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Drill-Cored Artificial Rock Pools Can Promote Biodiversity and Enhance Community Structure on Coastal Rock Revetments at Reclaimed Coastlines of Penang, Malaysia

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Abstract

Coastlines are drastically altered globally due to urbanisation and climate-related issues. As a response, communities build coastal defence structures to protect people and property. Although these infrastructures fulfil engineering demands of coastal defences, the trade-off to nature includes a decrease in biodiversity able to live on these structures because of the lack of topographic complexity. Several studies have tried to increase the surface complexity on coastal defence structures through eco-engineering habitat enhancements that mimic nature. However, few of these studies have been conducted in tropical regions where effects are more pronounce due to desiccation and extreme heat. In this study, water-retaining structures (in the form of rock-pools at depths 12 cm, and 5 cm) were drill-cored into coastal defence structures (i.e. granite rock revetments) on reclaimed coastlines in Penang Island, Malaysia. We found greater species richness and an increase in community structure in the drill-cored rock pools regardless of the depth of these artificial rock-pools. Positive habitat selection also occurred within micro-habitats of this scale. The drill-cored artificial rock pools in these tidal exposed revetments also provided niche-spaces for marine organisms found in low-tide or sub-tidal areas. These findings demonstrate the potential of this eco-engineered habitat enhancement as a means of promoting biodiversity on granite rock revetments, which can be applied either during design phase of a coastal development or retrospectively.

Keywords

Ecological engineering, topographic complexity, coastal zone management, blue-green infrastructure, conservation, sustainable development

Introduction

Coastlines the world over are increasingly altered to support the burgeoning human population. The tendency to populate shorelines have intensified development at coastal zones resulting in what is known as the "ocean sprawl" (Bishop et al., 2017; Firth et al., 2016b). At present, 31% of the human population, or 2.4 billion people, live within 100 km of the coast (Paleologos et al., 2019). By 2025, projections suggest a rise to 75% of the human population (Ware & Callaway, 2019). Consequently, artificial structures and land reclamation projects are replacing natural estuarine, coastal and marine habitats at a rapid rate—enabling more

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space for humans. Coupled with climate change effects (not limited to sea level rise and increasing storm threats) has resulted in a surge in the number of coastal defence schemes of various scales, designs and build to protect humans and property.

Although coastal defence structures contribute structural integrity and sense of safety to the communities, the trade-off to nature from an ecological perspective is the poor surrogate habitats for the marine biodiversity they impact and displace (Cacabelos et al., 2019; Evans et al., 2016; Firth et al., 2016b). Although coastal defence structures can provide habitat for some of the marine organisms from adjacent rocky shores (Firth et al., 2015; 2016a; Moschella et al., 2005), the new colonising community has been altered for the worse. Lower biodiversity and change to the community structure can lead to domination by invasive and opportunistic species (Aguilera et al., 2014; Firth et al., 2013; Pister, 2009). The main cause of this lies in the loss of topographic complexity found in natural coastal habitats such as rocky beaches, mangroves, and intertidal reefs (Strain et al., 2018; Ushiama et al., 2019; Waltham & Dafforn, 2018). Natural coastal habitats have physical complexities in the form of pits, grooves, crevices, overhangs, and tidal pools, which provide habitat, breeding grounds, and protective spaces for marine and coastal organisms. These human-made coastal defence structures, including granite rock revetments, concrete seawalls, jetties, and breakwaters are devoid of suitable complexity for the marine organisms to settle. Previous studies have proven the impact on loss in diversity and functioning of coastal habitats (Cacabelos et al., 2019; Heery et al., 2017; Nordstrom, 2014).

The reduction of crucial habitats and alteration of species compositions is likely to impact on the disturbance recovery potential of coastal ecosystems (Aguilera, 2018; Firth et al., 2016b; Waltham & Sheaves, 2018). Consequently, ecologists have attempted to apply concepts of ecological engineering or eco-engineering (as part of 'reconciliation ecology' in Rosenzweig & Michael, 2003) to promote biodiversity on artificial marine structures (O'Shaughnessy et al., 2020; Strain et al., 2018). Eco-engineering is the design sustainable ecosystems that integrate the needs of the human society with its natural environment, for the benefit of both (Mitsch & Jørgensen, 1989; Odum, 1962; Odum & Odum, 2003).

There are three (3) fundamental approaches to eco-engineering, see Figure 1: (i) hard (novel designs or modifications to existing seawalls, rock revetments, etc., which cannot be removed and where vegetation or soft sediments cannot be added, e.g. because wave-action is intensive) (Chapman & Underwood, 2011; Firth et al., 2014a); (ii) soft (employing sediments, vegetation such as mangroves or wetlands, or other habitat-forming organisms instead of shoreline infrastructure) (Morris et al., 2018; Temmerman et al., 2013); and (iii) hybrid (combining sediments, vegetation and/or habitat-forming organisms into hard shoreline infrastructure) (Bilkovic & Mitchell, 2013; Chapman & Underwood, 2011;

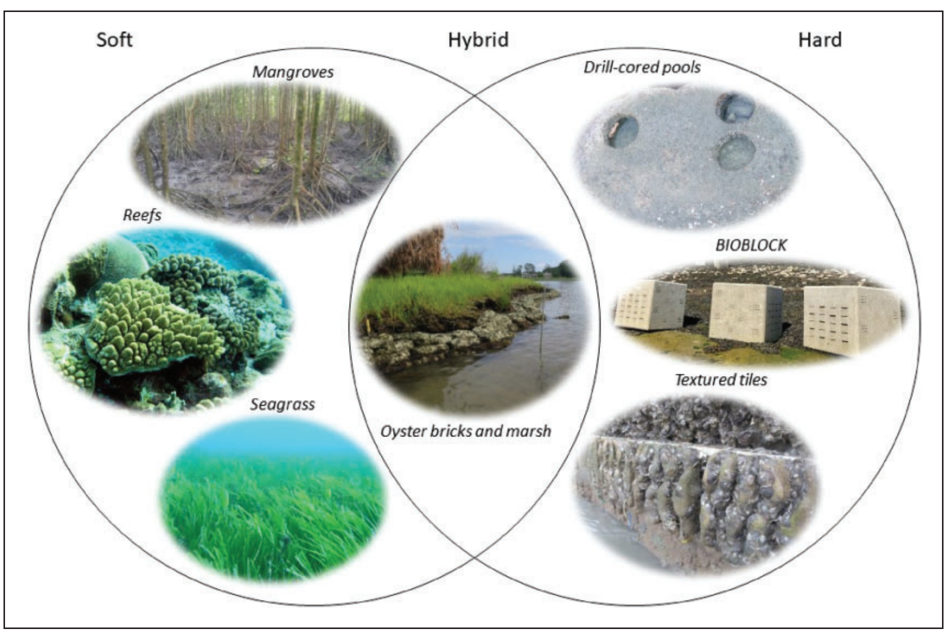

Figure 1. Ecological Engineering Approaches. Soft approaches involve the incorporation of natural habitats for coastal defence; hybrid approaches involve the combination of hard and soft approaches; and hard approaches involve physical manipulation of artificial structures. (Photo credits: Seagrass © Sim Yee Kwang; Oyster bricks and marsh © Janine Ledet; BIOBLOCK © ARC Marine.)

