Marine Pollution Bulletin 173 (2021) 112935

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Epibenthic communities from offshore platforms in the Arabian Gulf are structured by platform age and depth

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ARTICLE INFO

Keywords:
Artificial reefs
Sessile communities
Biodiversity
The Gulf
Qatar
Rigs to reefs

ABSTRACT

Oil and gas platforms act as artificial habitats for a myriad of marine organisms. In this study, we used opportunistic remotely operated vehicle (ROV) data to describe fouling assemblages through the characterization of functional groups in the Al Shaheen oil field, situated in Qatari waters. The surveys showed a strong vertical stratification, with the number of functional groups increasing from the surface to the bottom. In addition, the majority of functional groups had their highest frequency of occurrence in the 35–60 m interval. In turn, multivariate analyses showed a slight structure among platforms with different ages. The lowest number of functional groups occurred in the early ages (2–3 years old), and some groups either increased or decreased their frequency and abundance along the years. A step further is now required to determine whether these platform foundations should be converted to reefs after their decommissioning (i.e., Rigs to Reefs approach).

1. Introduction

Human-made constructions in the marine realm are becoming a pivotal habitat for sessile organisms (Airoldi et al., 2008; Bishop et al., 2017). Artificial substrates not only underpin changes in species composition through recruitment and settlement, but to the whole ecosystem functioning (Ponti et al., 2002). Thus, artificial substrates may be considered as a plausible alternative that aims to mimic natural substrates (Granneman and Steele, 2015; Perkol-Finkel et al., 2006), since they provide several benefits to the ecosystem such as, reef restoration of degrading communities, providing food source and shelter for fish and also promoting an increase of biomass of benthic invertebrates (Baine, 2001; Bailey-Brock, 1989). However, other studies have shown that artificial substrates are not a feasible alternative to natural reefs due to the potential negative impacts on biodiversity (Jagerroos and Krause, 2016). In addition, it has been observed that community structure and species composition of the recruited communities can greatly vary from adjacent natural areas (Feary et al., 2011; Sanabria-Fernandez et al., 2018).

In artificial substrates, fouling assemblages are subjected to recruitment of species from adjacent natural substrates throughout the time, with a first stage of recruiters – "*First-order recruiters*", formed by high-mobility species, e.g. fish and taxa with highly-dispersed planktonic stages, as well as, widely distributed species. However, this recruitment greatly depends on the type of the artificial materials, i.e. wood, concrete or metal and coatings applied, e.g. antifouling paints. A second stage of "*Second-order recruiters*" is developed afterwards with species that are able to compete for space and food, following a succession model (see Connell and Slatyer, 1977) in which initial settlers dominate the substratum delaying thus the appearance of secondary ones (Perkol-Finkel and Benayahu, 2005). The recruitment of sessile organisms, e.g. mollusks, corals, sponges and barnacles on the artificial substrates creates conditions for the settlement of other taxa, supporting higher reef species complexity and species interactions (Bram et al., 2005).

Artificial substrates in the Arabian Gulf have an extensive history since the first periods of fishing (Bartholomew and Feary, 2012). The main purpose of deploying artificial materials that were available at that time, such as wood or stones, was to support and improve fish catch

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https://doi.org/10.1016/j.marpolbul.2021.112935
Received 1 June 2021; Received in revised form 1 September 2021; Accepted 3 September 2021
Available online 22 September 2021

(Stone et al., 1991), and habitat restoration (Seaman, 2007). Therefore, in the Arabian Gulf region, artificial substrates can be considered a historical tool to support the marine economies and social life as they contribute to maintaining diverse ecological communities of benthic invertebrates, fish and other organisms (Burt et al., 2009a). Specifically about oil and gas platforms, although they are considered as non-planned artificial habitat, numerous cross beams and large interstitial spaces create both physical complexity for protection and add hard substratum throughout the water column for the establishment and proliferation of fouling organisms (algae and epifauna) and fish (e.g., Feary et al., 2011; Stachowitsch et al., 2002; Torquato et al., 2017). Importantly, the high vertical relief of the platforms, the upper depths and the deeper structure, allow sessile species to settle in the suitable depth at various life-stages.

In the Arabian Gulf oil and gas platforms started being established in the 1950s and currently contains over 800 oil platforms (Sheppard et al., 2010). Nevertheless, a large portion of these platforms is reaching their production lifespans and, therefore, a growing source of material for Rigs to Reefs (RTR), i.e., converting standing platforms into reefs, will be available soon. Although future decommissioning of their structure is an unavoidable issue, the biological composition inhabiting this artificial habitat is largely unknown, and complicates the debate on whether platform jackets should be completely removed after decommissioning or left in place as artificial reefs. In the Arabian Gulf this debate is urgent and delicate given the loss in natural reef habitat during the last decades, due to both coral bleaching and anthropogenic actions. Over 85% of the Arabian Gulf natural coral habitats are considered threatened (Burke et al., 2011) and artificial habitats in this area, including platforms, are seen to offset for this loss.

