Title: Coral cover remains suppressed three years after derelict net removal in a remote shallow water coral reef ecosystem

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Abstract

The uninhabited Northwestern Hawaiian Islands (NWHI) contain 70% of the shallow water coral reefs in the United States. An estimated 52 metric tons of derelict fishing nets accumulate here annually, becoming entangled in the reef structure and reducing coral cover. Here, we investigated the longevity of derelict net impacts on coral reef communities three years after net removal at Pearl and Hermes Atoll. Structure-from-Motion technology was used to resurvey net impact and control sites to determine whether coral cover rebounded at impact sites over time. Our results showed significantly lower coral cover at impact sites. Much of the bare substrate immediately exposed after net removal was also colonized by algae —not reef calcifiers. Continued monitoring of these sites will add clarity to the lasting nature of derelict nets on reefs, and supplementing net removal efforts with active restoration activities may assist in restoring the ecosystem function of impacted sites faster.

Introduction

Derelict fishing gear—fishing gear that has been lost, discarded, or abandoned in the ocean —can cause detrimental impacts to the marine environment. This gear has been shown to pose navigational hazards (Hong et al. 2017), entangle marine wildlife (Boland and Donohue 2003, Henderson 2001, Votier et al. 2011), and damage fragile coral reef habitats (Figueroa-Pico et al. 2020, Suka et al. 2020). Nearly 6% of all fishing nets utilized globally become lost at sea each year (Richardson et al. 2019), and negative impacts of these nets are exacerbated by advances in the durability and longevity of the plastics used to manufacture them (McElwee et al. 2012). Here, we assess the longevity of the impacts of modern, synthetic plastic fishing nets on shallow coral reef habitats three years after the nets were removed from the environment.

The Northwestern Hawaiian Islands (NWHI) are an uninhabited, subtropical archipelago in the North Pacific Ocean, containing numerous islands, atolls, and reef structures protected as part of the Papahānaumokuākea Marine National Monument. Despite their remoteness, the NWHI are subject to an unusually high amount of marine debris accumulation due to their central position within the North Pacific Subtropical Gyre (NPSG), close proximity to the Subtropical Convergence Zone (STCZ), and prevailing weather patterns that transport and direct floating debris to shorelines of the NWHI (Pichel et al. 2007, Kubota 1994). Dameron et al. (2007) estimated that over 52 metric tons of marine debris accumulate in this remote region every year, while Boland and Donohue (2003) found anywhere from 16-165 submerged debris items per km^2. Derelict fishing nets have been identified as the most frequent type of marine debris encountered throughout the NWHI (Donohue et al. 2001).

The NWHI are characterized by shallow-water lagoons containing reef communities composed primarily of branching *Porites* and *Pocillopora* corals (Maragos et al. 2004, Friedlander et al. 2005). Branching coral morphologies have been shown to frequently entangle derelict fishing gear, resulting in abrasion, fracturing, and fragmentation of corals on reefs in Thailand, the Indian Ocean, Indonesia, India and the Florida Keys (Arindra Putra et al. 2021, Chiappone et al. 2005, Mulochau et al. 2020, Patterson Edward et al. 2020, Valderamma Ballesteros et al. 2018). Suka et al. (2020) quantified a similar finding on shallow (1-3 m) lagoonal reefs at Pearl and Hermes Atoll in the NWHI. In that study in 2018, authors leveraged novel techniques of photogrammetry and structure-from-motion (SfM) to calculate benthic cover at reef sites impacted by derelict nets and at nearby control sites. After removing the nets entangled on the reef, Suka et al. (2020) found the underlying benthic substrate to have significantly reduced coral cover and greater cover of sand, crustose coralline algae, and bare substrate compared to unimpacted control sites. In this follow-up study, we resurveyed in 2021 the same net impact and control sites established by Suka et al. (2020) to ask whether corals recovered at these sites three years after the removal of the derelict fishing nets. To our knowledge, this is the first study to track the longevity of derelict net impacts on coral reef communities after net removal.