O'Shaughnessy et al., 2020). While most approaches are more effective when carried out concurrently with development, some approaches can be implemented retrospectively. New and existing coastal erosion control structures can be designed or retrofitted to provide a secondary function of providing habitat for coastal organisms and supporting biodiversity in marine built environments.

The hard approach in eco-engineering has been employed in previous studies to compensate for the loss of habitat and to promote biodiversity on coastal erosion control structures, in a retrospective manner. Studies conducted on rock pools show they function to retain water and provide refuge from fluctuations of temperature, desiccation stress, and predation. Artificial tide pools have been created by bolting water-retaining units to seawalls (Browne & Chapman, 2011; Chapman & Blockley, 2009; Hall et al., 2018; Morris et al., 2018), drill-coring holes into rock armour (Evans et al., 2016; Firth et al. 2014b), infilling existing core holes from quarrying practices with cement (Firth et al., 2014b), or casting holes into moulded concrete habitat units (e.g. BIOBLOCK; Firth et al. 2014b). In each of these studies, eco-engineered pools have provided some ecological benefit on structures, but they do not necessarily mimic or compensate for natural habitats (Evans et al., 2016).

Experiments have been geographically limited—mostly carried out in temperate countries (e.g., Browne & Chapman, 2011; Evans et al., 2016; Hall et al., 2018) with few experiments from the tropical region (Loke et al., 2014; Loke & Todd, 2016; Loke et al., 2019). The ecological effects of high temperatures and desiccation on intertidal organisms are known to be more pronounced in the tropics (Loke et al., 2019) and habitat enhancement such as rock pools may become stressful microhabitats rather than refugia under highly variable salinity and temperature regimes (Firth et al., 2014a). Given the unprecedented extent of coastal development and land reclamation projects in southeast Asia (Chee et al., 2017; Tay et al., 2018), it is essential to intensify research on eco-engineering coastal structures for marine biodiversity in tropical locations as effects of complexity on local species biodiversity are often site- and species-specific, varying following local abiotic and biotic stressors and niche requirements of the species pool.

The Penang Island coastline has been undergoing development for centuries, intensifying in the last few decades. This 299-km^2 island in the northwest coast of Peninsular Malaysia is at present one of the most densely populated places in the world with a population of 826,000 and a density of 2,762/km^2 (Department of Statistics Malaysia, 2019). The island has undergone several phases of coastal reclamation and progressed beyond the reclamation of shorelines to reclaiming of whole islands (Chee et al., 2017). The extents of natural coastal ecosystems such as mangroves, rocky and sandy beaches are developed into residential and commercial areas. Urbanisation is concentrated mainly on the east coast of the island (Chee et al., 2017). At the time of writing, further reclamation of three lesser islands at the south of Penang Island has been approved by the Penang State Government. New developments are usually fortified from coastal erosion and flooding by the use of hard coastal defence structures including seawalls, breakwaters, and rock revetments. The most commonly applied are rock revetments due to their lower cost.

In this proof-of-concept study, we investigate the performance of drill-cored artificial rock pools on granite rock revetments on developed shorelines in Penang, Malaysia. We aim to compare species richness and community structure in the artificial pools with adjacent granite rock surfaces on the rock revetment. The main hypotheses are: (i) the artificial rock pools will support more significant species richness than adjacent emergent rock surfaces; and (ii) deeper (12 cm) rock pools will support more significant species richness and community structure to shallower (5 cm) rock pools. Previous studies of drill-cored rock pools tested in the temperate climate of Wales, UK, did not find higher richness in 12 cm to 5 cm pools but did find that rock pools supported greater species richness than adjacent granite rock surfaces (Evans et al., 2016). In the tropical context of Penang, we expect the drill-cored rock pools to support greater species richness than emergent rock surfaces with deeper pools being more species and having a different community structure to shallow pools because of moisture and temperature stability provided by additional water volume. We also assess micro habitat selection within the surfaces (vertical side versus horizontal bottom) of the rock pools with a third hypothesis that: (iii) there would be greater species richness and community structure on the sides of rock pools compared to the bottom of the pools. This information would be useful in improving future designs of vertical and horizontal placements. Lastly, we discuss how the eco-engineering of new spaces to increase topographic complexity can function to promote biodiversity on coastal defences that are increasingly widespread in tropical coastal zones.

Materials and Methods

Study Sites

We installed drill-cored rock pools in at three chosen sites on the northeast coast of Penang Island, Malaysia in October 2015 (Figure 2): Straits Quay Marina (SQM; 5°27′34.26″N, 100°18′52.13″E), Karpal Singh Drive (KSD; 5°23′56.27″N, 100°19′53.12″E), and E&O Hotel

