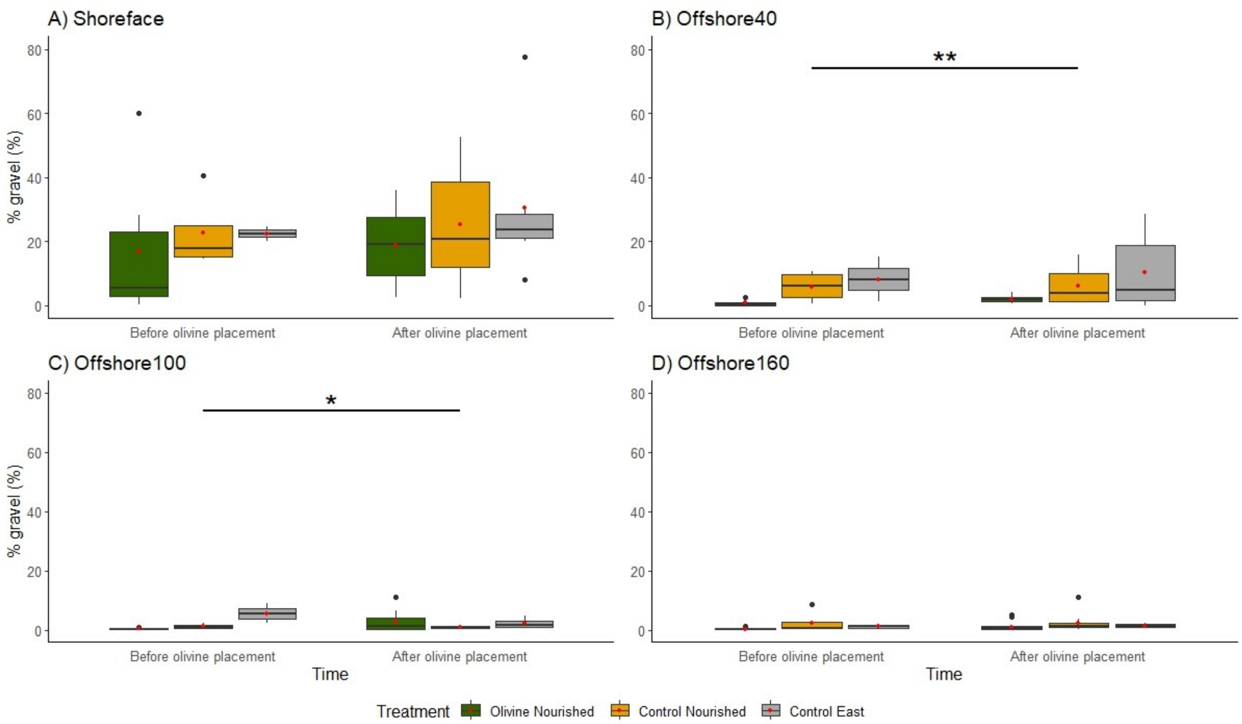

Figure S1 % gravel content calculated from sediment samples collected at three treatments, before/after olivine placement at A) Shoreface, B) Offshore40, C) Offshore100, and D) Offshore160 stations. Mean (red dot), median (horizontal line), 25th and 75th percentile (box), minimum and maximum value (vertical line), and outliers (black dot) are presented. The asterisk ** indicates significant general linear mixed model (GLMM) results for the Treatment factor at $p<0.01$ for shoreface station and * at $p<0.05$ for the interaction of Treatment*Time for offshore100 station.

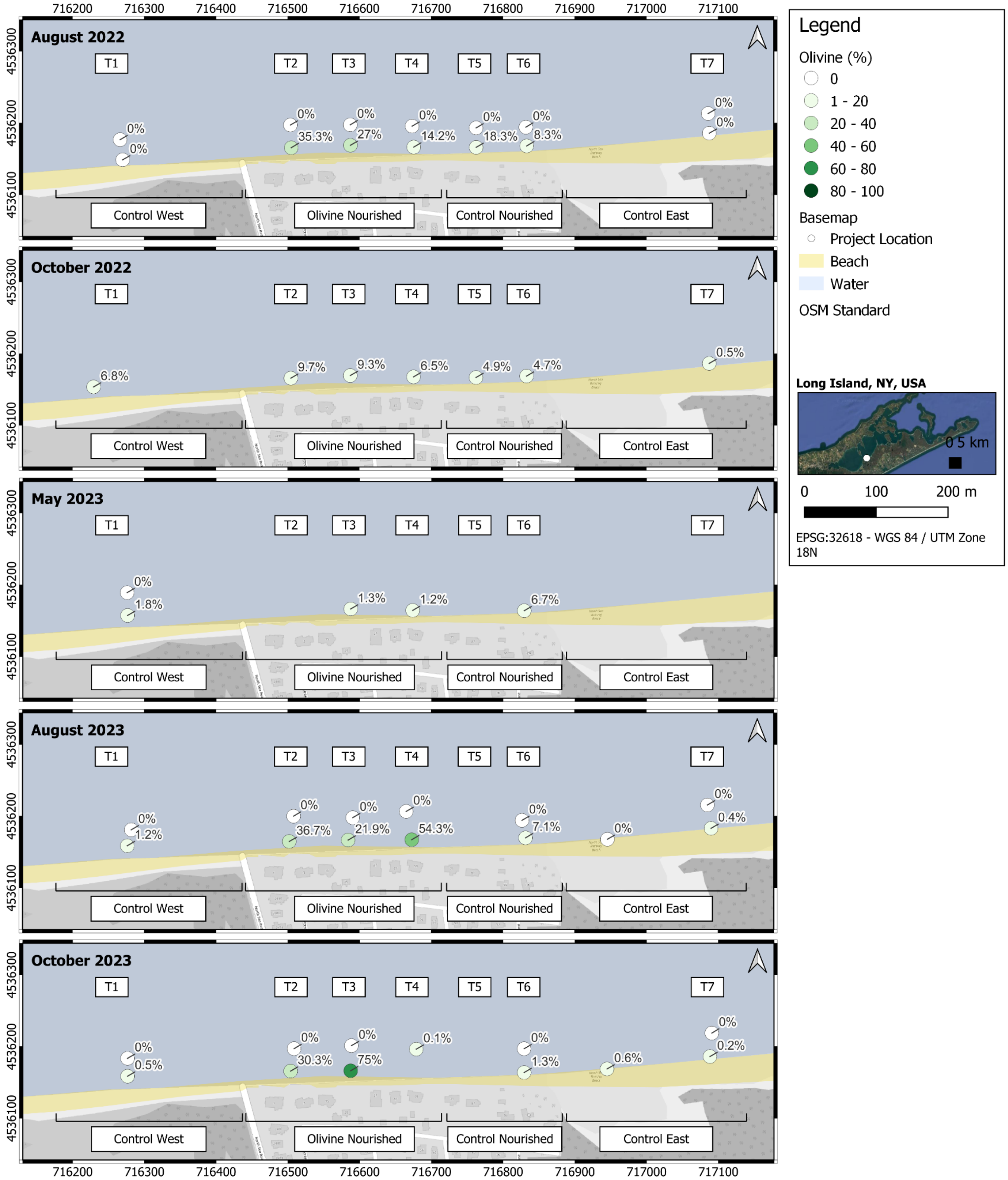

Figure S2 Olivine percent in the 3-5 cm sediment layer.

Table S1 Results of the GLMM for macrobenthos univariate characteristics among three Treatments, two Times, and their interaction. P values provided, with significant tests marked with bold font and an asterisk * showing significance at p<0.05, ** significance at p<0.01, and *** significance at p<0.001. Only significant results for pair-wise tests are provided.

		Shoreface		Offshore40		Offshore100		Offshore160	
		Abundance							
	df	chisq	p	chisq	p	chisq	p	chisq	p
Treatment	2	7.75	**0.021***	0.52	0.770	0.97	0.616	1.49	0.475
Time	1	9.43	**0.002***	0.04	0.839	0.02	0.879	0.06	0.800
Treatment X Time	2	16.40	**0.000*****	0.26	0.879	0.38	0.827	3.84	0.146
Pair wise		Before - Control East ≠ Control Nourished, Olivine Nourished After - Control East ≠ Olivine Nourished Control East before ≠ Control East after							
		Species richness (S)							
Treatment	2	0.41	0.819	2.825	0.244	0.50	0.777	0.68	0.711
Time	1	6.68	**0.010***	5.10	**0.024***	0.67	0.413	0.04	0.839
Treatment X Time	2	3.55	0.169	2.20	0.333	0.58	0.749	0.98	0.613
		Shannon diversity (H)							
Treatment	2	0.18	0.916	1.36	0.506	0.92	0.630	0.69	0.707

Time	1	1.23	0.268	0.20	0.655	0.007	0.931	0.01	0.922
Treatment X Time	2	3.35	0.187	1.33	0.515	0.60	0.745	0.52	0.771
		Pielou eveness (J)							
Treatment	2	0.18	0.916	1.36	0.506	0.92	0.630	0.69	0.707
Time	1	1.23	0.268	0.20	0.655	0.01	0.931	0.01	0.922
Treatment X Time	2	3.35	0.187	1.33	0.515	0.59	0.745	0.52	0.771
		Percent gravel							
Treatment	2	3.07	0.216	13.15	**0.001 ****	3.72	0.155	2.69	0.261
Time	1	0.43	0.510	0.26	0.611	2.77	0.096	0.03	0.875
Treatment X Time	2	0.19	0.905	0.13	0.936	7.18	**0.028***	0.37	0.830
				Olivine Nourished ≠ Control East		Before - Control East ≠ Olivine Nourished			

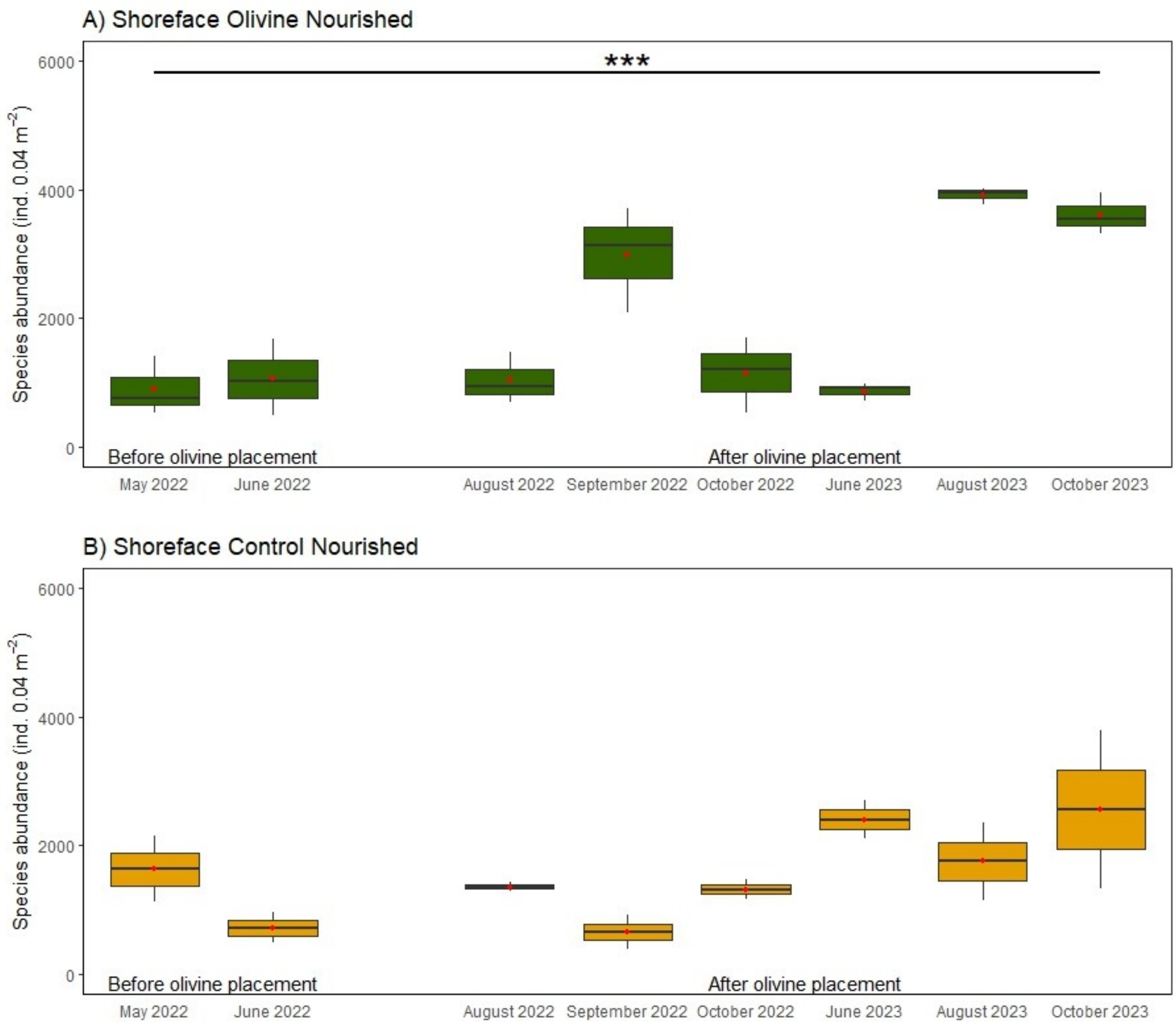

Figure S3 Macrobenthos abundance (indv. 0.04m^2) at A) Shoreface station, Olivine Nourished treatment, B) Shoreface station, Control Nourished; presented for each month to detect the time of species recovery. The asterisk *** indicates significant ANOVA results for the Season factor at $p<0.001$.

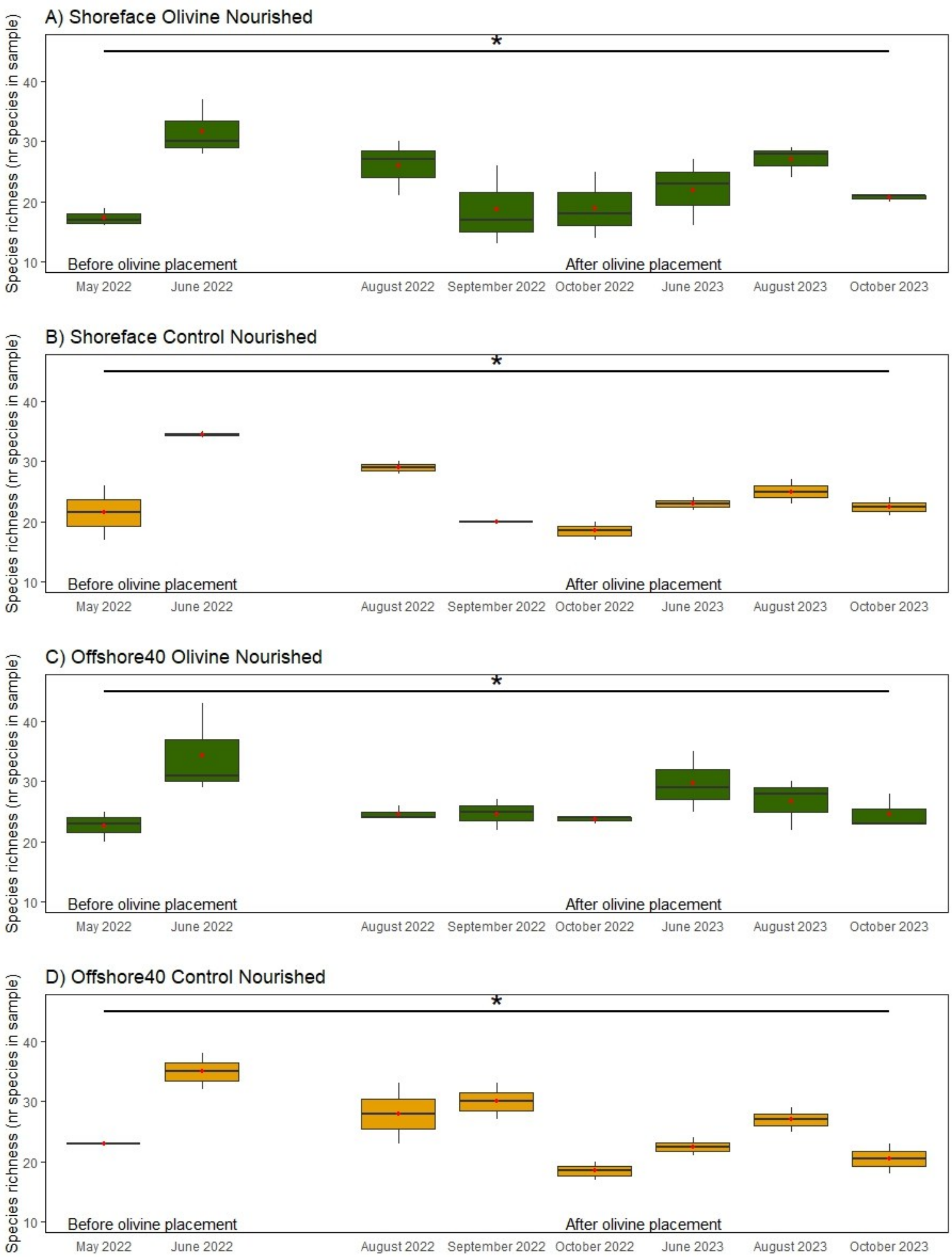

Figure S4 Species richness (number of species per sample) at A) Shoreface station, Olivine Nourished treatment, B) Shoreface station, Control Nourished, C) Offshore40 station, Olivine Nourished treatment, D) Offshore40 station, Control Nourished; presented for each month to detect the time of species recovery. The asterisk * indicates significant ANOVA results for the Season factor at $p<0.05$.