Methods

In September 2021, we successfully relocated and resurveyed 24 (15 net impact, 9 control) of the paired 'control-impact' sites originally marked at Pearl and Hermes lagoon in

2018 by Suka et al. (2020) (Fig. 1). Large (36") zipties were originally attached to the four corners of each reef site during initial surveys in 2018, and they were physically relocated in the field in 2021 to positively identify repeat sites. Five net impact sites were searched for and unfortunately not located in 2021. For any relocated net impact site for which we could not relocate its original control site, a new control site was established by swimming a predetermined distance (ranging from 15–28 m) along a randomized compass bearing from the impact site to the nearest reef area of similar depth that exhibited no evidence of previous net impact. Structure-from-motion (SfM) photogrammetry techniques were applied to digital imagery collected at each control and impact site from which percent cover estimates were derived.

At each site, a 3 × 3m^2 plot was imaged using a Nikon SL2 digital SLR camera by snorkeling in a cross-hatch pattern over the site while continuously taking photographs. Each survey consisted of hundreds of overlapping images of the benthos from a fixed height of 1 meter above the substrate. Ground control points were established from three 0.25m scale bars laid flat on the benthos with depth measurements recorded. Using Agisoft Metashape software (version 1.2.5 build 2735) along with protocol and parameters published by Burns et al. (2015), survey imagery was 'stitched' together to create an accurately scaled, two-dimensional orthophoto of each site (Suka et al. 2019).

Our intent was to assess benthic cover in 2021 within the original 'footprint' of the derelict net removed by Suka et al. in 2018. To achieve this, a shapefile of the net boundary delineated by Suka et al. (2020) was overlaid and repositioned on the recent orthophotos taken for this study in 2021 (Fig. 2). The shapefile was visually aligned to the original location of the derelict net using common identifiable features across both images. We eliminated three of the impact sites surveyed in 2021 (and their paired controls) from analysis as we could not reliably determine where to position the net shapefile on the 2021 orthophoto—resulting in 12 net impact sites for analysis. The same boundary shapefile was overlaid in the center of the paired control site orthophoto to ensure percent cover was estimated from a comparable reef area as impact sites. The benthic cover at each control and impact site was assessed from 20 random points placed within the net boundary shapefile of each orthophoto.

The benthic features at each point were then classified into one of six benthic categories: algae (grouping turf and macroalgae), sand, bare, coral, sponge, and crustose coralline algae (CCA) and then converted to percent cover for the site. To avoid surveyor bias only one annotator completed the classification of all sites in this study, and to ensure benthic categories were consistent with Suka et al. (2020), the same training and identification criteria were used as outlined in NOAA's standard operating procedure (Lamirand et al. 2022). The categories of macroalgae and turf algae from Suka et al. (2020) were merged for analysis due to identification challenges from the imagery.

In alignment with a Before-After-Control-Impact (BACI) study design, we used the benthic cover data generated from the 12 net impact and 12 nearby control sites surveyed in 2021 and the associated 'before' data from these same sites collected by Suka et al. (2020). We first investigated community-level shifts in benthic cover between net impact and control sites over time, using permutational multivariate analysis of variance (PERMANOVA). A fully crossed, two-factor PERMANOVA (factors: time, treatment) was performed on zero-adjusted Bray–Curtis dissimilarity matrices of benthic cover data. The PERMDISP2 procedure (Anderson 2006)—a multivariate analogue of Levene's test—was used to confirm multivariate homogeneity assumptions were met for both factors in the PERMANOVA. A Non-metric Multi-dimensional Scaling (nMDS) plot was used to visualize the benthic community composition at net impact and control sites across years. Univariate analysis of individual benthic functional groups were then conducted using a fully crossed, two-way ANOVA, with time and treatment treated as fixed effects (n=48). In both the PERMANOVA and ANOVA analyses, the main statistic of interest is the interaction term (time × treatment), which would be significant when a temporal change in cover occurred at the impact site but not at the control site (or vice versa).