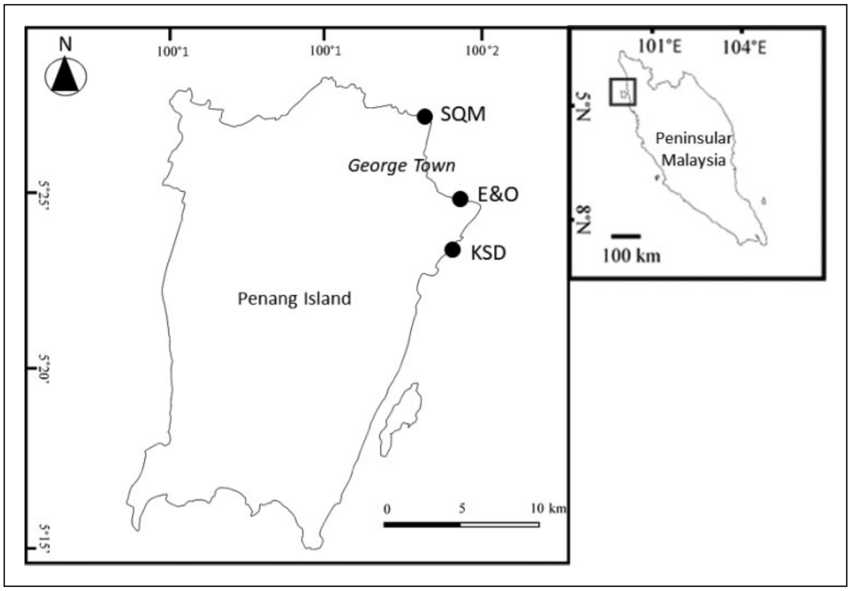

Figure 2. Location of Drill-Cored Rock Pools on Granite Rock Revetments on the Northeast Coast of Penang Island, Malaysia. SQM: Straits Quay Marina rock revetment, KSD: Karpal Singh Drive rock revetment, E&O: E&O Hotel rock revetment.

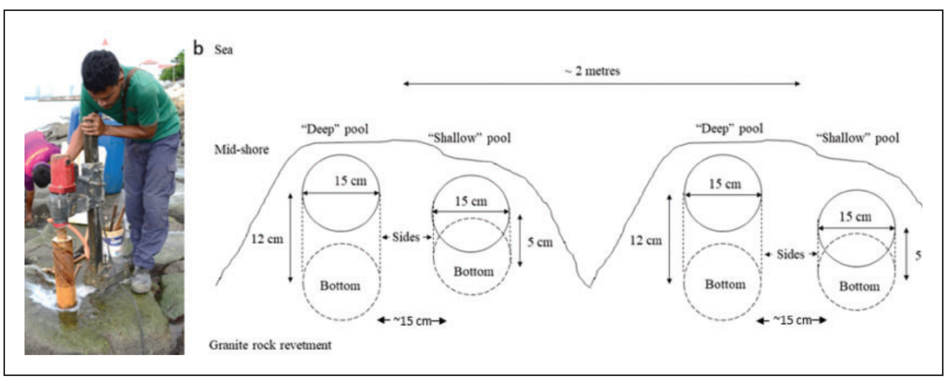

Figure 3. (A) Drill-coring 15 cm diameter artificial rock pools into horizontal granite surfaces of rock revetments at Straits Quay Marina, using a diamond-tipped drill corer. (B) Cross section view, dimensions, and arrangement of drill-cored artificial rock pools on granite rock revetments at study sites. Emergent surfaces were dispersed in between the rock pools.

(E&O; 5°25′26.46″N, 100°20′02.60″E). All three sites were chosen due to criteria to allow fair comparisons between sites i.e. revetments built using granite rock consisting of low gradients backed by concrete walls, and were all built on reclaimed parts of the shoreline. All three sites have surrounding habitats which were previously mudflats, with no natural rocky shores nearby. No documentation exists of any fishery related activity in these sites and it is assumed that any larval supply to populate the pools would drift with local circulation and would be dependent on the localised hydrodynamics to these directly seaward facing seawalls. All three sites experience semi-diurnal regime with tidal range of 0.2 – 3.5 m. There is little to no vegetation along the rock revetments. Prior to treatment for the experiment, the native organisms observed living on the surface of the rock revetments were dominantly barnacles.

Experimental Plots

At each site, thirty artificial rock pools were drill-cored into the horizontal granite surfaces at mid-tide, using a diamond-tipped drill corer (Figure 3A). The artificial rock pools made in Penang are the same dimensions as drill-cored pools previously trialled in a granite breakwater in Wales, UK (Evans et al., 2016), to allow for comparisons to be made in future studies. Pools made were cylindrical shaped with a diameter of 15 cm. Fifteen (15) pools had a depth of 5 cm ('shallow' pools), while the remaining fifteen (15) pools had a depth of 12 cm ('deep' pools) (Figure 3B). Pairs of 'shallow' and 'deep' pools were drilled adjacent with a spatial separation of ~15 cm, and each pair isolated with spatial separation of ~2 m to the next isolated pair. We then marked a total of thirty permanent quadrats of area sizes equal to the 'deep' and 'shallow' pools (specifically '742 cm^2 for the deep pool, and 413 cm^2 for the shallow pool) on the adjacent emergent rock surfaces. Before the commencement of the experiment, organisms found within these permanent quadrats were physically removed by scraping.

The artificial rock pools and adjacent emergent rock surfaces began their course of colonisation at the same time (Tzero). Both habitats in all three sites were monitored monthly for the first three months and half-yearly thereafter. During each survey, the number of mobile faunas was recorded in counts while sessile organisms and algae were recorded in percentage coverage.

Field observations during this period led us to believe that assemblages colonising the vertical sides of pools were different from those colonising the horizontal bottom surfaces. Therefore, an additional *ad hoc* survey was conducted in July (E&O) and August (SQM and KSD) in 2018 using a 10 cm^2 quadrats evaluate species richness and community structure between the vertical side and horizontal bottom surfaces of the 'shallow' and 'deep' pools in each of the sites. One quadrat was taken from each surface of the pool and measurements were taken from all 15 'shallow' and 15 'deep' pools at each site. Organisms found within the rock pools and emergent surfaces were identified to species level. When the species cannot be identified without destructive sampling, morphospecies was assigned. Raw data to this study can be accessed at: DOI: https://doi.org/10.6084/m9.figshare.12171135.

Environmental Parameters

During each site visit, environmental parameters were measured at all the pools of water for data on temperature, salinity, dissolved oxygen and pH. Additional water temperature data was noted from both the drill-cored pools and emergent surfaces. Salinity, dissolved oxygen and pH measurements were taken only at drill-cored pools.

To determine the rate of evaporation at the experimental sites, plastic containers with dimensions resembling the tidal pools (diameter = 11 cm, depths = 10 cm and 6 cm) were set up on the exposed surfaces of the rock revetments at the mid tidal level during the dry season. Each container was filled with 100 ml of seawater. The containers were left out for 5 hours corresponding to low tide periods. At the end of experiment, the water volume was measured again. Readings were recorded for three replicates and evaporation rates were calculated as volume of seawater lost over time (mL/h).