Table S2 Results of one-way ANOVA (factor - Month) for abundance and species richness tested only at the Olivine Nourished and Control Nourished treatment to detect the recolonization time. P values provided, with significant tests marked with bold font and an asterisk * showing significance at p<0.05, and *** significance at p<0.001. Only significant results for pair-wise tests are provided.

		Abundance		Species richness			
		Shoreface Olivine Nourished		Shoreface Olivine Nourished		Offshore40 Olivine Nourished	
	df	F value	p	F value	p	F value	p
Month	7	22.26	**4.05e-07 *** **	3.725	**0.0139 ***	2.91	**0.0364 ***
Pair wise		May22 ≠ September22, August23, October 23; June 22 ≠ September22, August23, October23		June22 ≠ May22, September22, October22		June22 ≠ May22	
		Shoreface Control Nourished		Shoreface Control Nourished		Offshore40 Control Nourished	
Month	7	1.612	0.259	4.198	**0.031***	4.121	**0.033***
Pair wise		-		June22 ≠ September22		June22 ≠ October22	

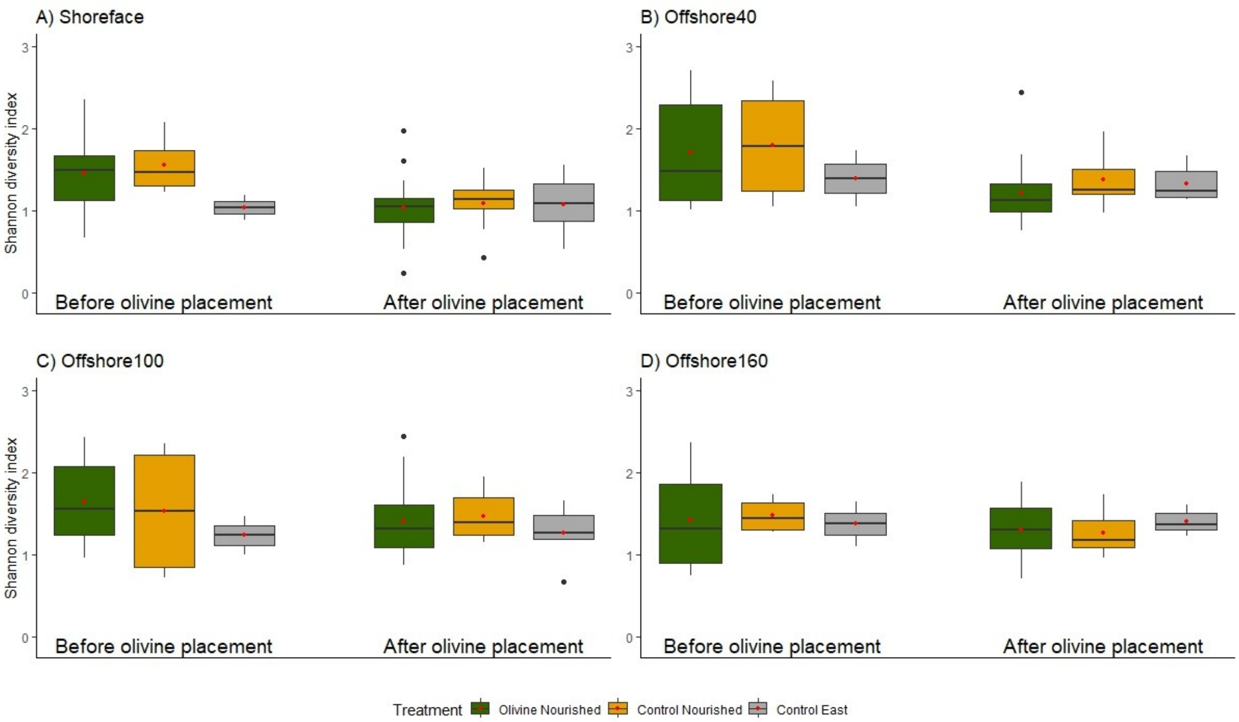

Figure. S5 Shannon diversity at three treatments, before and after olivine deployment at A) shoreface, B) offshore40, C) offshore100, and D) offshore160 stations. Mean (red dot), median (horizontal line), 25th and 75th percentile (box), minimum and maximum value (vertical line), and outliers (black dot) are presented.

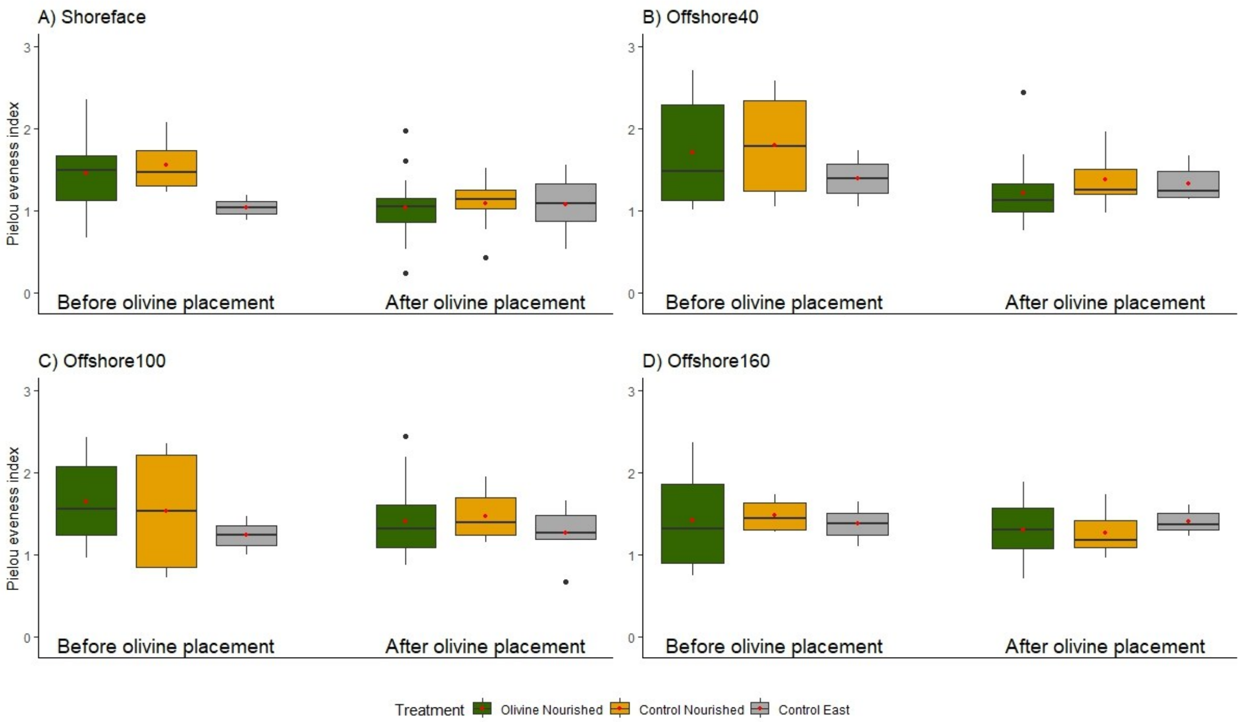

Figure. S6 Pielou eveness at three treatments, before and after olivine deployment at A) shoreface, B) offshore40, C) offshore100, and D) offshore160 stations. Mean (red dot), median (horizontal line), 25th and 75th percentile (box), minimum and maximum value (vertical line), and outliers (black dot) are presented.

Table S3 BACI Interactions summary. All analyses compared the interactions among the treatments listed as whole plots and before/after olivine placement as split plots (i.e., Before*Control East, After*Control East, Before*Olivine Nourished, After*Olivine Nourished, Before*Control Nourished, After*Control Nourished). Season effects (Spring, Summer, Fall) were removed prior to analysis. Eigenvalues are the amount of community variance explained. F and p values are permutation test results. Multiple comparisons used Bonferroni corrected error rate (0.05/3). Abbreviations: CE- Control East, OlN - Olivine Nourished, CN- Control Nourished.

	Whole Plots Included	**Eigenvalue**	**F**	**p**
Shoreface	Full (CE, OlN, CN)	0.171	2.082	**<0.001**
	Multiple Comparisons			
	CE, OlN	0.192	2.624	**0.002**
	OlN, CN	0.092	1.456	**0.014**
	CE, CN	0.205	2.139	0.049
Offshore40	Full (CE, OlN, CN)	0.178	2.31	**0.002**
	Multiple Comparisons			
	CE, OlN	0.138	1.831	0.136
	OlN, CN	0.148	2.634	**0.002**
	CE, CN	0.237	2.700	**<0.001**
Offshore100	Full (CE, OlN, CN)	0.179	2.566	**<0.001**
	Multiple Comparisons			
	CE, OlN	0.179	2.664	**0.002**
	OlN, CN	0.13	2.585	**<0.001**
	CE, CN	0.203	2.437	**0.009**
Offshore160	Full (CE, OlN, CN)	0.129	1.728	**0.025**
	Multiple Comparisons			
	CE, OlN	0.134	1.917	**0.009**
	OlN, CN	0.103	1.911	0.094
	CE, CN	0.143	1.588	**0.013**

Table S4 Fraction of variance explained by season, before/after olivine placement and Control East/Olivine Nourished/Control Nourished interactions, and continuous environmental variables. Each component in the RDA analysis was added stepwise. Continuous environmental variables were selected based on Bonferroni corrected family error rate (0.05/4).

	Season	**Interaction**	**Env. Var.**	**Sum**
Shoreface	0.170	0.171	0.056	0.397
Offshore40	0.205	0.178	0.170	0.553
Offshore100	0.262	0.179	0	0.441
Offshore160	0.274	0.129	0.042	0.445

Table S5 Forward selection RDA summary after removing the effects of season and treatment interactions. Eigenvalues are the amount of community variance explained. F and p values are permutation test results. Selection used Bonferroni corrected error rate (0.05/).

		Eigenvalue	**F**	**p**
Shoreface	% gravel	0.056	3.628	**<0.001**
	% olivine	0.029	1.890	0.038
Offshore40	Water Depth	0.139	11.302	**<0.001**
	Penetration Depth	0.031	2.609	**0.011**
	% gravel	0.014	1.210	0.248
Offshore100	Penetration Depth	0.026	1.931	0.051
Offshore160	Water Depth	0.042	2.936	**0.002**
	Penetration Depth	0.028	2.008	0.019

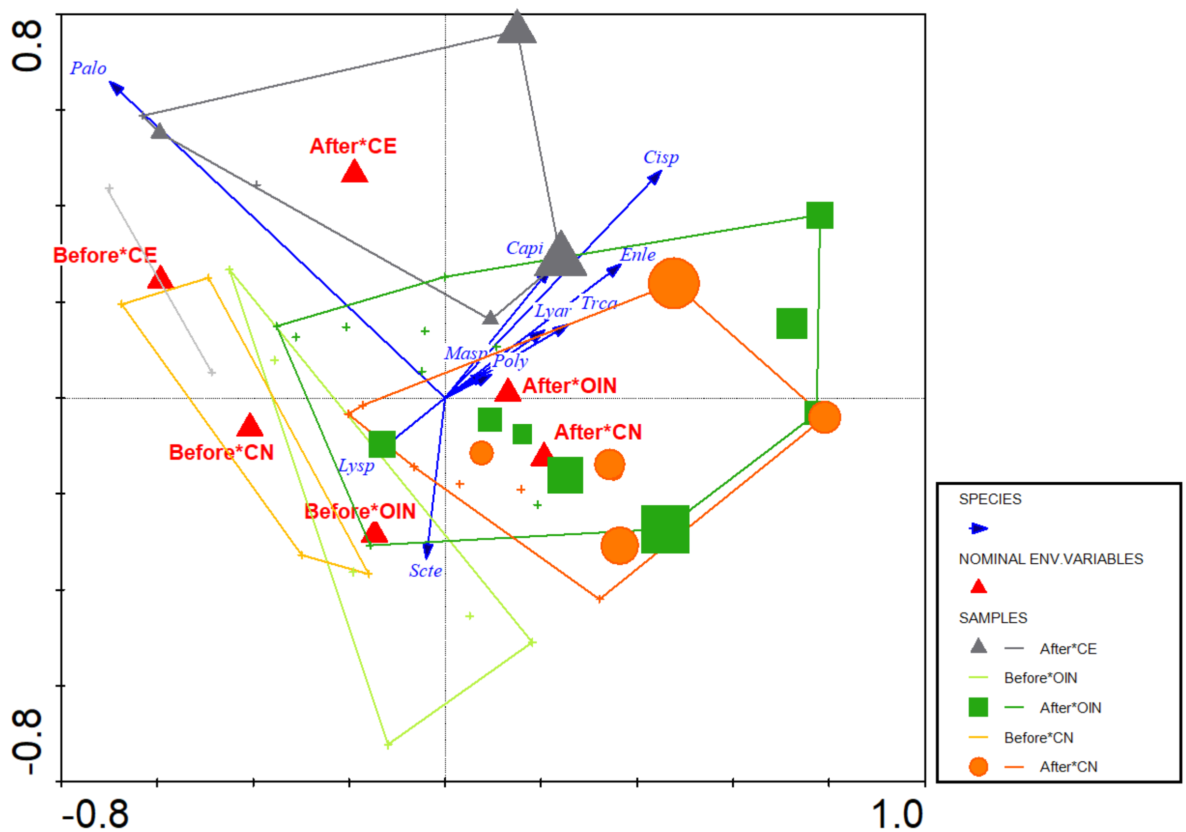

Figure S7.1. Hellinger transformed abundance of opportunistic polychaete Capitella spp. (Capi) in the offshore100 superimposed on the results of the RDA analysis.