All benthic cover data are publicly accessible through the National Center for Environmental Information archives (Pacific Islands Fisheries Science Center, 2022). For each comparison, benthic cover values were extremely left skewed and thus arcsin square root transformed. Net boundary shapefiles were overlaid and percent cover data were generated using ArcMap v10.6.1. All data analyses were conducted in *R* Version 4.1.2. (R Core Team 2021). PERMANOVA analyses were conducted using the vegan package version 2.6-4 and pairwise_adonis.R function (Oksanen et al. 2022). ANOVA analyses were conducted using the stats package version 3.6.2 (R Core Team 2021) and *rstatix* package version 0.7.0 (Kassambara 2021).

Discussion

While the benthic community differed over time and treatment (PERMANOVA, Table 1, Fig. 3), we do not see evidence of an interactive effect between time and treatment that would indicate benthic communities at net impact sites are changing differently over time from control sites. In other words, we do not see evidence that the benthic community at net impacts sites are showing signs of recovery over time, but rather that the initial impacts of derelict nets documented by Suka et al. (2020)---less coral and more CCA, sand, and bare substrate—persist through time.

A similar result was found examining each benthic functional group individually. For all of the individual functional groups tested (except BARE), we did not see any significant interaction effect either (Table 2). For example, there is a significant difference in the coral cover by treatment, but not in treatment by time, indicating no such recovery of coral cover at net impact sites.

Despite three years elapsing since derelict nets were removed from the lagoonal reefs in Pearl and Hermes Atoll, impact sites had significantly lower coral cover than nearby control sites—indicating that derelict net impacts to coral reef systems persist for years after nets themselves have been removed (Table 2, Fig. 4). Coral cover at control sites averaged 13.0% (± 5.2 % SE) in 2021, while the mean value at impact sites during the same period was 3.5% (± 1.4 % SE). Conversely, sand and CCA cover were significantly more abundant at impact sites—both in 2018 and 2021. Across years, sand cover was almost four times higher at impact sites compared to nearby controls, averaging 3.8% (± 2.1 % SE) and <1.0% (± 1.0 % SE) in 2021 respectively. CCA cover was initially high at impact sites immediately after net removal, but was significantly reduced during follow-up surveys in 2021. Meanwhile, algae cover significantly increased over the survey period dominating the benthos of both treatments in 2021.

Comparing the net impact sites in 2018 (immediately following the removal of derelict nets) to the recent surveys in 2021 offered insight into how successional change in the benthos occurred post-disturbance (Fig. 4). The 2018 impact sites were characterized by abundant bare substrate and sand in addition to considerable algal cover. By 2021, this bare substrate was reduced to zero and sand cover dropped to about one-fourth of its initial level in 2018 (mean: 16.6% ± 4.7 % SE) to an average of 3.8% (± 2.1 % SE) in 2021. Over this same time period, the algal cover doubled. These results suggest that much of the bare substrate exposed after net removal was colonized by algae—not coral or CCA. The ability of algae to outcompete reef calcifiers in the wake of disturbance has been noted in other central Pacific reef systems, like the Maldives (Harris et al. 2015, Smith et al. 2016). While declines in coral cover persisted from 2018 to 2021 at the impact sites, algal cover did not differ significantly between control and impact sites (Table 2). Rather, algal cover exhibited a significant temporal effect such that algal abundances were higher 2021 than 2018, irrespective of whether a site was impacted by a derelict net. This increase in algal cover over time, coupled with the persistence of depressed coral cover values in the net impact sites suggest that coral recovery within the net impact scars may be unlikely without management intervention.

It is possible that removing the nets themselves caused damage to the underlying and nearby reef as the process involved cutting, tugging, and pulling the plastic out of the environment.