To determine if seasonality affected the species richness, atmospheric temperature for monsoon seasons during the sampling period was also plotted. The temperature was measured at CEMACS, Teluk Bahang, Pulau Pinang, Malaysia.

Data Analyses

The univariate analyses were performed using SPSS ver. 26 (IBM Corp., Armonk, NY, USA). PERMANOVA and SIMPER analyses were performed using PAST software (ver. 3.25) (Hammer et al., 2001).

To address hypothesis 1 that the artificial rock pools would support greater species richness than adjacent emergent rock surfaces, we calculated total richness and species accumulation based on presence/absence data were pooled over replicates ($n = 30$ for SQM, KSD and E&O; $n = 90$ for all sites) and plotted over time (36 months). Analysis of variance (ANOVA) was applied to test for differences in mean species richness after 36 months between the two habitats. A one-way design was used, with fixed factor Habitat (two levels: 'pools', 'emergent'), and $n = 10$. Data from 'deep' and 'shallow' treatments were pooled for this analysis since we found no significant effect of depth on richness. A two-way ANOVA was also conducted, with fixed factors Habitat (two levels: 'pools', 'emergent') and Site (three levels: 'SQM', 'KSD', 'E&O').

To address hypothesis 2 that deeper (12 cm) rock pools would support greater species richness than, and different community structure to, shallower (5 cm) ones, the analysis of variance (ANOVA) was applied to test for differences in mean species richness (after 36 months) between the two depths. A one-way design was used, with fixed factor Depth (two levels: 'deep', 'shallow'), and $n = 10$. Permutation analysis of variance (PERMANOVA) (Anderson, 2005) with Bray-Curtis similarities after 9999 permutations was used to assess the differences in multivariate species assemblages. A two-way ANOVA was also conducted, with fixed factors Depth (two levels: 'deep', 'shallow') and Site (three levels: 'SQM', 'KSD', 'E&O').

To address hypothesis 3 that there would be greater species richness and a different community structure on the vertical sides of pools compared to the horizontal bottoms, we calculated the mean species richness (based on presence/absence data) were obtained over replicates ($n = 15$) from the two depths ('deep' 12 cm; 'shallow' 5 cm) for each surfaces ('side'; 'bottom') of the three sites and presented in bar chart. For the subsequent statistical analyses, depths ('deep' 12 cm; 'shallow' 5 cm) of the two surfaces were pooled together ($n = 30$). Analysis of variance (ANOVA) was applied to test for differences in mean species richness between the two surfaces. A one-way design was used, with fixed factor Surface (two levels: ‘side’, ‘bottom’). Permutation analysis of variance (PERMANOVA) (Anderson, 2005) with Bray-Curtis similarities after 9,999 permutations was used to assess the differences in multivariate species assemblages. SIMPER analysis was applied to calculate the percentage contributions of individual species to dissimilarity between habitat communities (Clarke, 1993). A two-way ANOVA was also conducted, with fixed factors Surface (two levels: ‘side’, ‘bottom’) and Site (three levels: ‘SQM’, ‘KSD’, ‘E&O’).

Results

Comparing Artificial Pools With Emergent Surfaces on the Rock Revetment

Artificial rock pools provided habitat for all species found on surrounding emergent surfaces and significantly more (Figures 4 and 5). At each of these granite rock revetment sites, Straits Quay Marina (SQM), Karpal Singh Drive (KSD) and E&O Hotel (E&O) the pools supported species which would otherwise be absent on the adjacent emergent surfaces. These include anemones, polychaetes, bryozoans, molluscs, arthropods, and green and red macroalgae (Figure 4A to C). Mobile arthropods, polychaetes, and bryozoans were not found on emergent surfaces at any of sites (Figure 4D).

Total species richness in the different habitats fluctuated over the duration of monitoring, but the rock pool habitats supported more species in almost all surveys (Figure 6). Species accumulation curves revealed that the total species pool supported by both artificial rock pools and emergent surfaces continued to rise steadily over the first 18–24 months, before reaching an asymptote (Figure 6A, B, D). However, the artificial rock pool habitats consistently supported more species, with almost double the number of species of sessile or mobile organisms, and macroalgae species coverage (Figures 4 and 6). The pools at the E&O Hotel site did not reach an asymptote post 36 months (Figure 6C), suggesting that increase in diversity may lead to increase in different organisms utilising the space over time.

Overall, after 36 months, the mean species richness in the drill-cored rock pools (13.0 ± 1.7 s.e.) was significantly greater than on the emergent surfaces (5.8 ± 1.1 s.e.) ($F_{1,18} = 12.903$, $p = 0.002$) (Table S1). From two-way ANOVA analysis, we found a significant difference in the species richness between the artificial rock pools and the emergent rock surfaces ($F_{1,54} = 32.620$, $p < 0.001$) (Table S6), but no significant difference in richness between sites ($F_{2,54} = 2.987$, $p = 0.059$) (Table S6).