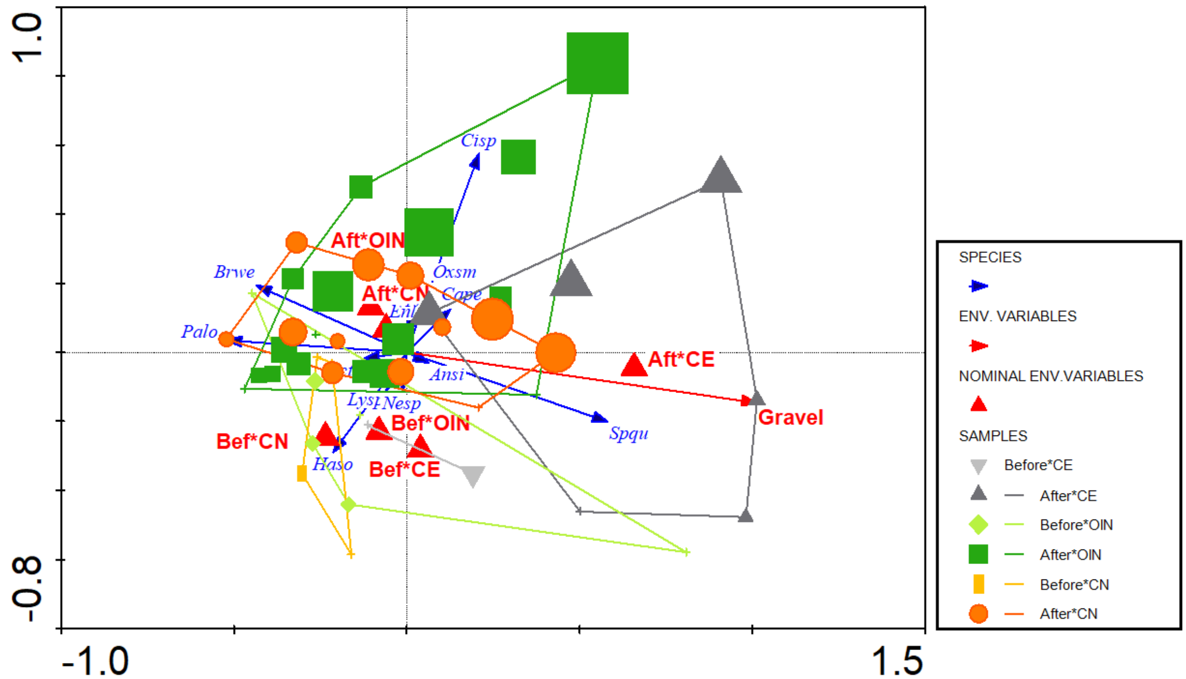

Figure S7.2 Hellinger transformed abundance of cirratulid polychaetes (*Tharyx acutus* and *Kirkegaardia baptisteae*) (Cisp) in the shoreface superimposed on the results of the RDA analysis.

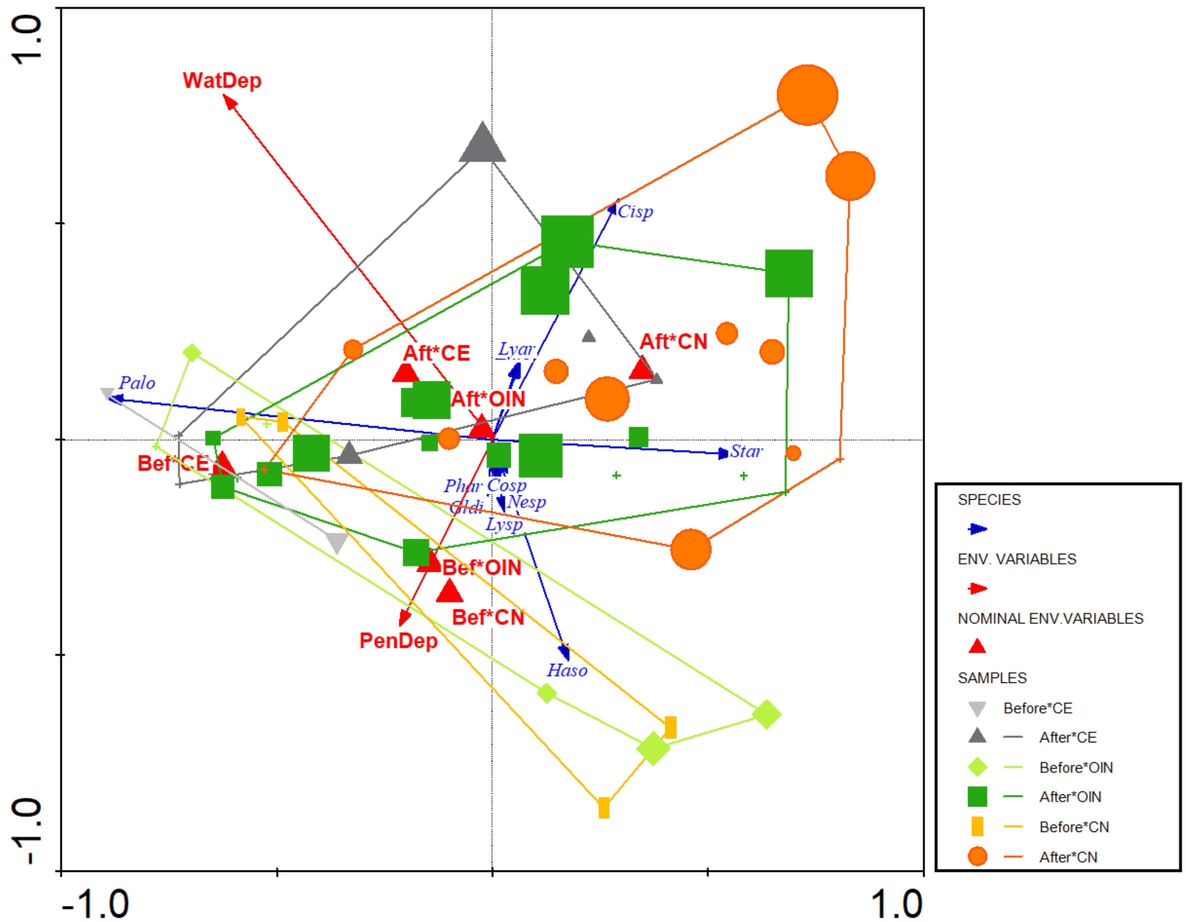

Figure S7.3 Hellinger transformed abundance of cirratulid polychaetes (*Tharyx acutus and Kirkegaardia baptisteae*) (Cisp) in the offshore40 superimposed on the results of the RDA analysis.

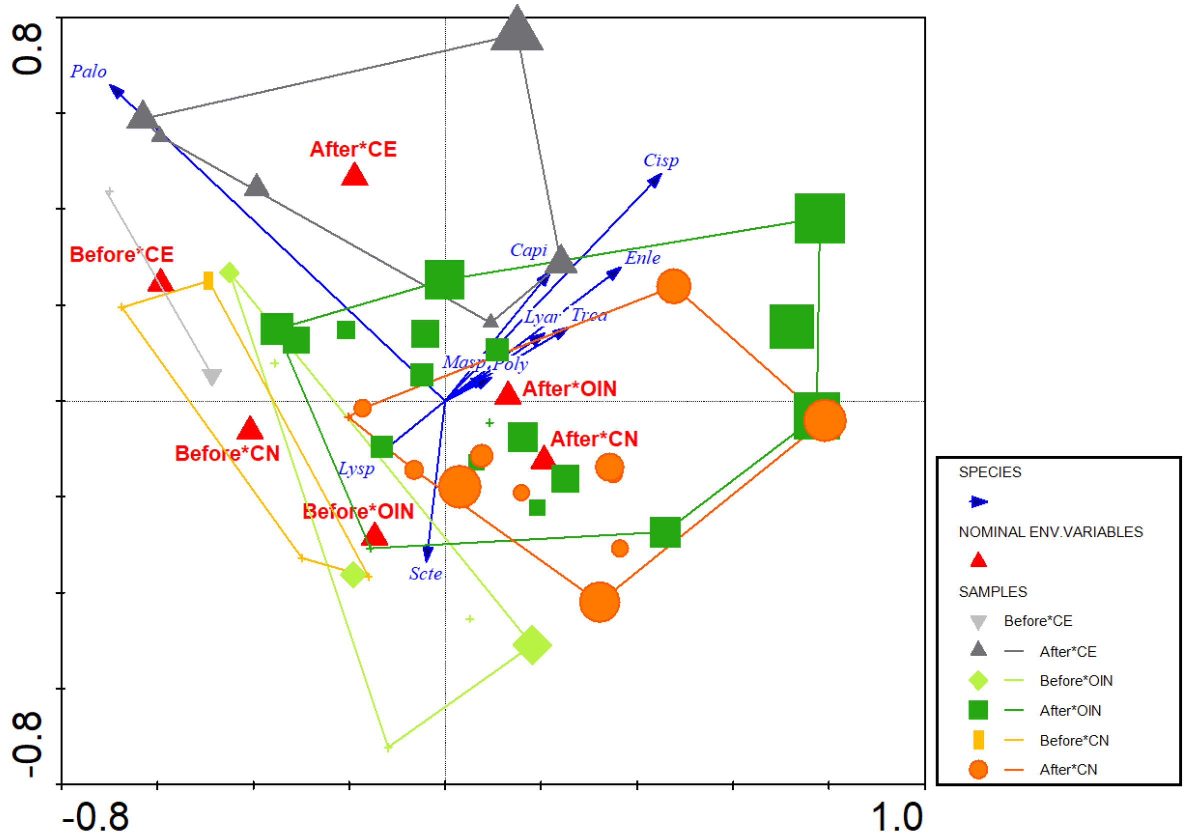

Figure S74. Hellinger transformed abundance of cirratulid polychaetes (*Tharyx acutus and Kirkegaardia baptisteae*) (Cisp) in the offshore100 superimposed on the results of the RDA analysis.

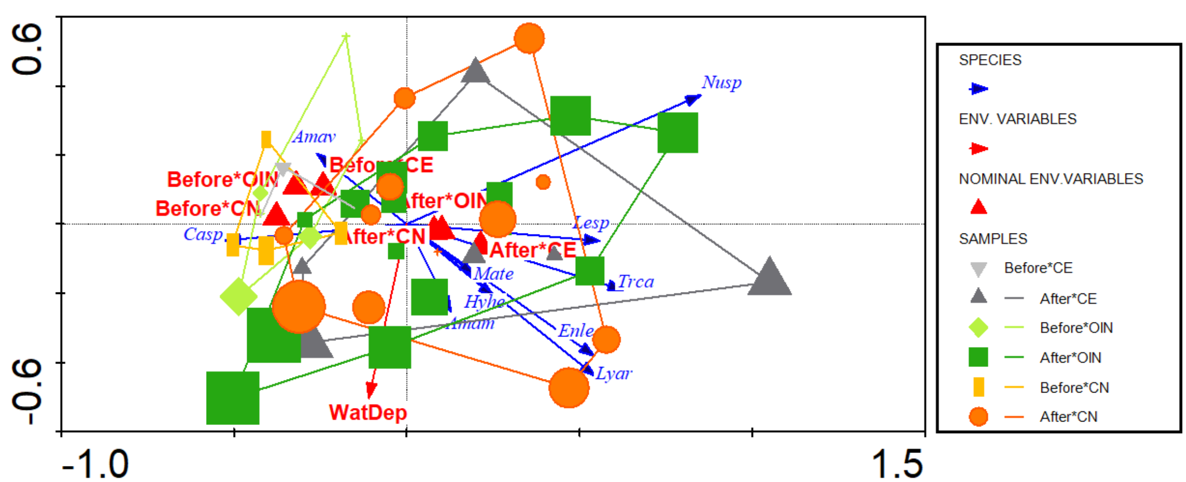

Figure S7.5 Hellinger transformed abundance of cirratulid polychaetes (*Tharyx acutus and Kirkegaardia baptisteae*) (Cisp) in the offshore160 superimposed on the results of the RDA analysis.

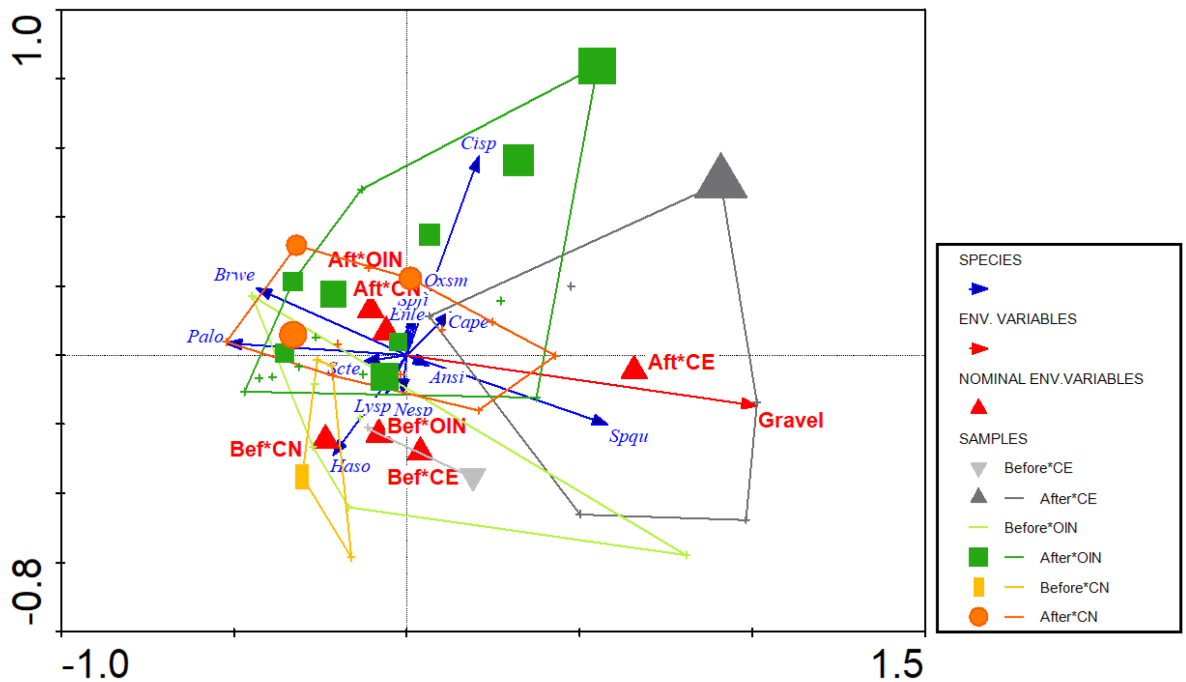

Figure S7.6. Hellinger transformed abundance of the cumacean *Oxyurostylis smithi* (Oxsm) in the shoreface superimposed on the results of the RDA analysis.

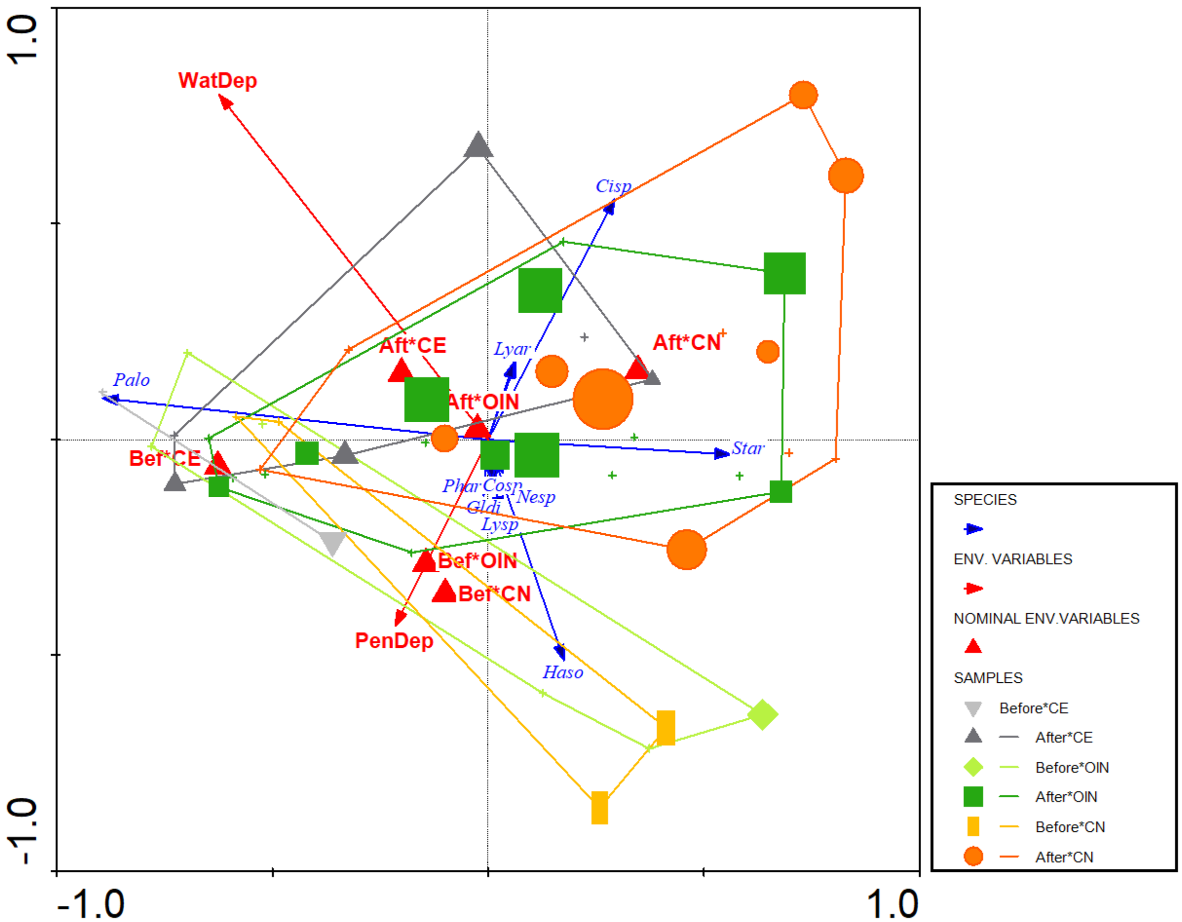

Figure S7.7 Hellinger transformed abundance of the cumacean *Oxyurostylis smithi* (Oxsm) in the offshore40 superimposed on the results of the RDA analysis.