The primarily monospecific coral community of the lagoon at Pearl and Hermes may have also contributed to this lack of recovery seen. The dominant coral species present, *Porites compressa*, has some of the weakest skeletal strength of Hawaiian corals (Rodgers et al. 2003) and is known to yield high rates of fragmentation and breakage, especially when subject to disturbances (Dollar 1982, Rodgers et al. 2003) or entanglement with derelict fishing gear (Halperin pers. comm., Mueller et al. 2022, Suka et al. 2020). Furthermore, Ying et al. (2021) showed calcification rates of branching *Porites* taxa significantly decreased when the corals remained in contact with derelict nets, as in this study where net entanglement was present directly on live coral. Lastly, because *P. compressa* relies on asexual reproduction and the survival/growth of broken branches around the periphery (Highsmith 1982), the high cover of algae within the net footprint of impact sites detected after net removal may have outcompeted and smothered any incoming broken branches. Hence, the prolonged impacts of derelict fishing nets to suppress coral cover even after the net itself is removed may be unique to reefs dominated by fragile, branching coral species like *P. compressa.*

Exactly how far these results extend to predict how other reef habitats with more mixed coral communities would respond to similar impacts is yet to be determined. For example, Valderamma Ballesteros et al. (2018) found derelict nets caused less fragmentation than expected due to the low fragility of the coral taxa comprising the reefs of their study area in the Gulf of Thailand. Other branching coral taxa in Hawaii show similar impacts as more *Pocillopora meandrina* colonies were found dead or damaged in fished areas comparatively, where large proportions were entangled in fishing line (18-44%) (Asoh et al. 2004).

Other studies in shallow Hawaiian reefs have shown variable results regarding the natural recovery of *Porites compressa* after impacts. Thirty years ago, scientists observed a rapid recovery of *P. compressa* four years after a major fresh-water mortality event in Kaneohe Bay, Oahu (Jokiel et al. 1993). More recently on the north shore of Kaua'i, researchers observed *P. compressa* dominating coral community composition at sediment impact sites, but at densities lower than pre-disturbance baseline values (Rodgers et al. 2021). In terms of physical impacts, *P. compressa* fragments showed considerable recovery in Hawaii after a short period of trampling (9 days), when also allowed a considerably longer recovery period (11 months) (Rodgers et al. 2003).

It is important to note limitations in the power and scope of this study as a result of the small sample size, long duration between resurvey of sites, and statistical methods employed. The authors encountered challenges relocating survey sites and aligning structure-from-motion models across years. Using more permanent markers (i.e. rebar stakes) in the field for denoting both the sites and net boundaries would aid in site location and alignment over time - both of which would increase the amount of data available for analysis. Additionally, with the three years between site surveys it is possible that these findings reflect some other process other than net entanglement and removal that could be more relevant on a shorter time scale. The authors did however constrain control site selection to similar depths and small geographic distances (<30 m) from net impact sites to reduce the likelihood of different stochastic environmental effects between treatments. Lastly, a limitation of the simple BACI sampling design employed here is that the temporal dimensions are binary (i.e. before vs. after) and potentially important patterns within either time period cannot be readily distinguished (Underwood 1992, Stewart-Oaten and Bence 2001). Consideration of temporal processes and variance in BACI has been recommended, but is contingent on data availability (Stewart-Oaten et al. 1986, Stewart-Oaten and Bence 2001) --- which the authors don't have in this case unfortunately. Derelict nets appear to play a major role in reshaping the reef community once they become entangled, and although the impacts described here may not be due to net entanglement exclusively, the study shows these impacts persist at least three years later.

Thus, it is perhaps still too early to expect full recovery of the coral community from net impacts at Pearl and Hermes. Continued monitoring to track the fate of these impact sites will add further clarity to the lasting nature of derelict fishing gear on shallow water reefs in the NWHI. While beyond the scope of this dataset (associated explicitly with funded marine debris removal missions), future studies could include a comparison of benthic cover at sites where nets are left in place to provide a more complete picture of net removal impacts. Supplementing the ongoing net removal efforts in the region with active restoration activities like coral outplanting may assist in restoring the ecosystem function of impacted sites at a faster rate than natural recovery.