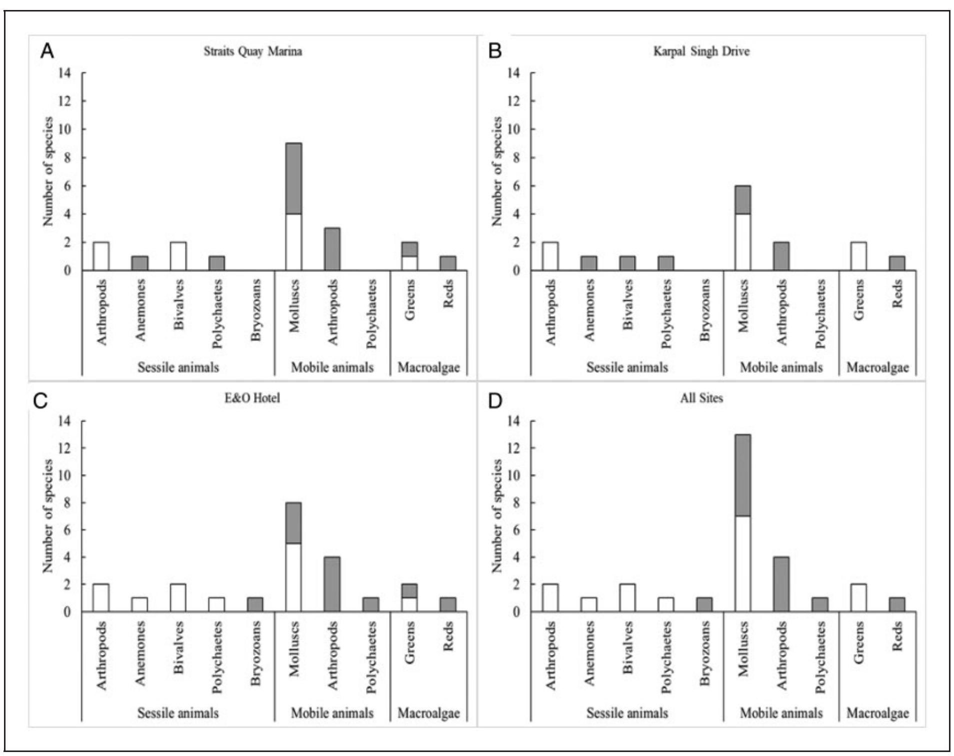

Figure 4. Total Number of Species in Major Taxa Recorded in Rock Pools and on Emergent Surfaces (White Bars) and Additional Species Recorded Exclusively in Artificial Rock Pools (Grey Bars) After 36 months at (A) Straits Quay Marina, (B) Karpal Singh Drive, (C) E&O Hotel and (D) at All Sites. Data pooled over 30 replicates for SQM (A), KSD (B) and E&O Hotel (C) and 90 replicates for all sites (D).

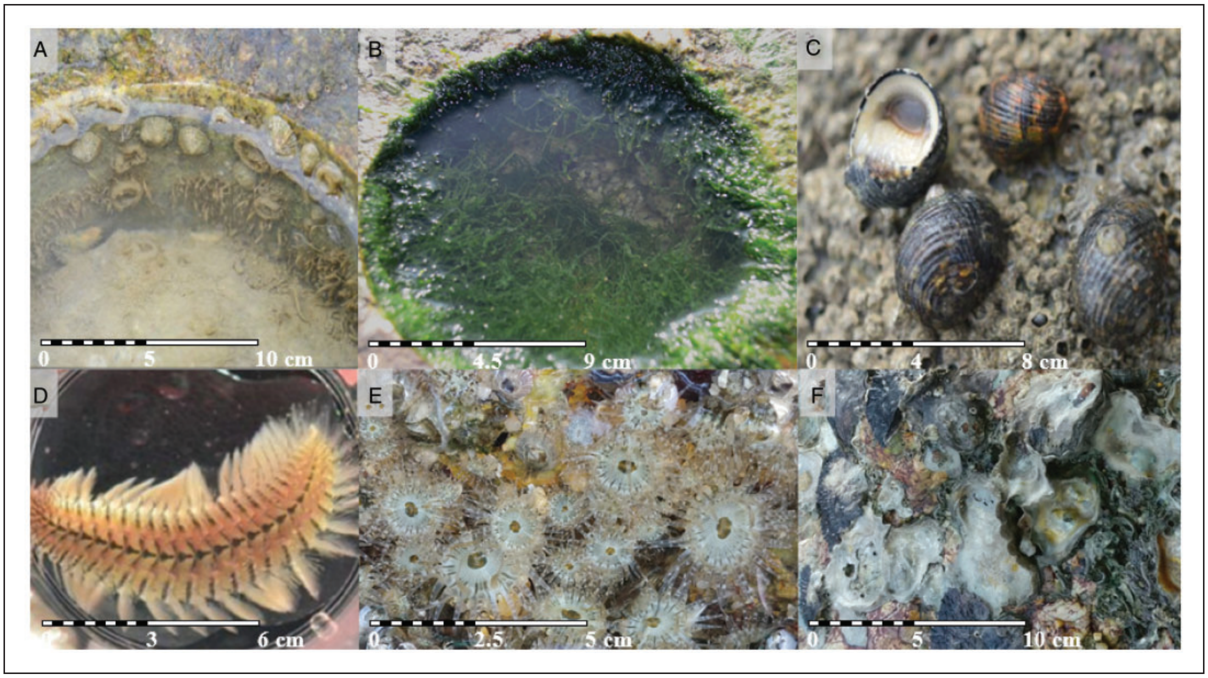

Figure 5. Organisms Found Within the Artificial Rock Pools. (A) Limpets, polychaetes and algae, (B) *Penaeus merguiensis* and green algae with *Nerita* sp. egg capsules on the fronds, (C) *Nerita chamaeleon*, (D) polychaete, (E) *Anthopleura nigrescens*, and (F) *Saccostrea cucullata*.

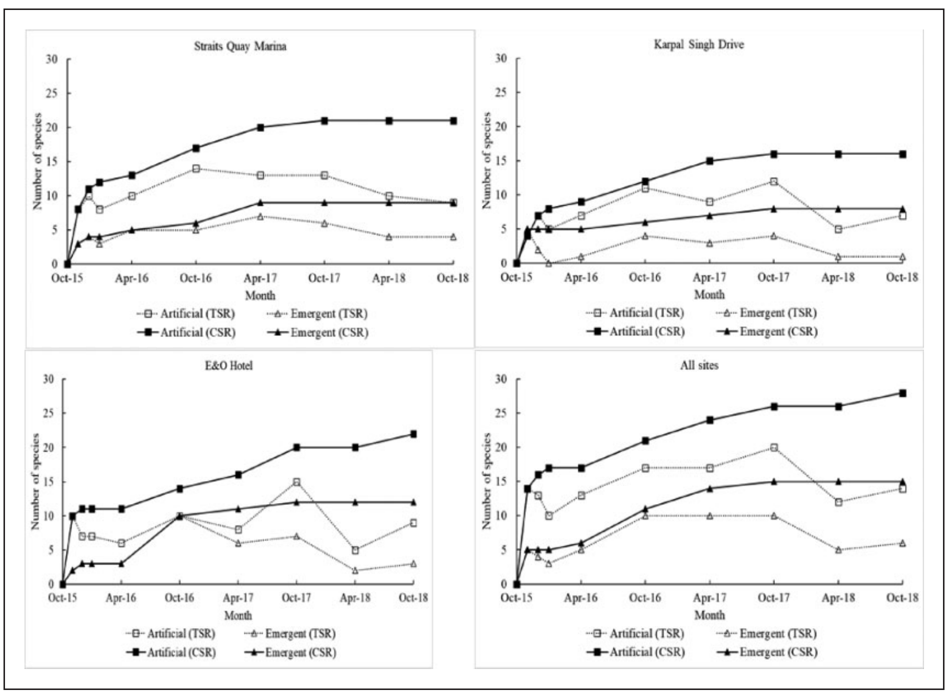

Figure 6. Total Species Richness (TSR: Dashed Lines) and Cumulative Number of Species (CSR: Solid Lines) Recorded in Artificial Rock Pools (Squares) and on Emergent Rock Surfaces (Triangles) Over 36 Months.