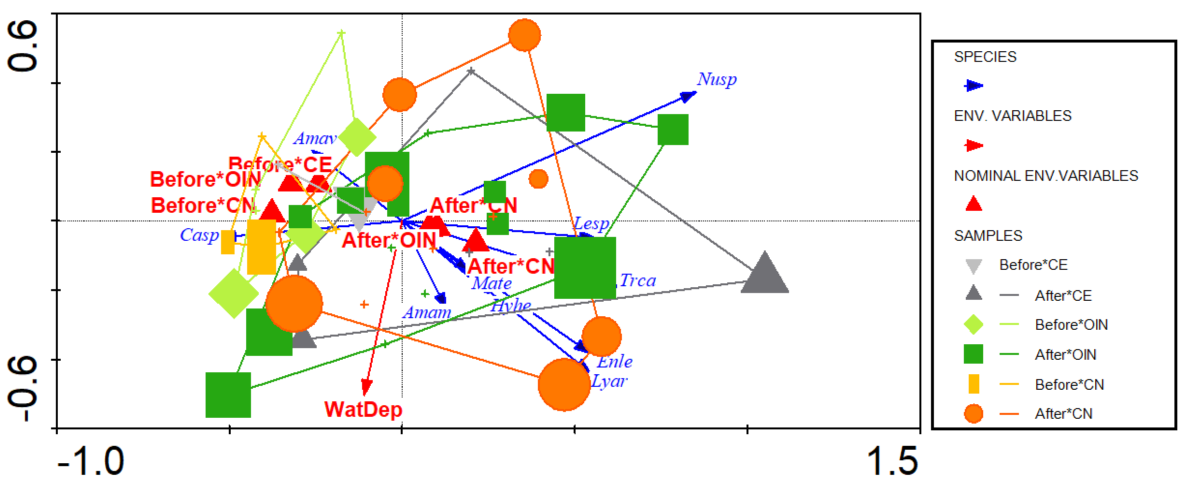

Figure S7.8 Hellinger transformed abundance of the cumacean *Oxyurostylis smithi* (Oxsm) in the offshore160 superimposed on the results of the RDA analysis.

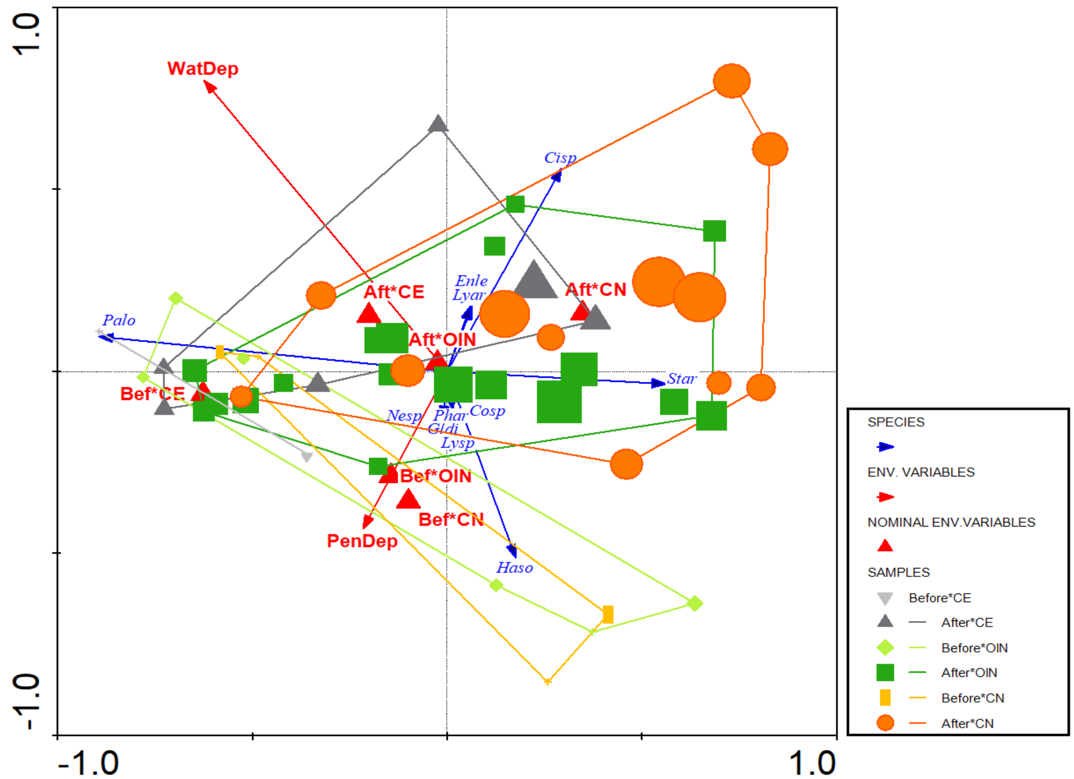

Figure S7.9 Hellinger transformed abundance of the bivalve G*emma gemma* (Gege) in the offshore40 superimposed on the results of the RDA analysis.

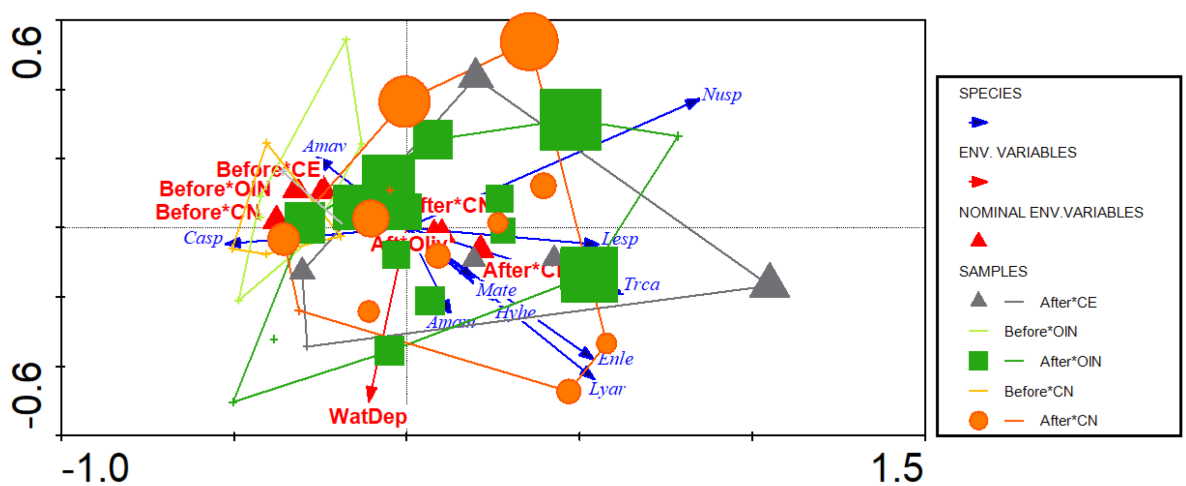

Figure S7.10 Hellinger transformed abundance of the bivalve *Nucula* spp (Nusp) in the offshore160 superimposed on the results of the RDA analysis.

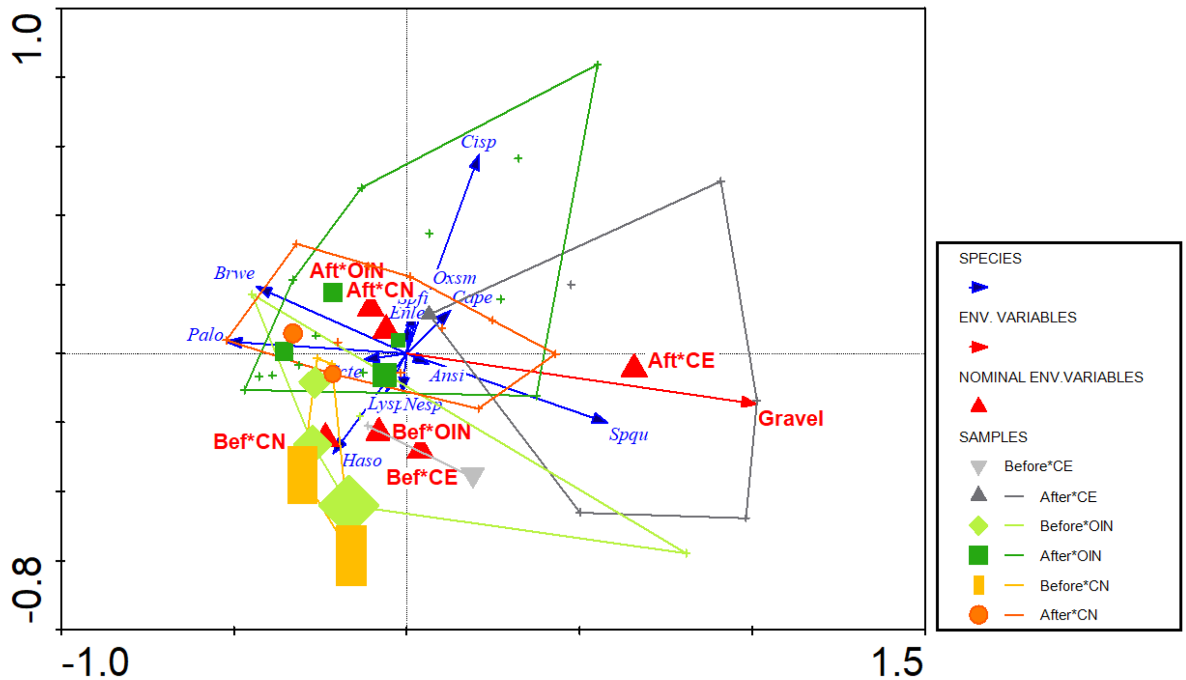

Figure S7.11 Hellinger transformed abundance of the gastropod *Haminella solitaria* (Haso) in the shoreface superimposed on the results of the RDA analysis.

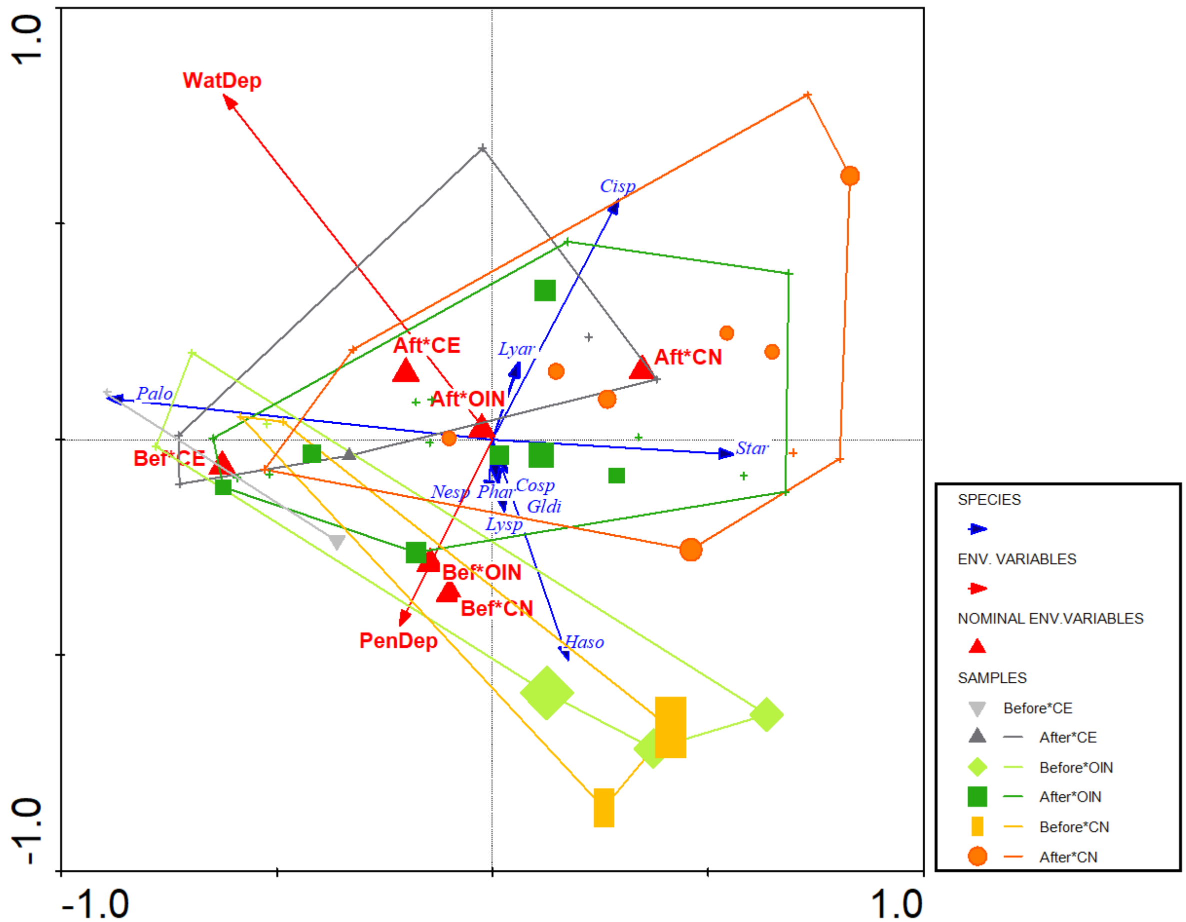

Figure S7.12 Hellinger transformed abundance of the gastropod *Haminella solitaria* (Haso) in the offshore40 superimposed on the results of the RDA analysis.