Figures

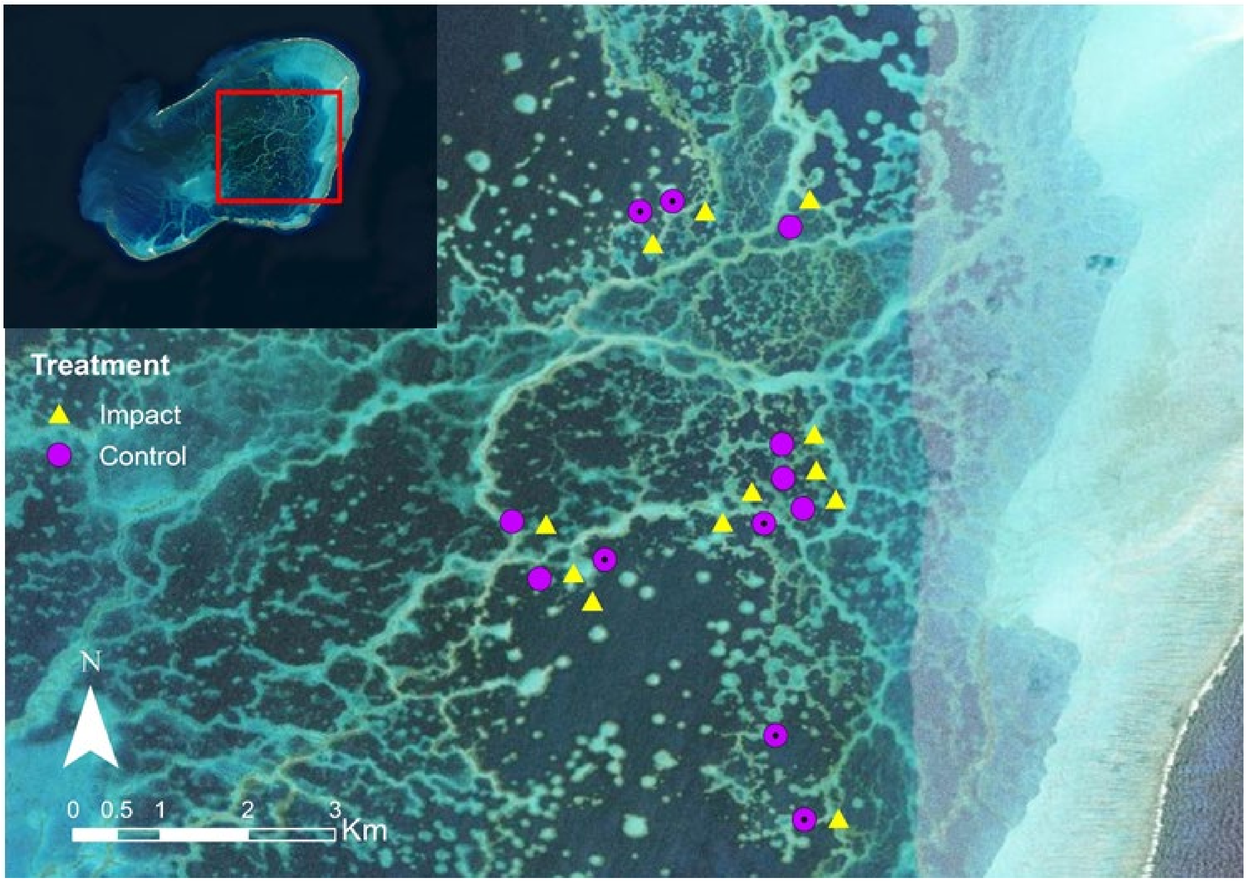

Fig. 1 Map of Pearl and Hermes Atoll in the Northwestern Hawaiian Islands archipelago in the central Pacific. Location of impact sites (yellow triangles) and unimpacted control sites (purple circles) are denoted within the reticulated reefs of the shallow-water lagoon. Control sites surveyed in both years are denoted with black center dot.