Comparing Deep and Shallow Artificial Rock Pools

There was no significant difference in mean species richness ($F_{1,18} = 0.008$, $p = 0.932$) (Table S2) between "deep" (12 cm) (11.4 ± 1.6 s.e.) and "shallow" (5 cm) (11.2 ± 1.7 s.e.) artificial rock pools or community structure (pseudo-$F_{1,18} = 0.197$, p(perm) $= 0.941$) (Table S3) after 36 months. From two-way ANOVA analysis, there was no significant difference in the species richness

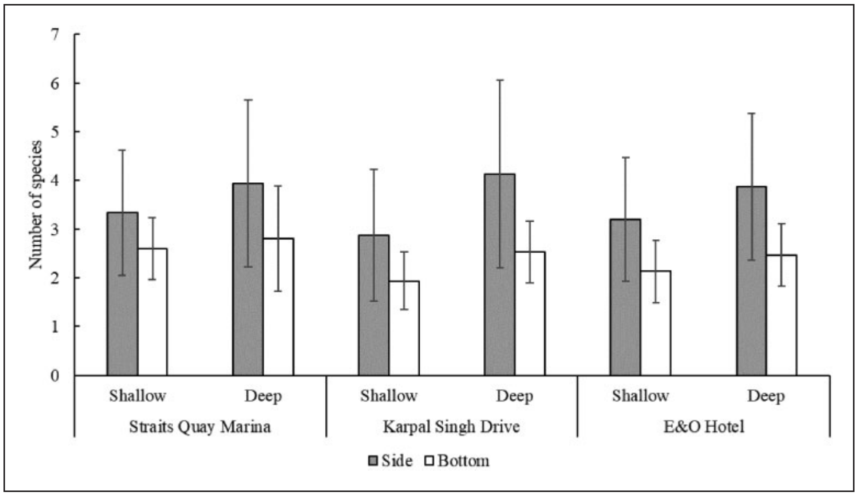

Figure 7. Mean Species Richness (With Standard Deviation) on Side (Grey Bars) and Bottom (White Bars) Surfaces Between Deep and Shallow Artificial Rock Pools at Straits Quay Marina, Karpal Singh Drive and E&O Hotel After 33 Months (for E&O Hotel) and 34 Months (for Straits Quay Marina and Karpal Singh Drive).

between the "deep" and "shallow" artificial rock pools ($F_{1,54} = 0.817$, $p = 0.370$) (Table S7) and sites ($F_{2,54} = 3.047$, $p = 0.056$) (Table S7).

Comparing Vertical Sides and Horizontal Bottom Surfaces of Artificial Rock Pools

The vertical sides and horizontal bottom surfaces were significantly different in species richness ($F_{1,58} = 25.655$, $p < 0.001$) (Table S4) and community structure (pseudo-$F_{1,58} = 59.640$, p(perm) < 0.001) (Table S5). From two-way ANOVA analysis, we found a significant difference in the species richness between the vertical sides and horizontal bottom surfaces ($F_{1,174} = 39.160$, $p < 0.001$) (Table S8), but no significant difference in richness between sites ($F_{2,174} = 1.030$, $p = 0.359$) (Table S8). The dissimilarity was attributed to two groups: sessile animal and algae (pseudo-F = 74.650, p(perm) < 0.001) and mobile animals (pseudo-F = 14.350, p(perm) <0.001) (Table S5). The total species richness on the vertical sides was significantly higher than on the horizontal bottom surfaces in all of the drill-cored rock pools after 33 months (for E&O Hotel) and 34 months (for SQM and KSD) (Figure 7). Regardless of depth, the number of species present on the sides were higher than the bottom surfaces of the pools (Table 1). SIMPER analysis (Table 2) reported that more than 90% of the dissimilarity observed between the two surfaces was attributed to two green macroalgae species, *Bryopsis* sp. (47.15%) and *Ulva reticulata* (15.52%), which were significantly more abundant on horizontal bottom surfaces. On the other hand, organisms like barnacles *Amphibalanus amphitrite* (18.51%) and mobile molluscs, *Cellana radiata* (6.18%) and *Siphonaria guamensis* (3.84%), showed preference and significantly more abundance on the vertical side surfaces of drill-cored rock pools.

Environmental Parameters

Temperature was the highest on emergent surfaces, slightly decreased in shallow pools and lowest in deep pools (Table 3). Salinity and pH did not differ much between deep and shallow pools. Dissolved oxygen was higher in shallow compared to deep pools. Evaporation rates were higher in shallow compared to deep pools.

Discussion

The incorporation of drill-cored artificial rock pools to create topographic complexity has enabled the significant increase in species richness and enhancement of community structure of organisms living on the mid-tide rock revetments at all three sites. All sites show a doubling of the number of species found inhabiting artificial rock pools, otherwise not found on the emergent surfaces of the rock revetments in the monitored 36-month period. The total species richness at all three sites fluctuated slightly over the sampling period of 36 months with no similarity among the patterns of fluctuation at all three sites. However, total species richness seemed to decrease in April and increase in October. Local temperatures are usually elevated from February to Jun (Figure S1) corresponding to the dry season and the effects from heat and desiccation could have contributed to total species richness decrease observed in April. In contrast, local temperatures are generally lower from July to January (Figure S1) and the milder weather may prove less stressful for more species. Even though fluctuations were observed in total species richness, the

Table 1. Presence and absence of species on side and bottom surfaces of deep and shallow artificial rock pools at each site.