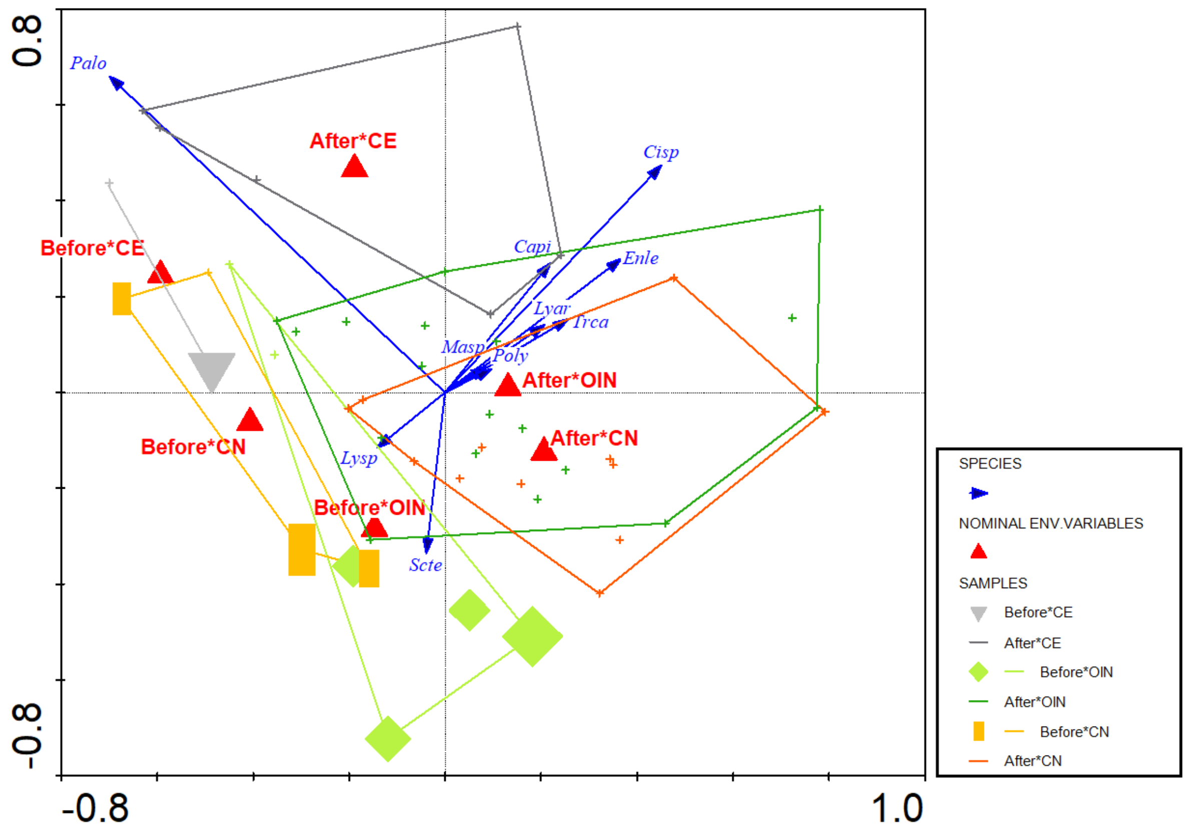

Figure S7.13 Hellinger transformed abundance of bivalve *Lyonsia spp* (Lysp) in the offshore100 superimposed on the results of the RDA analysis.

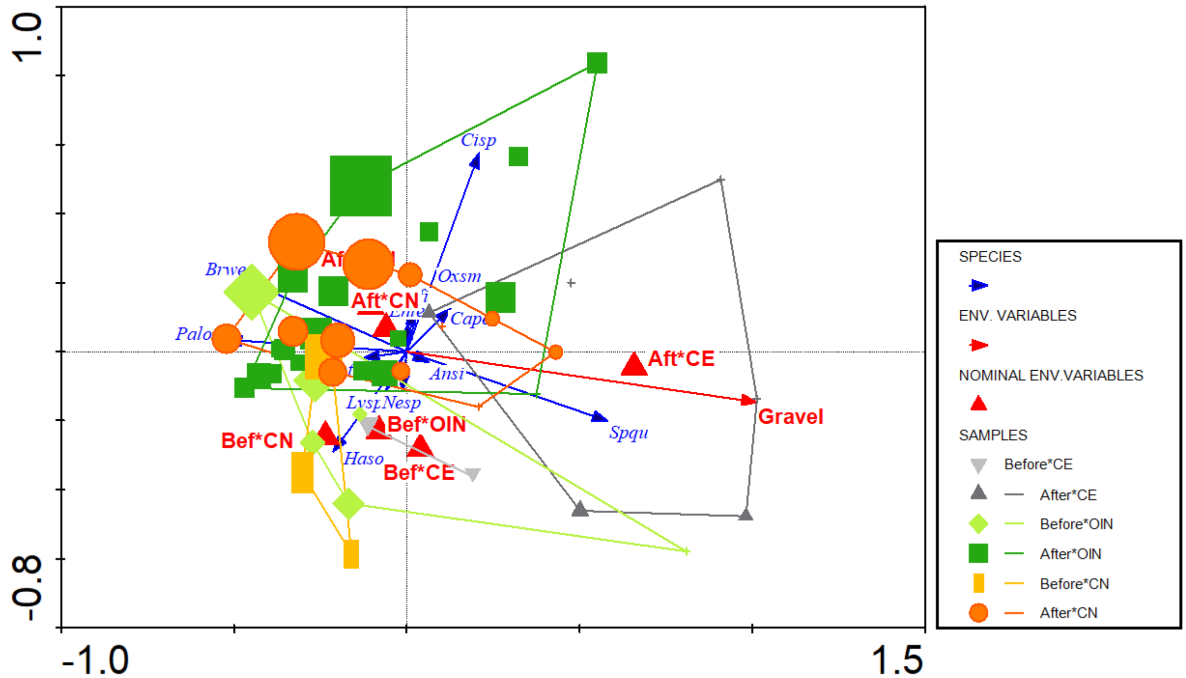

Figure S7.14 Hellinger transformed abundance of the polychaete Brania wellfleetensis (Brwe) in the shoreface superimposed on the results of the RDA analysis.

Table S6.1 Indicator species results for intertidal treatment groups. Plus signs (+) identify the group. Green cells delineate positive indicators for After*Olivine Nourished, After*Control Nourished, or After*(Olivine Nourished + Control Nourished). Red cells identify negative indicators for those treatment groups. The p-value is the significance level of the indicator value. Group index tabulates different treatment groups. NAs are values not possible to estimate either because they were present in all treatment groups or totally absent.

Intertidal	**Before*Control East**	**Before*Olivine Nourished**	**Before* Control Nourished**	**After* Control East**	**After* Olivine Nourished**	**After* Control Nourished**	**Group index**	**√IndVal.g**	**p-value**
Pisa				+			1	0.694	0.008
Ansi				+			1	0.488	0.335
Pego				+			1	0.408	0.374
Nasp				+			1	0.350	0.839
Pagu				+			1	0.335	0.905
Arca					+		2	0.333	0.713
Iltr					+		2	0.333	0.714
Masp					+		2	0.236	1.000
Boim						+	3	0.289	0.624
Hapr						+	3	0.289	0.624
Casp	+						4	0.758	0.016
Grsp	+						4	0.720	0.032
Stbe	+						4	0.707	0.041
Spbo	+						4	0.622	0.070
Exdi	+						4	0.651	0.102
Spfi	+						4	0.461	0.458
Gldi			+				6	0.707	0.006
Amav			+				6	0.600	0.075
Stbo			+				6	0.500	0.124
Cosp	+			+			9	0.504	0.397
Sphy			+	+			11	0.710	0.035
Elle			+	+			11	0.450	0.756
Gyvi					+	+	12	0.483	0.446
Lyar					+	+	12	0.365	0.790
Tasp					+	+	12	0.365	0.800
Capu					+	+	12	0.258	1.000
Enle					+	+	12	0.258	1.000
Trca					+	+	12	0.258	1.000
Cave		+			+		14	0.497	0.422
Hyla		+			+		14	0.409	0.751
Ammv		+				+	17	0.333	0.807

Glam	+		+				20	0.666	0.013
Paca	+		+				20	0.740	0.016
Clzo	+		+				20	0.544	0.139
Phar	+		+				20	0.491	0.342
Nupr		+	+				21	0.572	0.086
Posp		+	+				21	0.447	0.223
Idba		+	+				21	0.390	0.726
Glsp				+	+	+	22	0.745	0.032
Prhe				+	+	+	22	0.726	0.040
Acca				+	+	+	22	0.471	0.658
Poly				+	+	+	22	0.441	0.761
Xasp				+	+	+	22	0.333	0.984
Cela	+		+	+			30	0.641	0.302
Chco	+	+	+				41	0.813	0.004
Eusa	+	+	+				41	0.786	0.006
Misc	+	+	+				41	0.839	0.008
Rhep	+	+	+				41	0.754	0.012
Nesp	+	+	+				41	0.764	0.015
Lysp	+	+	+				41	0.707	0.019
Haso	+	+	+				41	0.679	0.072
Mosp	+	+	+				41	0.630	0.083
Acsp	+	+	+				41	0.632	0.096
Sylo	+	+	+				41	0.756	0.227
Stsp	+	+	+				41	0.525	0.337
Cisp	+			+	+	+	42	0.874	0.035
Capi	+			+	+	+	42	0.707	0.099
Pojo	+		+	+	+		46	0.793	0.295
Crsp	+	+	+	+			51	0.739	0.058
Cape	+	+	+	+			51	0.433	0.622
Runa	+	+	+	+			51	0.442	0.673
Amag	+	+	+		+		55	0.689	0.159
Glmu	+	+		+	+	+	57	0.500	0.840
Oxsm	+		+	+	+	+	58	0.577	0.591
Gege	+		+	+	+	+	58	0.707	0.651
Mira	+	+	+	+	+		60	0.639	0.749
Poex	+	+	+	+		+	61	0.845	0.004
Brwe	+	+	+		+	+	62	0.932	0.031
Scte	+	+	+		+	+	62	0.740	0.121
Hyhe	+	+	+		+	+	62	0.630	0.825

Lesp	+	+	+	+	+	+	63	0.979	NA
Lept	+	+	+	+	+	+	63	0.804	NA
Near	+	+	+	+	+	+	63	0.692	NA
Palo	+	+	+	+	+	+	63	0.990	NA
Spqu	+	+	+	+	+	+	63	0.968	NA
Star	+	+	+	+	+	+	63	0.764	NA
Amam	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mate	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nepi	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nusp	NA	NA	NA	NA	NA	NA	NA	NA	NA
Savu	NA	NA	NA	NA	NA	NA	NA	NA	NA
Spoc	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table S6.2 Indicator species results for inshore treatment groups. Plus signs (+) identify the group. Green cells delineate positive indicators for After*Olivine Nourished, After*Control Nourished, or After*(Olivine Nourished + Control Nourished). Red cells identify negative indicators for those treatment groups. The p-value is the significance level of the indicator value. Group index tabulates different treatment groups. NAs are values not possible to estimate either because they were present in all treatment groups or totally absent.

Inshore	**Before*Control East**	**Before*Olivine Nourished**	**Before* Control Nourished**	**After* Control East**	**After* Olivine Nourished**	**After* Control Nourished**	**Group index**	**vIndVal.g**	**p-value**
Nusp				+			1	0.581	0.082
Pego				+			1	0.408	0.375
Mate				+			1	0.326	0.808
Nasp					+		2	0.460	0.458
Trca					+		2	0.236	1.000
Savu						+	3	0.408	0.352
Idba						+	3	0.438	0.372
Poly						+	3	0.289	0.625
Pisa						+	3	0.289	0.626
Tasp						+	3	0.351	0.723
Xasp						+	3	0.265	0.903
Nepi	+						4	0.707	0.044
Stbo	+						4	0.633	0.070
Chco	+						4	0.584	0.075
Masp	+						4	0.555	0.133
Stbe	+						4	0.540	0.149

Cape	+						4	0.474	0.384
Gyvi	+						4	0.486	0.398
Amav		+					5	0.559	0.103
Glam		+					5	0.577	0.103
Clzo		+					5	0.577	0.105
Spbo		+					5	0.340	0.608
Hyla			+				6	0.500	0.124
Cosp			+				6	0.550	0.149
Ammv				+	+		7	0.491	0.460
Boim				+	+		7	0.408	0.525
Arca				+	+		7	0.354	0.700
Enle				+		+	8	0.384	0.769
Amam				+		+	8	0.333	0.807
Ansi				+		+	8	0.300	0.950
Iltr					+	+	12	0.516	0.328
Poex	+	+					19	0.710	0.039
Hapr	+	+					19	0.617	0.080
Cave	+	+					19	0.666	0.092
Paca	+		+				20	0.751	0.006
Elle	+		+				20	0.420	0.710
Casp	+		+				20	0.514	0.820
Lysp		+	+				21	0.775	0.013
Posp		+	+				21	0.622	0.038
Prhe				+	+	+	22	0.872	0.001
Glsp				+	+	+	22	0.816	0.004
Lyar				+	+	+	22	0.373	0.923
Misc	+	+	+				41	0.840	0.0003
Gldi	+	+	+				41	0.816	0.006
Eusa	+	+	+				41	0.781	0.007
Acsp	+	+	+				41	0.779	0.010
Nesp	+	+	+				41	0.707	0.019
Phar	+	+	+				41	0.627	0.044
Sylo	+	+	+				41	0.625	0.044
Grsp	+	+	+				41	0.549	0.186
Mira	+	+	+				41	0.690	0.189
Mosp	+	+	+				41	0.577	0.284
Star		+		+	+	+	43	0.942	0.025
Capu		+		+	+	+	43	0.378	0.987
Spqu			+	+	+	+	44	0.766	0.082

Capi			+	+	+	+	44	0.676	0.342
Sphy			+	+	+	+	44	0.612	0.362
Runa	+	+		+		+	48	0.555	0.430
Nupr	+	+	+	+			51	0.490	0.339
Stsp	+		+		+	+	53	0.629	0.542
Crsp	+	+	+		+		55	0.792	0.020
Haso	+	+	+			+	56	0.706	0.252
Cela	+	+	+			+	56	0.586	0.577
Acca	+		+	+	+	+	58	0.787	0.052
Hyhe	+		+	+	+	+	58	0.765	0.361
Glmu	+		+	+	+	+	58	0.714	0.541
Oxsm	+		+	+	+	+	58	0.704	0.560
Near		+	+	+	+	+	59	0.707	0.544
Exdi	+	+	+	+	+		60	0.578	0.487
Scte	+	+	+		+	+	62	0.922	0.038
Rhep	+	+	+		+	+	62	0.915	0.053
Lept	+	+	+		+	+	62	0.769	0.414
Pojo	+	+	+	+	+	+	63	0.816	NA
Cisp	+	+	+	+	+	+	63	0.890	NA
Amag	+	+	+	+	+	+	63	0.924	NA
Gege	+	+	+	+	+	+	63	0.957	NA
Brwe	+	+	+	+	+	+	63	1.000	NA
Lesp	+	+	+	+	+	+	63	1.000	NA
Palo	+	+	+	+	+	+	63	1.000	NA
Pagu	NA	NA	NA	NA	NA	NA	NA	NA	NA
Spfi	NA	NA	NA	NA	NA	NA	NA	NA	NA
Spoc	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table S6.3 Indicator species results for midshore treatment groups. Plus signs (+) identify the group. Green cells delineate positive indicators for After*Olivine Nourished, After*Control Nourished, or After*(Olivine Nourished + Control Nourished). Red cells identify negative indicators for those treatment groups. The p-value is the significance level of the indicator value. Group index tabulates different treatment groups. NAs are values not possible to estimate either because they were present in all treatment groups or totally absent.