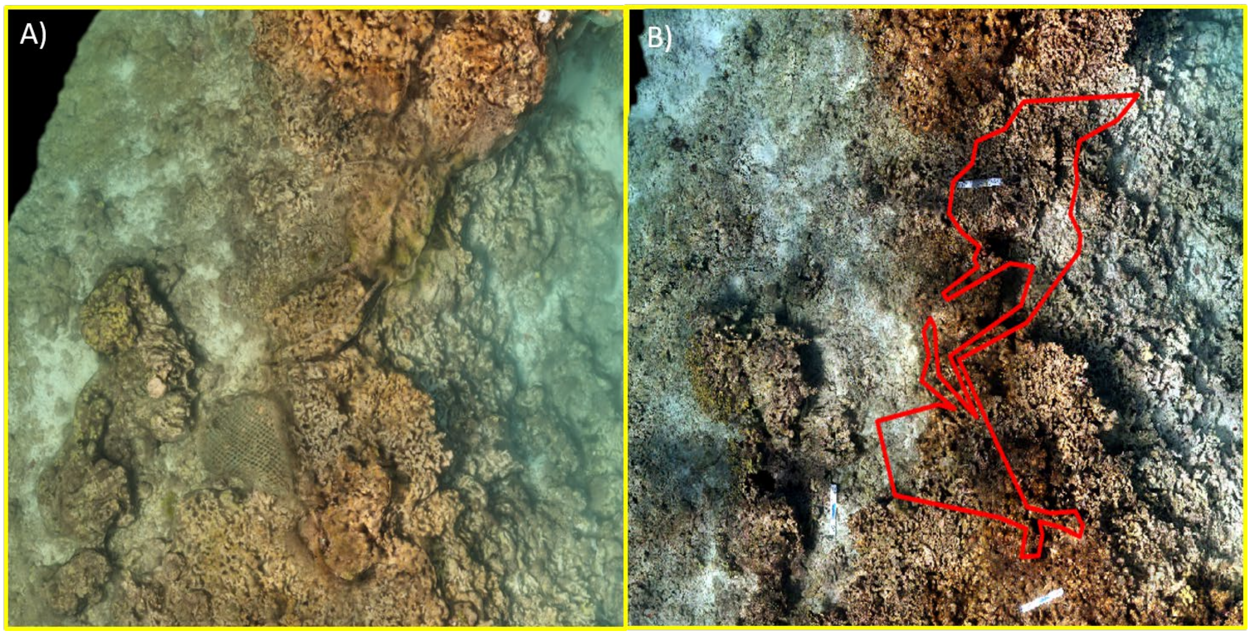

Fig. 2 *In situ* mosaics from impact sites. A) Mosaic from impact site prior to net removal in 2018 collected by Suka et al. (2020). B) Resurvey of same impact site in 2021 with net outline realigned (red).