		Pools sides						Pools bottom					
	Species/sites	Straits Quay Marina (S)	Straits Quay Marina (D)	Karpal Singh Drive (S)	Karpal Singh Drive (D)	E&O Hotel (S)	E&O Hotel (D)	Straits Quay Marina (S)	Straits Quay Marina (D)	Karpal Singh Drive (S)	Karpal Singh Drive (D)	E&O Hotel (S)	E&O Hotel (D)
Sessile animals	*Amphibalanus amphitrite*	X	X	X	X	X	X	X	X	X	X	X	X
	Chthamalus malayensis		X		X	X	X						
	Anthopleura nigrescens	X	X	X	X	X	X	X	X	X	X	X	X
	Saccostrea cucullata	X	X	X	X			X	X	X	X		
	Sabellastarte sp.			X	X								
Mobile animals	*Littoraria undulata*	X	X	X	X	X	X						
	Nerita articulate	X	X										
	Nerita chamaeleon	X	X					X					
	Neothais marginatra					X	X						
	Cellana radiata	X	X			X	X						
	Siphonaria guamensis			X	X								
	Penaeus merguiensis								X		X		X
	Grapsus albolineatus								X				
	Myomenippe hardwickii								X				
Macro-algae	*Ulva reticulata*					X	X					X	X
	Bryopsis sp.	X	X	X	X			X	X	X	X		
Total species richness		8	9	7	8	7	7	5	7	4	5	3	4

S = shallow; D = deep.

Table 2. Differences (< and >) in mean abundances [counts (#) or percentage cover (%)] of species recorded on side and bottom surfaces of artificial pools at all sites after 33 months (for E&O Hotel) and 34 months (for Straits Quay Marina and Karpal Singh Drive).

Taxon	Mean pool side		Mean pool bottom	Contrib. %	Cumulative %	Av. dissim
Bryopsis sp. (%)	13.0000	<	48.3000	47.1500	47.1500	25.2900
Amphibalanus amphitrite (%)	26.8000	>	15.1000	18.5100	65.6700	9.9300
Ulva reticulata (%)	5.8900	<	17.7000	15.5200	81.1900	8.3250
Cellana radiata (#)	5.1600	>	0.0000	6.1820	87.3700	3.3160
Siphonaria guamensis (#)	3.2200	>	0.0000	3.8440	91.2100	2.0620
Penaeus merguiensis (#)	0.0000	<	2.2600	3.1540	94.3700	1.6920
Chthamalus malayensis (%)	1.8300	>	0.0000	2.1450	96.5100	1.1510
Anthopleura nigrescens (#)	0.7330	>	0.6670	1.2290	97.7400	0.6591
Littoraria undulata (#)	0.6560	>	0.0000	0.8664	98.6100	0.4647
Saccostrea cucullata (#)	0.4000	>	0.1110	0.5496	99.1600	0.2948
Sabellastarte sp. (#)	0.1890	>	0.0000	0.2411	99.4000	0.1293
Neothais marginatra	0.1890	>	0.0000	0.2411	99.6400	0.1293
Nerita articulata (#)	0.1220	>	0.0000	0.1709	99.8100	0.0917
Nerita chamaeleon (#)	0.0778	>	0.0333	0.1416	99.9500	0.0760
Grapsus albolineatus (#)	0.0000	<	0.0222	0.0340	99.9800	0.0182
Myomenippe hardwickii (#)	0.0000	<	0.0111	0.0155	100.0000	0.0083

Species are listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community). Contrib. %, percentage contribution to multivariate dissimilarity; Cumulative %, cumulative total of the observed dissimilarity; Av. dissim, average dissimilarity across all pairs of samples. Overall average dissimilarity = 53.64%.

Table 3. Temperature, salinity, dissolved oxygen, pH and evaporation rates for deep and shallow pools and temperature on emergent surfaces.

	Shallow pool	Deep pool	Emergent surface
Temperature (°C)	28.08 ± 1.97	27.93 ± 1.80	29.88 ± 0.32
Salinity (ppt)	32.13 ± 4.40	32.20 ± 3.58	–
Dissolved oxygen (mg/L)	8.01 ± 3.86	6.96 ± 3.32	–
pH	7.57 ± 0.76	7.47 ± 0.64	–
Evaporation rate (ml/h)	2.56 ± 0.37	1.76 ± 0.56	–

cumulative species richness in the artificial pools and on emergent surfaces at all three sites increased over time with artificial pools yielding consistently higher values compared to its surrounding emergent surfaces.

Eco-engineering on hard structures purpose-built for controlling coastal erosion, such as the rock revetments in this study are known to enhance biodiversity and conserve marine species on otherwise inhospitable urban habitats (Loke et al., 2019). Eco-engineering achieves this through creation of structural complexity (Hall et al., 2018; Loke & Todd, 2016; Waltham & Sheaves, 2018) and research has repeatedly shown increase of species richness and abundance of intertidal organisms through this approach (Loke et al., 2019). By adding complexity onto coastal defence structures, the properties of shade and moisture are introduced, and this minimizes temperature fluctuations, stress from desiccation, and facilitates the recruitment of intertidal organisms (Firth et al., 2013; Metaxas & Scheibling, 1993; Seabra et al., 2011). In this study, highly adaptable barnacles were dominant with very few other species living on the emergent surfaces. Interestingly, organisms adapted to low-tide (e.g. anemones), and sub-tidal regimes (e.g. shrimps, crab, red algae) were found thriving in our artificial rock pools at the mid-tide level. This suggests that the artificial rock pools provided environmental conditions similar to the low-tide or sub-tidal conditions (e.g. water retention or increased habitat complexity and/or surface texture) which enabled the extension of the vertical distribution of some species to mid-tide level on the rock revetments. Similar observations have been made in temperate region studies by Evans et al. (2016) whereby an extension to the distribution of some of its low-tide benthic organisms implies the artificial rock pools could support viable populations of these taxa. Interventions such as artificial rock pools can indeed improve environmental conditions on and increase the capacity of rock revetments to support nature, which is often limited in available habitat and reduced in survivorship when faced with human-made structures.

Many benthic organisms recorded exclusively in the artificial rock pools (e.g, bryozoans, polychaete, red macroalgae) were present in much lower abundances overall than the common species (e.g. barnacles). The artificial rock pools also supported several species of mobile organisms that were not otherwise living on the emergent rock surfaces (e.g. arthropods, polychaetes, as well as some species of molluscs). The scarcity of mobile organisms leading to low biodiversity on coastal defences was previously reported (Chapman, 2003; Evans et al., 2016; Pister, 2009) citing several factors including habitat variability (e.g. pits, grooves, pools, overhangs and availability) (Chapman, 2003; Firth et al., 2015).