Midshore	**Before*Control East**	**Before*Olivine Nourished**	**Before* Control Nourished**	**After* Control East**	**After* Olivine Nourished**	**After* Control Nourished**	**Group index**	**√IndVal.g**	**p-value**
Xasp				+			1	0.516	0.191
Ansi				+			1	0.408	0.374
Spfi				+			1	0.408	0.375
Pagu				+			1	0.326	0.807
Spqu						+	3	0.458	0.340
Pisa						+	3	0.359	0.608
Grsp						+	3	0.289	0.626
Cape	+						4	0.707	0.042
Stbo	+						4	0.656	0.044
Clzo	+						4	0.630	0.070
Savu	+						4	0.561	0.082
Pego	+						4	0.570	0.116
Hapr	+						4	0.557	0.121
Spbo	+						4	0.520	0.171
Mate		+					5	0.472	0.342
Misc		+					5	0.361	0.450
Acsp			+				6	0.580	0.099
Cosp			+				6	0.500	0.125
Elle			+				6	0.463	0.147
Sylo			+				6	0.472	0.168
Spoc			+				6	0.432	0.259
Tasp				+	+		7	0.518	0.315
Iltr				+		+	8	0.527	0.185
Hyla				+		+	8	0.408	0.428
Poex	+			+			9	0.781	0.008
Exdi			+	+			11	0.608	0.274
Poly					+	+	12	0.365	0.792
Stbe					+	+	12	0.316	0.902
Boim					+	+	12	0.258	1.000
Casp	+	+					19	0.610	0.260

Cave	+		+				20	0.539	0.337
Nesp		+	+				21	0.775	0.011
Glam		+	+				21	0.632	0.032
Prhe				+	+	+	22	0.913	0.000
Nusp				+	+	+	22	0.882	0.000
Glsp				+	+	+	22	0.782	0.010
Capi				+	+	+	22	0.707	0.073
Lyar				+	+	+	22	0.527	0.456
Idba				+	+	+	22	0.500	0.552
Enle				+	+	+	22	0.441	0.762
Nepi				+	+	+	22	0.333	0.993
Amam		+		+	+		24	0.365	0.827
Arca		+		+		+	27	0.511	0.412
Masp			+	+		+	28	0.389	0.905
Paca		+	+	+			31	0.487	0.285
Posp		+			+	+	33	0.333	0.993
Eusa	+	+	+				41	0.892	0.000
Lysp	+	+	+				41	0.816	0.006
Nupr	+	+	+				41	0.767	0.009
Amav	+	+	+				41	0.764	0.015
Gldi	+	+	+				41	0.645	0.022
Mosp	+	+	+				41	0.669	0.053
Mira	+	+	+				41	0.685	0.127
Sphy	+			+	+	+	42	0.831	0.178
Crsp	+	+	+	+			51	0.662	0.075
Hyhe		+	+		+	+	54	0.698	0.320
Near		+	+		+	+	54	0.712	0.322
Phar	+	+	+			+	56	0.532	0.225
Haso	+	+	+			+	56	0.649	0.288
Stsp	+	+	+			+	56	0.568	0.639
Cisp	+	+		+	+	+	57	0.907	0.054
Glmu	+	+		+	+	+	57	0.739	0.182
Runa		+	+	+	+	+	59	0.626	0.744
Cela		+	+	+	+	+	59	0.532	0.925
Trca	+	+	+	+		+	61	0.813	0.243
Scte	+	+	+		+	+	62	0.957	0.001
Acca	+	+	+	+	+	+	63	0.957	NA
Amag	+	+	+	+	+	+	63	0.990	NA
Ammv	+	+	+	+	+	+	63	0.629	NA

Brwe	+	+	+	+	+	+	63	0.979	NA
Capu	+	+	+	+	+	+	63	0.677	NA
Gege	+	+	+	+	+	+	63	0.979	NA
Gyvi	+	+	+	+	+	+	63	0.479	NA
Lesp	+	+	+	+	+	+	63	0.901	NA
Lept	+	+	+	+	+	+	63	0.804	NA
Oxsm	+	+	+	+	+	+	63	0.736	NA
Palo	+	+	+	+	+	+	63	1.000	NA
Pojo	+	+	+	+	+	+	63	0.645	NA
Rhep	+	+	+	+	+	+	63	0.968	NA
Star	+	+	+	+	+	+	63	0.968	NA
Chco	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nasp	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table S6.4 Indicator species results for offshore treatment groups. Plus signs (+) identify the group. Green cells delineate positive indicators for After*Olivine Nourished, After*Control Nourished, or After*(Olivine Nourished + Control Nourished). Red cells identify negative indicators for those treatment groups. The p-value is the significance level of the indicator value. Group index tabulates different treatment groups. NAs are values not possible to estimate either because they were present in all treatment groups or totally absent.

Offshore	**Before*Control East**	**Before*Olivine Nourished**	**Before* Control Nourished**	**After* Control East**	**After* Olivine Nourished**	**After* Control Nourished**	**Group index**	**√IndVal.g**	**p-value**
Paca				+			1	0.511	0.178
Pego					+		2	0.333	0.711
Ansi					+		2	0.333	0.714
Poly					+		2	0.333	0.810
Hyla					+		2	0.236	1.000
Misc					+		2	0.236	1.000
Xasp					+		2	0.236	1.000
Clzo	+						4	0.778	0.011
Gldi	+						4	0.785	0.011
Grsp		+					5	0.525	0.164
Acsp		+					5	0.345	0.513
Nesp			+				6	0.707	0.006
Spoc			+				6	0.594	0.072
Elle				+	+		7	0.354	0.721
Savu		+		+			10	0.478	0.257

Pisa					+	+	12	0.365	0.790
Boim					+	+	12	0.316	0.903
Spqu					+	+	12	0.258	1.000
Spbo	+		+				20	0.799	0.009
Hapr	+		+				20	0.510	0.212
Cave		+	+				21	0.703	0.035
Glam		+	+				21	0.632	0.043
Stbo		+	+				21	0.656	0.052
Cape		+	+				21	0.447	0.209
Cosp		+	+				21	0.447	0.211
Stbe		+	+				21	0.489	0.340
Masp		+	+				21	0.522	0.457
Nusp				+	+	+	22	0.898	0.000
Glsp				+	+	+	22	0.782	0.011
Capi				+	+	+	22	0.553	0.372
Idba				+	+	+	22	0.527	0.438
Mira				+	+	+	22	0.527	0.450
Amam				+	+	+	22	0.500	0.555
Lyar				+	+	+	22	0.441	0.757
Iltr				+	+	+	22	0.408	0.833
Tasp				+	+	+	22	0.408	0.845
Enle		+	+	+			31	0.620	0.290
Stsp		+	+	+			31	0.634	0.402
Posp		+	+	+			31	0.420	0.409
Runa		+			+	+	33	0.716	0.107
Exdi		+	+		+		37	0.652	0.442
Casp	+	+	+				41	0.878	0.000
Eusa	+	+	+				41	0.871	0.000
Nupr	+	+	+				41	0.857	0.000
Amav	+	+	+				41	0.866	0.001
Lysp	+	+	+				41	0.800	0.002
Sylo	+	+	+				41	0.645	0.022
Crsp	+	+	+				41	0.723	0.028
Haso	+	+	+				41	0.574	0.403
Lesp	+			+	+	+	42	0.861	0.037
Near	+			+	+	+	42	0.689	0.245
Trca	+			+	+	+	42	0.717	0.536
Prhe		+		+	+	+	43	0.926	0.000
Sphy		+		+	+	+	43	0.906	0.009

Mate		+		+	+	+	43	0.408	0.961
Hyhe			+	+	+	+	44	0.595	0.631
Gyvi		+	+		+	+	54	0.570	0.469
Arca		+	+		+	+	54	0.474	0.761
Mosp	+	+	+			+	56	0.604	0.119
Phar	+	+	+			+	56	0.568	0.355
Glmu	+	+		+	+	+	57	0.821	0.247
Capu		+	+	+	+	+	59	0.921	0.038
Nepi		+	+	+	+	+	59	0.442	0.995
Cela	+	+	+	+		+	61	0.605	0.387
Acca	+	+	+	+	+	+	63	1.000	NA
Amag	+	+	+	+	+	+	63	0.990	NA
Ammv	+	+	+	+	+	+	63	0.791	NA
Brwe	+	+	+	+	+	+	63	0.990	NA
Cisp	+	+	+	+	+	+	63	0.924	NA
Gege	+	+	+	+	+	+	63	0.990	NA
Lept	+	+	+	+	+	+	63	0.816	NA
Oxsm	+	+	+	+	+	+	63	0.764	NA
Palo	+	+	+	+	+	+	63	1.000	NA
Poex	+	+	+	+	+	+	63	0.791	NA
Pojo	+	+	+	+	+	+	63	0.750	NA
Rhep	+	+	+	+	+	+	63	0.935	NA
Scte	+	+	+	+	+	+	63	0.935	NA
Star	+	+	+	+	+	+	63	0.777	NA
Chco	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nasp	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pagu	NA	NA	NA	NA	NA	NA	NA	NA	NA
Spfi	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table S7 Taxa List and Taxa Abbreviation Codes

Taxa	**Taxonomic Group**	**Code**
Acanthohaustorius spp *(A. millsi, A. shoemakeri)*	Amphipoda	Acsp
Acteocina canaliculata	Gastropoda	Acca
Americhelidium americanum	Amphipoda	Amam
Ameritella agilis	Bivalvia	Amag
Ampelisca spp *(A. abdita, A. vadorum)*	Amphipoda	Amav
Ampelisca spp *(A. macrocephala, A. verrilli)*	Amphipoda	Ammv
Anomia simplex	Bivalvia	Ansi
Aricidea catherinae	Polychaeta	Arca
Boonea impressa	Gastropoda	Boim
Brania wellfleetensis	Polychaeta	Brwe
Caecum pulchellum	Gastropoda	Capu
Capitella spp	Polychaeta	Capi
Capitellidae spp juveniles (not *Capitella* spp)	Polychaeta	Casp
Caprella penantis	Amphipoda	Cape
Caulleriella venefica	Polychaeta	Cave
Cerebratulus lacteus	Heteronemertea	Cela
Chiridotea coeca	Isopoda	Chco
Cirratulidae spp (*Tharyx acutus,Kikegaardia baptisteae*)	Polychaeta	Cisp
Clymenella zonalis	Polychaeta	Clzo
Corophium spp	Amphipoda	Cosp
Crepidula spp (*not C. plana*)	Gastropoda	Crsp
Elasmopus levis	Amphipoda	Elle
Ensis leei	Bivalvia	Enle
Eumida sanguinea	Polychaeta	Eusa
Exogone dispar	Polychaeta	Exdi
Gemma gemma	Bivalvia	Gege
Glycera americana	Polychaeta	Glam
Glycera dibranchiata	Polychaeta	Gldi
Glycera spp (*G. americana, G. dibranchiata*)	Polychaeta	Glsp
Glycinde multidens	Polychaeta	Glmu
Grandidierella sp	Amphipoda	Grsp

Gyptis vittata	Polychaeta	Gyvi
Haloclava producta	Actiniaria	Hapr
Haminella solitaria	Gastropoda	Haso
Hypereteone heteropoda	Polychaeta	Hyhe
Hypereteone lactea	Polychaeta	Hyla
Idunella barnardi	Amphipoda	Idba
Ilyanassa trivittata	Gastropoda	Iltr
Leitoscoloplos spp	Polychaeta	Lesp
Leptosynapta spp	Holothuroidea	Lept
Lyonsia arenosa	Bivalvia	Lyar
Lyonsia spp (*L. arenosa, L. hyalina*)	Bivalvia	Lysp
Macoploma tenta	Bivalvia	Mate
Maldanidae spp	Polychaeta	Masp
Microphthalmus sczelkowii	Polychaeta	Misc
Microprotopus raneyi	Amphipoda	Mira
Monoculodes sp	Amphipoda	Mosp
Naticidae sp (juveniles)	Gastropoda	Nasp
Neanthes arenaceodentata	Polychaeta	Near
Nemertinea spp (Including juvenile *Cerebratulus lacteus*)	Nemertinea	Nesp
Nephtys picta	Polychaeta	Nepi
Nucula proxima	Bivalvia	Nupr
Nucula spp (*N. proxima, N. tenuis*)	Bivalvia	Nusp
Oxyurostylis smithi	Cumacea	Oxsm
Pagurus longicarpus	Decapoda	Pagu
Parapionosyllis longicirrata	Polychaeta	Palo
Parougia caeca	Polychaeta	Paca
Pectinaria gouldii	Polychaeta	Pego
Phyllodoce arenae	Polychaeta	Phar
Pinnixa sayana	Decapoda	Pisa
Polycirrus eximius	Polychaeta	Poex
Polydora spp	Polychaeta	Poly
Polydora spp (juvenile)	Polychaeta	Posp
Polygordius jouinae	Polychaeta	Pojo
Prionospio heterobranchia	Polychaeta	Prhe

Rhepoxynius epistomus	Amphipoda	Rhep
Rudilemboides naglei	Amphipoda	Runa
Sabellaria vulgaris	Polychaeta	Savu
Scoletoma tenuis	Polychaeta	Scte
Sphaeroma quadridentatum	Isopoda	Spqu
Sphaerosyllis hystrix	Polychaeta	Sphy
Spio filicornis	Polychaeta	Spfi
Spiochaetopterus oculatus	Polychaeta	Spoc
Spiophanes bombyx	Polychaeta	Spbo
Sthenelais boa	Polychaeta	Stbo
Streblospio benedicti	Polychaeta	Stbe
Streptosyllis arenae	Polychaeta	Star
Stylochus spp (*S. ellipticus, S. zebra*)	Polycladida	Stsp
Syllides longocirratus	Polychaeta	Sylo
Tagelus spp	Bivalvia	Tasp
Travisia carnea	Polychaeta	Trca
Xanthidae spp (juveniles)	Decapoda	Xasp

Table S8 Results of the GLMM for macrobenthos trace metals accumulation among three Treatments, two Times, and their interaction. P values provided, with significant tests marked with bold font and an asterisk * showing significance at $p<0.05$, ** significance at $p<0.01$, and *** significance at $p<0.001$. Only significant results for pair-wise tests are provided.

		shoreface		offshore		shoreface		offshore		shoreface		offshore	
		Ni				**Cr**				**Co**			
	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	1.44	0.49	3.59	0.17	4.35	0.11	0.89	0.64	0.63	0.73	7.14	**0.03***
Treatment	2	2.82	0.24	2.96	0.23	3.81	0.15	2.34	0.31	0.14	0.93	3.29	0.19
Time X Treatment	4	7.89	0.11	6.65	0.16	7.78	0.10	7.69	0.10	1.12	0.89	9.16	0.06
		-		-		-		-		-		Oct22 ≠ June2022, June2023	
		Hg				**Mn**				**Sr**			
	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	1.65	0.44	18.31	**0.00*****	20.91	**2.876e-05*** **	0.43	0.81	11.57	**0.003****	1.81	0.41
Treatment	2	1.41	0.49	1.54	0.46	1.67	0.43	1.72	0.42	0.003	1.00	0.34	0.85
Time X Treatment	4	No interaction due to lack of data for June 2022 for olivine treatment (below detection limits)		5.28	0.26	3.07	0.55	4.38	0.36	0.32	0.99	2.83	0.59
		-		Oct22 ≠ June22, June23		June22 ≠ Oct22		-		Oct22 ≠ June22, June23			
		Al				**Cd**				**Fe**			

	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	3.70	0.16	1.89	0.39	5.46	0.06	2.40	0.12	4.02	0.13	3.90	0.14
Treatment	2	2.22	0.33	3.36	0.19	6.07	**0.05***	0.36	0.84	2.29	0.31	5.12	0.08
Time X Treatment	4	4.61	0.33	8.84	0.07*	4.39	0.36	7.89	0.09	4.95	0.29	16.47	**0.002****
		-		-		-		-		-		Oct22 - Olivine ≠ Control West	
		Cu				**Pb**				**Zn**			
	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	0.83	0.66	1.01	0.57	0.28	0.87	4.51	0.10	1.02	0.59	0.79	0.67
Treatment	2	2.75	0.25	0.43	0.81	0.41	0.82	0.61	0.74	1.39	0.49	5.76	0.06
Time X Treatment	4	1.97	0.74	8.46	0.08	0.40	0.98	5.48	0.24	2.35	0.67	12.02	**0.02***
		-				-		-		-		Olivine - June2022 ≠ June 2023	
		Ag				**As**				**Mo**			
	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	4.56	0.10	2.35	0.31	3.66	0.16	19.73	**5.194e-05*****	2.19	0.33	20.49	**3.536e-05*****
Treatment	2	8.74	**0.01***	0.23	0.89	5.05	0.08	2.55	0.28	0.31	0.86	1.86	0.39
Time X Treatment	4	7.48	0.11	1.74	0.78	2.50	0.64	4.75	0.31	1.43	0.84	4.22	0.38
pair-wise		Control West ≠ Control Nourished				-		Oct2022 ≠ June2022, June2023		-		Oct 2022 ≠ June2022, June2023	
		Sb				**Se**				**U**			

	df	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p	chisq	p
Time	2	3.61	0.16	2.84	0.25	2.38	0.30	4.29	0.12	0.67	0.71	3.33	0.19
Treatment	2	1.38	0.50	0.81	0.67	1.16	0.56	0.41	0.82	0.04	0.98	2.39	0.30
Time X Treatment	4	3.07	0.55	6.38	0.17	1.09	0.89	9.70	**0.04***	0.49	0.97	6.78	0.15
		-		-		-		Olivine, Control Nourished - Oct2022 ≠ June2022, June 2023		-		-	