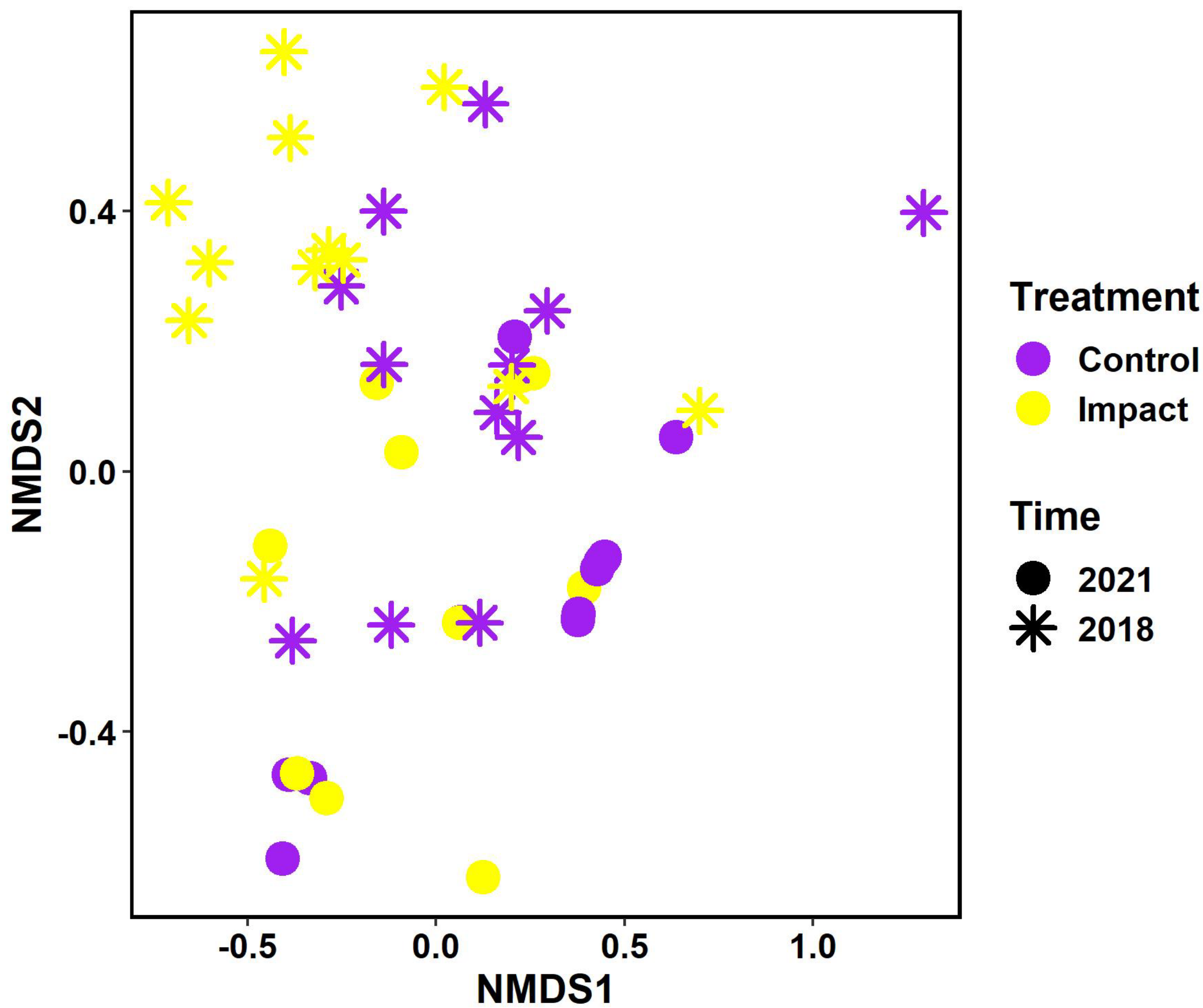

Fig. 3 nMDS plot of benthic community composition (% cover) of control (purple) versus net impact (yellow) sites at Pearl and Hermes over time.