Deeper rock pools were expected to have milder fluctuations in environmental conditions and thus support higher diversity compared to shallower pools. Past research (Metaxas & Scheibling, 1993) show that the effects of heat and desiccation are usually more pronounced in shallower rock pools and indeed were reported to have lower diversity (Martins et al., 2007). However, like the study conducted by Evans et al. (2016), we found no significant difference between the 12-cm and the 5-cm artificial pools in terms of richness and community structure after 36 months even though higher temperature and evaporation rates were observed for shallower pools. Since the depth of the pools has no significant effect on the richness and community structure, the intervention application would then depend on other factors such as construction constraints of the artificial rock pool (e.g. time, cost, manpower). It is also important to note that although species richness and community structure remained the same, abundance was greater in the deeper 12-cm compared to the shallower 5-cm rock pools. This is because the deeper rock pools provided a larger surface area of colonisation and had a greater extent of preferred vertical surfaces and inclination could have provided more radiative shade for organism colonisation.

Preliminary observations reveal that the marine organisms in this study were selecting different surfaces to attach and live. The two green macroalgae species *Bryopsis* sp. and *Ulva reticulata* significantly more abundant on horizontal bottom surfaces. Some organisms including certain barnacles and mobile molluscs, showed preference and abundance on the vertical side surfaces of drill-cored rock pools. The selection of microhabitat by these marine organisms was clearly revealed by the *ad hoc* survey and data analyses. Benthic polychaetes and all the gastropods species were found exclusively on the vertical side surfaces, while all the mobile arthropod species were found exclusively on the horizontal bottom surfaces of the artificial rock pools. The likely cause of such vertical surface preference is sedimentation avoidance for the benthic polychaetes and gastropods, and for mobile arthropods, to seek refuge from large predators like birds and otters. The cylindrical shape of the artificial rock pools also provided ample space for certain barnacles (such as *Amphibalanus amphitrite*), anemone, and oysters to utilize both horizontal and vertical surfaces. It was interesting to note that the other species of barnacles, *Chthamalus malayensis*, could only be found on the vertical side surfaces as opposed to the utilization of both surfaces by the *A. amphitrite*. The *C. malayensis* seemed to prefer periodical emersion to complete submersion in the artificial rock pools.

Another atypical observation was the habitat selection of both side and bottom surfaces within the rock pools by some species including the green macroalgae. It was common to observe sedimentation at the bottom of the artificial rock pools during low tide periods. It is highly likely that sediments were flushed out of the pools during ebb and flow of tides to expose bottom surfaces and allow for photosynthesis and survival of the green algae. These observations highlight the importance of design in eco-engineering as different species have preferential habitats selection. When planning for interventions in habitats for built marine environments, especially for a tropical setting, it can be designed to incorporate enough variability, suitable depths, optimised inclination, and sufficient shade to enable conducive colonisation of native marine organisms.

Man-made structures along the coastal zone, such as the granite rock revetments in this study, tend to be colonised by hardy, opportunistic, and invasive species (Dafforn et al., 2009, 2012; Glasby et al., 2007). These structures are corridors for invasive species which could lead to disparate (Mayer-Pinto et al., 2018a; 2018b) or even disruption of local ecological functioning (Airoldi et al., 2015; Bishop et al., 2017). Therefore, another aim of science-led eco-engineering is to design habitat enhancements to mimic natural characteristics as closely as possible. This can encourage the settlement of native species and inhibit proliferation of invasive species. The addition of artificial rock pools onto the rock revetments at the three sites facilitated the colonisation of native species only. Throughout the three years of monitoring, no invasive species were found within these pools or on the emergent surfaces of the rock revetment.

Besides creating habitat for nature on human-made structures and compensating the loss of biodiversity through development of natural ecosystems, habitat enhancements may be designed to promote the colonisation of commercially important species (Chapman & Blockley, 2009; Dugan et al., 2011). In Bangladesh, eco-engineering of shellfish reefs has provided defence, enhanced food production, and alleviated poverty by providing a source of income for the local community there (Tangelder et al., 2015; Ysebaert et al., 2017). Boulder habitats were considered for the recruitment and survival of abalone (Haliotis sp.) of commercial importance in the American Pacific coast (Liversage & Chapman, 2018). In this proof-of-concept study, the drill-cored rock artificial rock pools were also utilised by species of high commercial value such as oysters, shrimps, and mussels. Each of these species contributes significantly to the Malaysian economy through fisheries and aquaculture and have wholesale values amounting to millions of dollars per year (FAO, 2019).

Implications to Conservation

In Malaysia, guidelines for ethical and responsible development of the natural environment is stated in the National Policy on Biological Diversity 2016–2025. Developers and engineers of coastal zones are now beginning to consider incorporating ecological values into their large-scale reclamation projects. Increasing incentives and support for the greening of grey infrastructure in the built marine environment now exist. We were interested in a proof-of-concept that eco-engineered rock pools in human-made coastal revetments would increase biodiversity and enhance community structure in the tropical setting of Penang Island similar to temperate counterpart sites.

After 36 months of monitoring the artificial rock pools compared to emergent rock surfaces on the rock revetments, we have proven that species richness and community structure was significantly enhanced with our interventions. While the depth of artificial rock pools is not a factor, preferential habitat selection could occur within microhabitats of this scale between the vertical and horizontal surfaces created. Additionally, the drill-cored artificial rock pools at a mid-tide level can provide a space for a broad range of settlement of marine organisms from those adapted to low-tide or sub-tidal areas to inhabit. The drill-cored rock pools were also found to encourage the colonization of native species only but acknowledge the time of construction is also an important consideration to deter the colonization of non-native species.

We demonstrate the potential of these habitat enhancements in a tropical setting and advocate its consideration for future coastal zone development projects. Eco-engineering approaches can produce significant local biodiversity benefits through creation of living spaces that mimic natural habitats. They limit the spread of invasive and opportunistic species on coastal infrastructure and promote regional species dispersal by providing "stepping stones". Blue-green infrastructure have also been credited to improve supporting, provisioning, regulating, and cultural services.

Scale-up projects of artificial rock pools could reveal broader beneficial impacts on the local economy and society. Engagement of coastal zone developers to adopt this habitat enhancement intervention can prove to be economical, efficient, and robust when used concurrently during the design phase, or incorporated in retrospect of their development projects. The intervention of artificial rock pools in defence structures can function, to a certain extent, as surrogate habitat to promote biodiversity and compensate some of the deleterious impacts from the construction of man-made infrastructure. However, it is important to reiterate that although the techniques were successful when applied in our experimental sites, one size does not fit all and the chances of success greatly depends on local abiotic and biotic stressors as well as habitat requirements of the species pool. It should also be cautioned that eco-engineering approaches should not be used to gain approval for harmful development.

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Supplemental material

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