		V			
	df	chisq	p	chisq	p
Time	2	3.26	0.19	5.73	0.06
Treatment	2	0.60	0.74	3.64	0.16
Time X Treatment	4	2.03	0.73	13.18	**0.01***
		-		Olivine, Control Nourished - Oct2022 ≠ June2022, June 2023; Oct2022 - Control West ≠ Olivine	

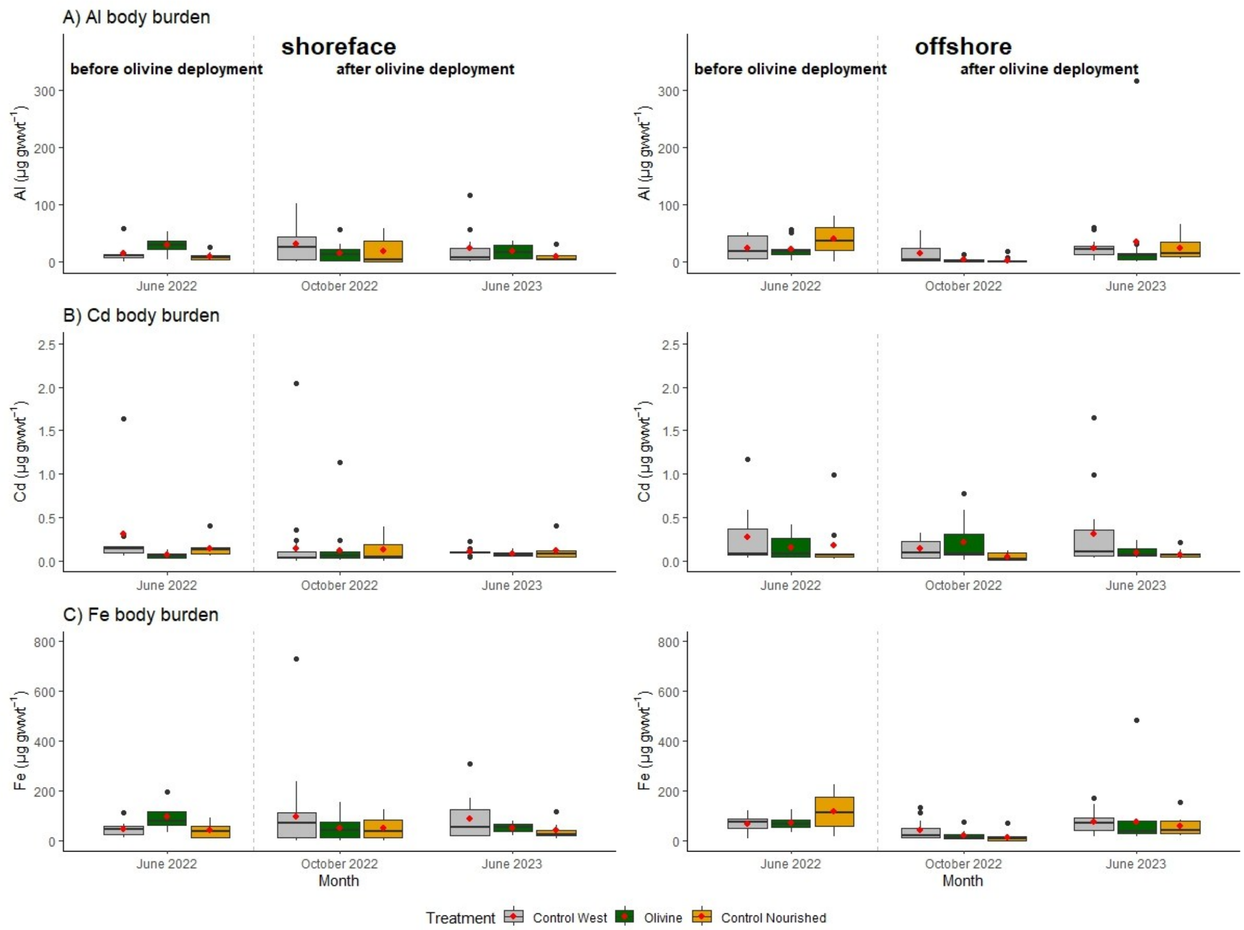

Fig. S8 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) Al body burden, B) Cd body burden, C) Fe body burden.

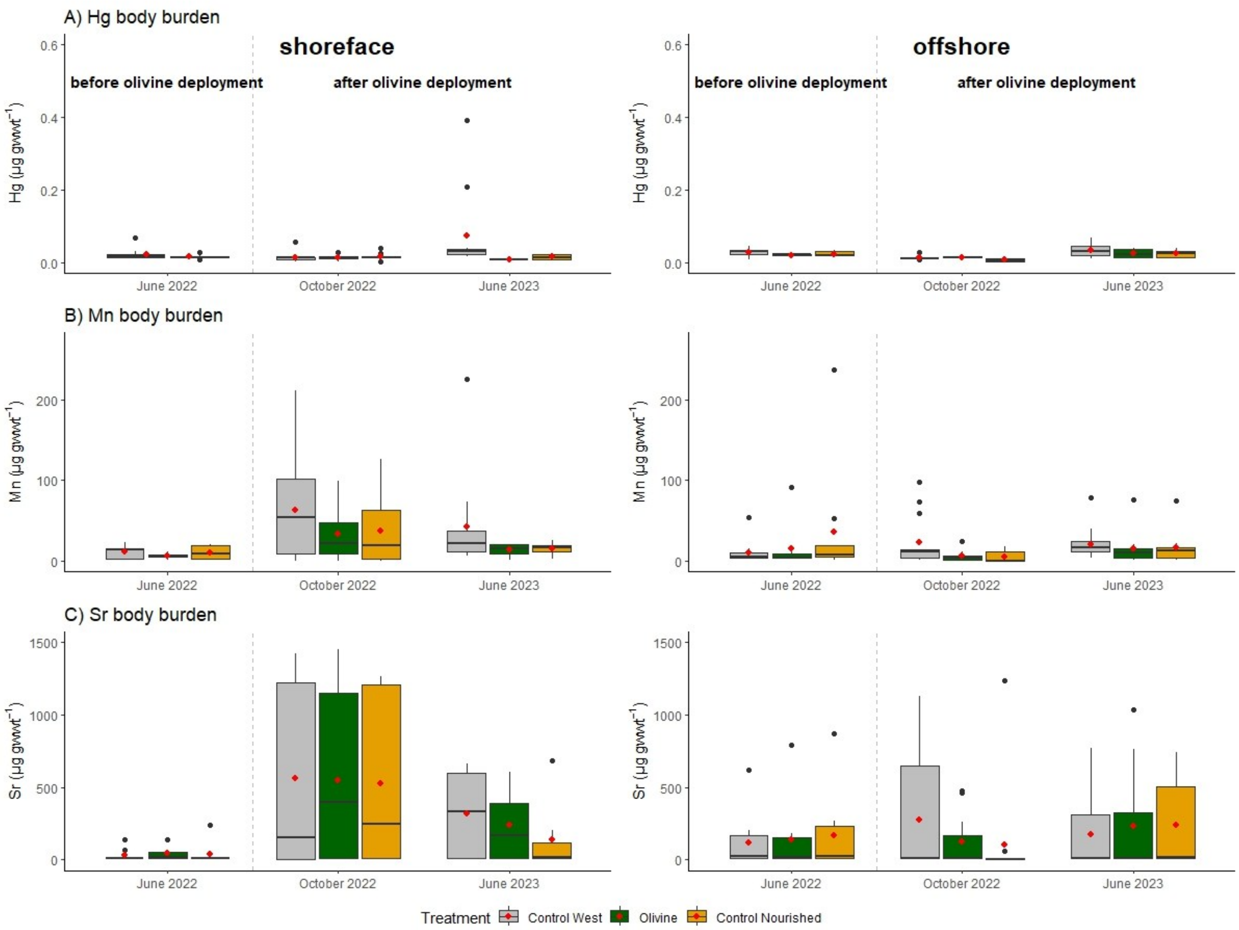

Fig. S9 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) Hg body burden, B) Mn body burden, C) Sr body burden.

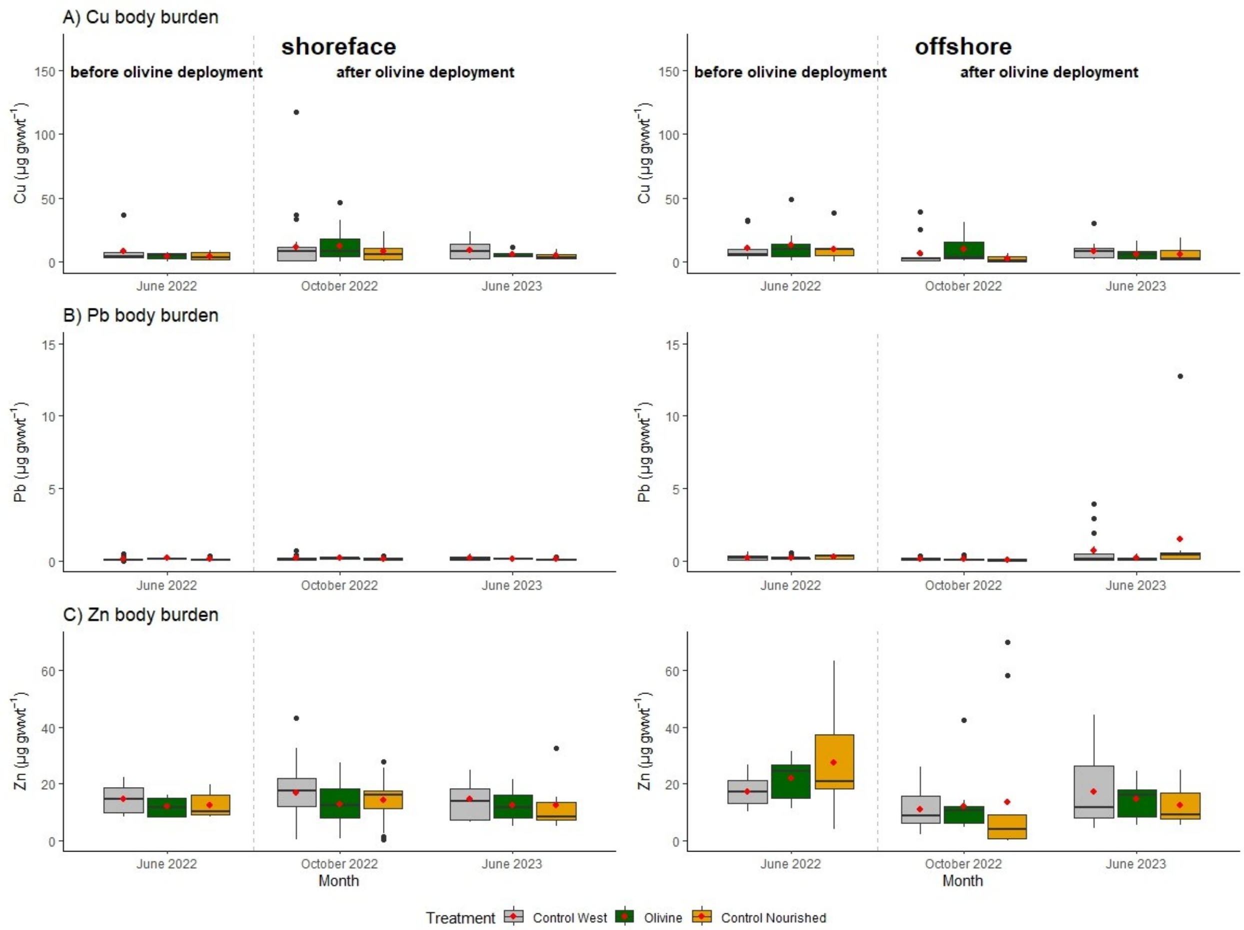

Fig. S10 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) Cu body burden, B) Pb body burden, C) Zn body burden.

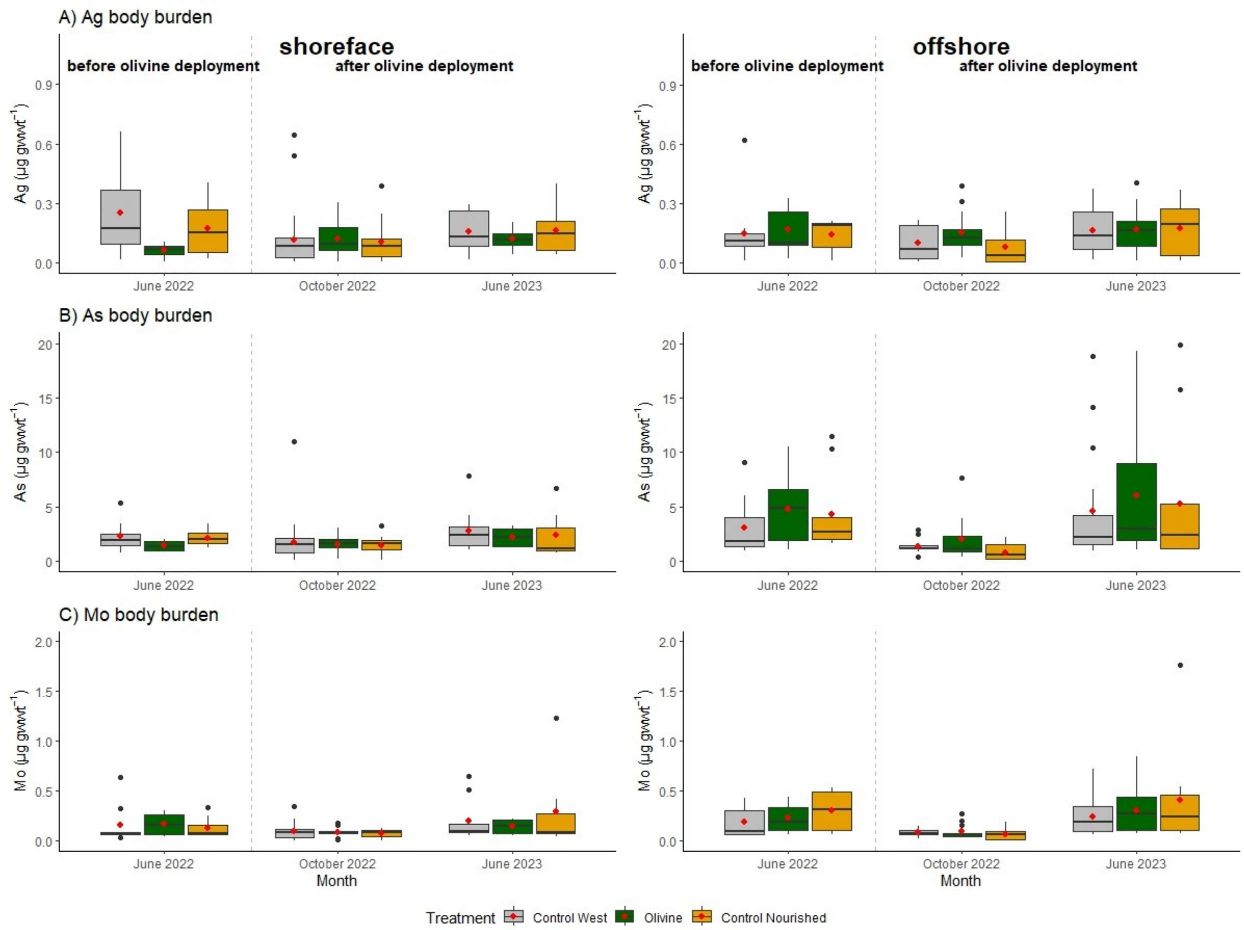

Fig. S11 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) Ag body burden, B) As body burden, C) Mo body burden.