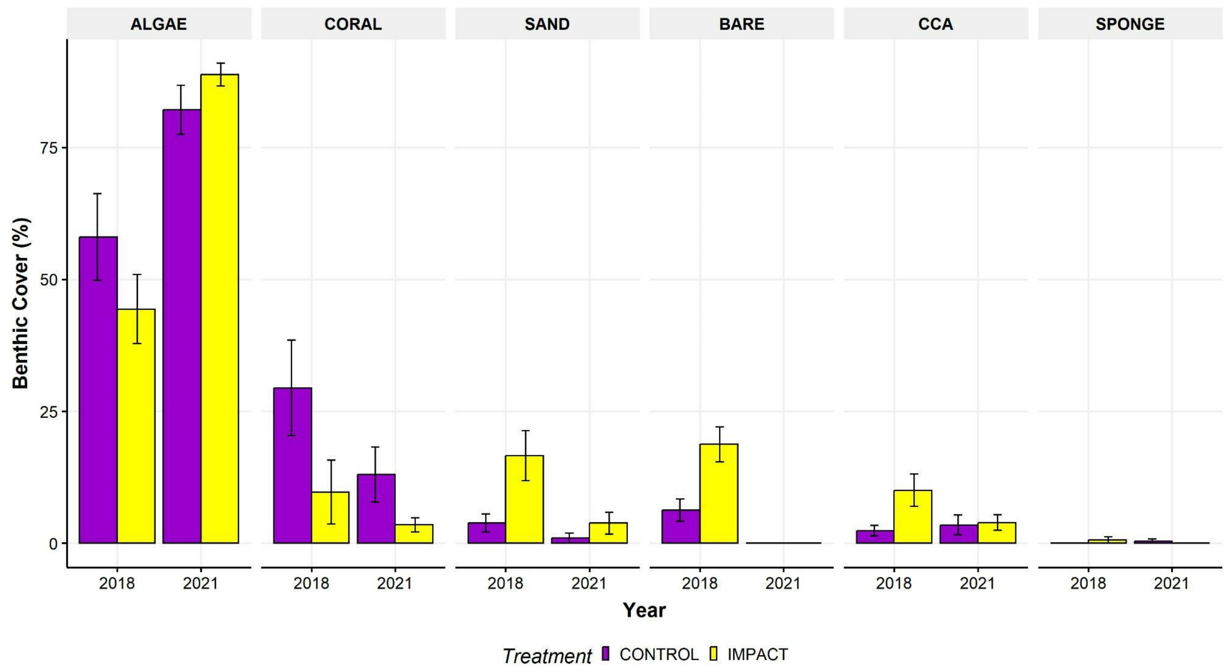

Fig. 4 Benthic cover of net impact (yellow) and control sites (purple) surveyed across years.

Tables

Table 1. PERMANOVA results (degrees of freedom, sum of squares, pseudo-F-ratio, and p-value based on permutation) for benthic cover (%) where TIME and TREATMENT were treated as fixed effects. Significant p-values ($p < 0.05$) are shown in bold.

Effect	df	SS	Pseudo-F	P (permutation)
Time	1	0.97	16.16	**0.001**
Treatment	1	0.39	7.06	**0.001**
Time x Treatment	1	-0.03	0.00	0.995
Residuals	44	2.45		

Table 2. Two-way ANOVA results (sum of squares, degrees of freedom, F-value, and p-value) for the six functional benthic groups (%) where TIME and TREATMENT were treated as fixed effects. Significant p-values ($p < 0.05$) are shown in bold.

Coral	Effect	SS	df	F	p-value
	Time	2.040	1	2.445	0.125
	Treatment	5.625	1	6.742	**0.013**
	Time x Treatment	0.181	1	0.217	0.643
CCA	**Effect**	**SS**	**df**	**F**	**p-value**
	Time	0.000	1	0.012	0.918
	Treatment	0.153	1	5.401	**0.025**
	Time x Treatment	0.048	1	1.704	0.199
Algae	**Effect**	**SS**	**df**	**F**	**p-value**
	Time	0.528	1	8.173	**0.006**
	Treatment	0.106	1	1.643	0.207
	Time x Treatment	0.175	1	2.712	0.107
Sand	**Effect**	**SS**	**df**	**F**	**p-value**
	Time	0.044	1	1.240	0.271
	Treatment	0.319	1	8.940	**0.005**
	Time x Treatment	0.058	1	1.633	0.208
Bare	**Effect**	**SS**	**df**	**F**	**p-value**
	Time	0.236	1	14.949	**0.000**
	Treatment	0.291	1	18.448	**0.000**
	Time x Treatment	0.146	1	9.224	**0.004**
Sponge	**Effect**	**SS**	**df**	**F**	**p-value**
	Time	0.002	1	0.823	0.369
	Treatment	0.003	1	1.177	0.284
	Time x Treatment	0.005	1	1.984	0.166

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