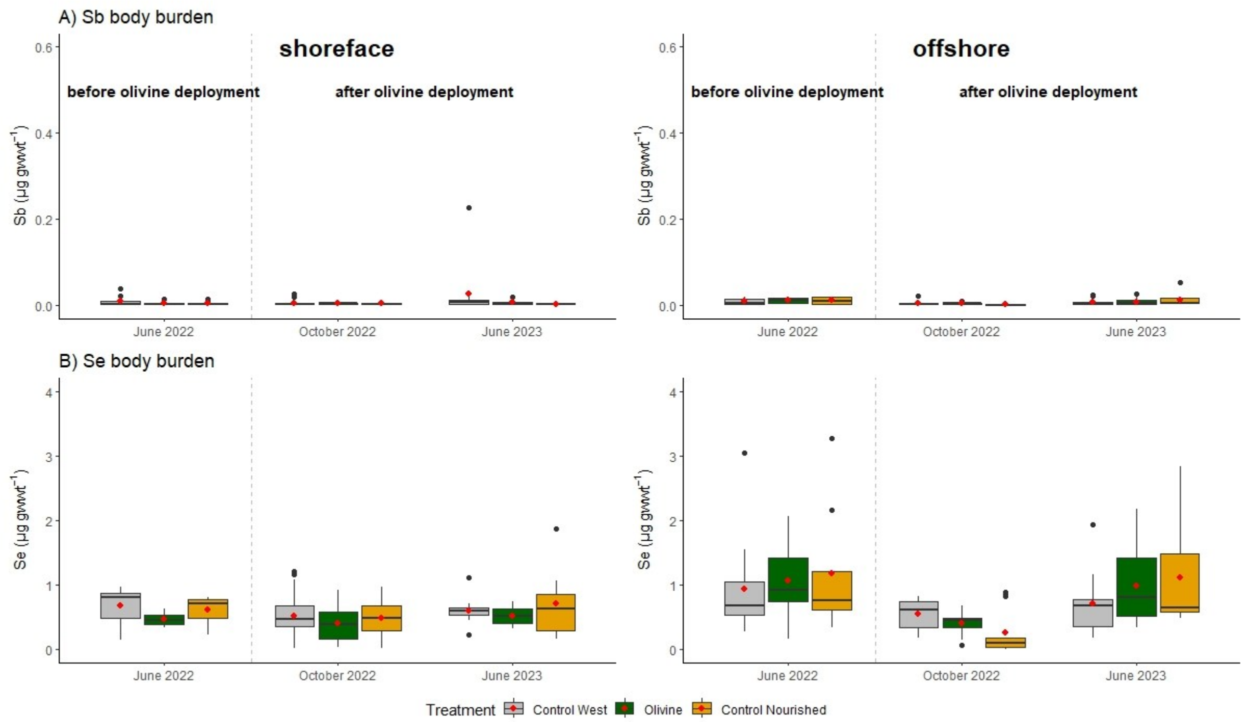

Fig. S12 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) Sb body burden, B) Se body burden.

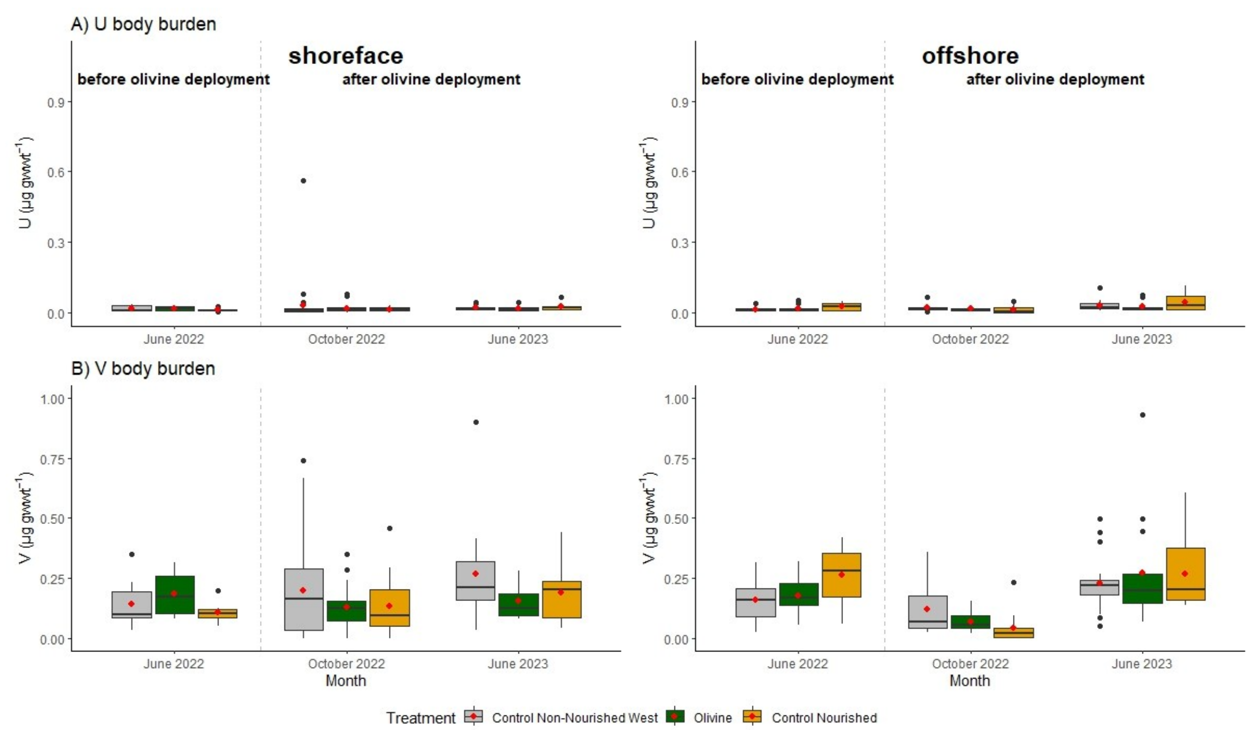

Fig. S13 Macrobenthos trace metals accumulation at three treatments, before/after olivine placement at shoreface and offshore locations A) U body burden, B) V body burden.

Table S9 Sediment composition at macrobenthos sampling locations.

			% Gravel		% Sand		% Mud	
treatment	station	time	mean	sd	mean	sd	mean	sd
Control East	Offshore40	After olivine placement	10.4	12.2	88.1	11.9	1.6	0.5
		Before olivine placement	8.2	9.9	90.5	9.6	1.3	0.3
	Shoreface	After olivine placement	30.6	24.1	68.1	23.8	1.2	0.5
		Before olivine placement	22.4	3.3	76.1	3.4	1.5	0.1
	Offshore100	After olivine placement	2.3	1.7	95.7	1.5	1.9	0.4
		Before olivine placement	5.6	4.7	92.9	4.8	1.5	0.05
	Offshore160	After olivine placement	1.5	0.8	96.0	1.5	2.4	1.1
		Before olivine placement	1.3	1.3	95.7	3.2	3.0	1.9

Control Nourished	Offshore40	After olivine placement	6.3	5.7	92.2	5.6	1.6	0.5
		Before olivine placement	5.9	4.8	92.6	4.4	1.5	0.4
	Shoreface	After olivine placement	25.3	15.7	73.67	15.5	1.2	0.5
		Before olivine placement	22.7	12.2	76.0	11.9	1.3	0.4
	Offshore100	After olivine placement	1.0	0.5	97.1	0.8	1.9	0.6
		Before olivine placement	1.2	1.0	97.0	0.9	1.8	0.3
	Offshore160	After olivine placement	2.4	3.0	95.1	2.9	2.6	1.0
		Before olivine placement	2.6	4.1	95.1	4.6	2.4	0.5
Olivine Nourished	Offshore40	After olivine placement	2.0	1.1	96.2	1.0	1.8	0.4
		Before olivine placement	0.8	1.0	97.5	0.8	1.7	0.2

	Shoreface	After olivine placement	18.9	11.6	79.6	11.3	1.5	0.8
		Before olivine placement	17.0	23.4	81.9	23.1	1.1	0.3
	Offshore100	After olivine placement	2.6	3.0	95.3	3.1	2.0	0.9
		Before olivine placement	0.5	0.3	97.4	0.9	2.1	0.9
	Offshore160	After olivine placement	1.1	1.5	96.3	2.0	2.5	1.3
		Before olivine placement	0.5	0.5	97.2	0.8	2.3	0.5

S2 Detailed Methods

S2.1 XRF

X-ray fluorescence (XRF) analysis was conducted using a Bruker Tracer 5G handheld XRF analyzer, an energy-dispersive X-ray fluorescence (EDXRF) device. The instrument was used to quantify the nickel (Ni) concentration in sediment samples as a proxy for percent (%) olivine content. This proxy was based on the assumptions that the quartz-rich native sediments have little to no Ni and that the vast majority of Ni in the project feedstock was housed within olivine.

Commonly, samples for XRF analysis are ground into a fine powder, which homogenizes the sample, and pressed into a puck to reduce matrix effects. However, this sample preparation is time intensive and expensive. Given the volume of samples that required analysis for this project, as well as the naturally-occurring fine grain size of the native beach sand and olivine feedstock, a method was developed that bypassed sample grinding and pressing, or otherwise additional preparation.

Sediment samples were sieved to the < 2 mm fraction and then subsampled to ~10g using a sediment splitter with a 0.25" chute. In some rare cases, subsampling was done using the quartering method[1]. Sediment samples were not powdered or pressed but were added directly to a 31 mm closed X-ray sample cell and sealed with a 0.16 mil thick Ultralene film. Each sample was analyzed for either 120 or 180 seconds using the Geoexploration analysis method. A custom-built sample spinner was used during analysis. This device replaced manual sample rotation, standardizing rotational speed and orientation. The Bruker 5g has an 8 mm diameter analysis window and approximately 0.31 mm depth penetration.

To verify the XRF's operating performance, two standards were measured alongside samples: the USGS certified reference material, BHVO-2, a basalt standard with a certified Ni concentration (119.80 ppm), as well as the Bruker in-house CS-M2 standard, which does not have a certified Ni concentration. The standards were powdered and pressed, in accordance with standard XRF sample preparation. Over the course of the experiment, the BHVO-2 standard, when measured for 120 seconds, produced a Ni concentration of 117.3 ± 9.7 ppm (2SD) (n=26) with an accuracy of ± 3.8% and when measured for 180 seconds produced a Ni concentration of 121.5 ± 8.2 ppm (2SD) (n=29) with an accuracy of ± 3.1%, demonstrating agreement between the two analysis methods as well as the certified Ni value. Additionally, the CS-MS standard, when measured for 120 seconds, produced a Ni concentration of 52.1 ± 4.1 ppm (2SD) (n=28) and when measured for 180 seconds, produced a Ni concentration of 52.4 ± 9.3 ppm (2SD) (n=26), demonstrating agreement between the two analysis methods and similar precision to the BHVO-2 standard.

To convert Ni concentrations to % olivine, a calibration curve (Fig. S1) was constructed with standards prepared by combining the project feedstock with quartz-rich dune sand collected adjacent to the project site in ratios ranging from 0% feedstock to 100% feedstock. % feedstock was then converted to % olivine by multiplying by 0.85 based on the feedstock's mineralogy (section Methods, Sediment mineralogy). The calibration standards were treated identically to samples in that they were not powdered or pressed prior to XRF analysis and thus captured matrix effects representative of project samples. The calibration standards were measured multiple times to account for the inherent instrument error as well as variability resulting from the non-standard preparation of sediments. Ultimately, the calibration curve produced a polynomial best fit (r^2 = 0.9861), consistent with greater matrix effects at increasingly high levels of olivine content. The polynomial fit may be due to the high levels of other metals present in the olivine such as Fe and Cr. A selection of project samples were used to validate the calibration curve. Seven samples were analyzed by XRD[2] to determine their true % olivine content, which ultimately ranged from 3.1% to 40.5%. When measured by XRF, all project samples fell within the 95% prediction interval for the calibration curve (Fig. S1).

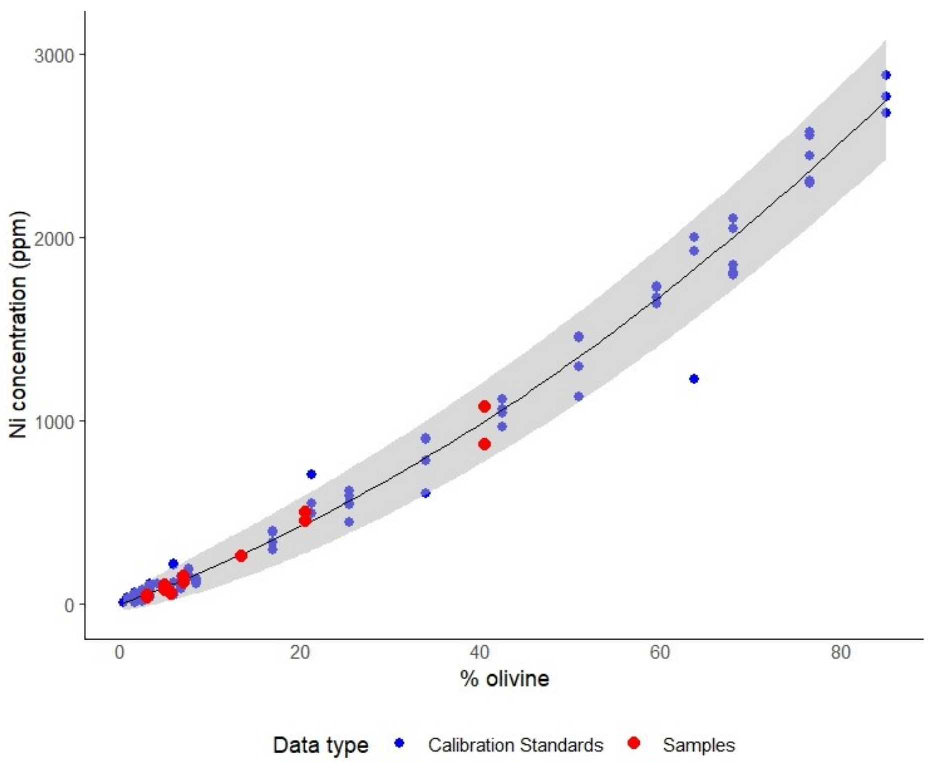

Figure S14. % olivine calibration curve.

While the calibration curve is able to accurately predict % olivine of project samples, across both standards and samples, the absolute Ni concentration reported by the XRF was consistently lower than expected based on the known % olivine content and the known Ni concentration of the feedstock (2514 ppm, as reported by the manufacturer, Sibelco). Thus, while this approach is useful for determining % olivine of sediments, its ability to determine the true Ni concentration of sediment requires further calibration.

S2.2 Description of macrobenthos data analysis exclusion criteria.

In the current study, Nematoda and Oligochaeta together constituted 57 - 91% and 63 - 85% of the total species abundance before and after olivine placement, respectively.

The Control West treatment was identified as not providing an appropriate baseline for comparison. Before olivine placement, the mean abundance at Control West shoreface station was 1338.0 ± 1262.9 ind. 0.04 m^{-2}, presenting very high variability. This variability was caused by the difference in Crepidula spp. abundance in two samples - 1466 vs. 0 ind. 0.04 m^{-2}. The high variability observed at the Control West station was found to interfere with the BACI analysis; therefore, it was excluded from the final analysis.

References

1. SCDOT. Standard methods of test for materials (Laboratory Procedures Manual). (2008).
2. Jankowska, E. *et al.* Limited impact on oysters in first-of-its-kind field trial of marine carbon dioxide removal (mCDR) strategy. *CDRXIV* https://cdrxiv.org/preprint/326 (2025).