A major impediment to understanding the effects of oil and gas platforms on marine biodiversity has been the restrictions for researchers to access these submerged structures. In fact, besides being located in relatively inaccessible environments for traditional SCUBA diving, oil fields are considered top-security areas with an exclusion zone of at least 500 m around the structures. Alternatively, routine inspection and maintenance surveys using remotely operated vehicles (ROV's) are carried out to monitor the integrity of underwater installations. In biological surveys, ROV's have been used as part of effective methods to gain insight into the organisms present on offshore platforms, as they allow for the inventory of large numbers of species present on vast amounts of surface area and at all depths (e.g., Ajemian et al., 2015; Torquato et al., 2017).

Since RTR programs do not consider retaining the full vertical extent of the platforms, an evaluation of how the ecological functional groups composition and their relative abundance may change vertically is important for estimating the potential environmental impacts on these functional groups after removing the upper portion of the submerged structures. In addition, the assemblage composition on artificial habitat changes over time (Bram et al., 2005), such that temporal characterization of recruitment on the platform's jacket is pivotal to decide whether the structures should be removed or maintained. Therefore, this study aims to explore fouling assemblages through the characterization of functional groups composition considering environmental factors that may affect them, such as depth and age since platform installation.

2. Material and methods

2.1. Study area and artificial habitat description

The Arabian Gulf is a young sedimentary basin (ca. 15,000 years old) located in a subtropical region. During the last glacial maximum, when the sea level was 120 m lower than the present, the Gulf region had its ground almost completely exposed (Sheppard et al., 2010). Nowadays, the seawater floods the ca. 1000 km length of the Arabian Gulf, with a maximum width of 370 km and mean depth of 35 m, rarely exceeding 100 m depth (Siebold, 1973; Vaughan et al., 2016). Restricted water exchange with open-ocean, through the Strait of Hormuz, and regional climate associated with desert condition due to surrounded hyper-dried lands, create extreme environmental conditions in the Arabian Gulf, which is characterized by hyper saline water (often >42 ppt; Swift and Bower, 2003) and highly variable sea surface temperatures (SST) among seasons (Nesterov et al., 2021). During the summertime, the Gulf becomes the warmest sea on Earth, with SST frequently exceeding 35 °C (Vaughan et al., 2016), whereas SST below 13 °C are common in the wintertime (Coles, 2003).

This study was carried out in the Al Shaheen oil field, situated in the north of the Qatari exclusive economic zone (EEZ), ca. 90 km far from the coast. The Al Shaheen field was first discovered in the mid-70s though the development of the reservoirs commenced in the early 90s (Thomasen et al., 2005). Thus, this oil field plays a key role as long-lasting (> 20 years) artificial substrates in offshore environments at the Arabian Gulf. Presently, the Al Shaheen field encompasses 20 platforms belonging to 9 locations (A-I), with platforms differing according to their height, year of installation and function (Fig. 1).

2.2. ROV survey of fouling community

Annual technical routines were conducted by Mærsk Oil Qatar using a ROV (mod. SAAB Seaeye Surveyor Plus 229) to inspect submerged platform structures. Data were obtained from 4510 video footages, which were available to assess fouling communities on platforms' jackets. They were recorded in five years (2007, 2009, 2010, 2011, 2014), at 8 locations and 14 platforms from the Al Shaheen oil field (Table 1).

Previous analyses showed that the position of the platforms (i.e., locations) did not have any correlation with the fouling community (Range et al., 2018). Therefore, videos were selected to focus on depth intervals and platform age groups. Depth encompassed twelve intervals (each spanning 5 m) from surface to sea bottom. Since the platforms are situated in different water depths and thereby vary their height, a maximum depth of 60 m was chosen for sake of comparison. Age groups ranged from 2 to 17 years old, that is, the difference between year of platform installation (1997 - 2009) and video recording (2007–2014; see Table 1). Furthermore, a preliminary analysis was performed to determine the appropriate time intervals of each sampling unit. To do so, four different depths (15, 30, 45 and 60) were selected and results showed that after 30 s the proportion of functional groups did not change significantly at any of those depths.

To capture the fouling community in this study, we randomly selected a total of 68 videos where the ROV moved vertically along the platform, while the 30s-time interval was set for the consistent depth interval (e.g., 15–20 m, 20–25 m, and so on). If the ROV stopped or moved irregularly, the timer was stopped, and resumed as the ROV got back to course, otherwise another video was selected to cover the remaining depth intervals of the same platform. Thus, although opportunistic, our survey can be considered similar to continuous roving transect (CRT) methods (see Ajemian et al., 2015), where video transects of thirty seconds each were performed at twelve depth intervals for thirteen platform age groups. These results in a total of 156 age * depth combinations, for which 3 independent replicate videos were used, amounting to a total of 468 sampling units.

The CATAMI Classification Scheme (CCS; Althaus et al., 2015) was adapted to identify fouling organisms recorded in ROV footages. A total of 17 biological components were considered (Supplementary Information; Table S1) at each depth range. Species abundance was visually estimated as the percentage area covering the hard substratum, following a semi-quantitative SACFOR scale (Hiscock, 1990; Super-abundant: 80-100% [numeric equivalent; 6], Abundant: 40-79% [5], Common: 20-39% [4], Frequent: 10-19% [3], Occasional: 5-9% [2] and Rare: 1-5% [1]).

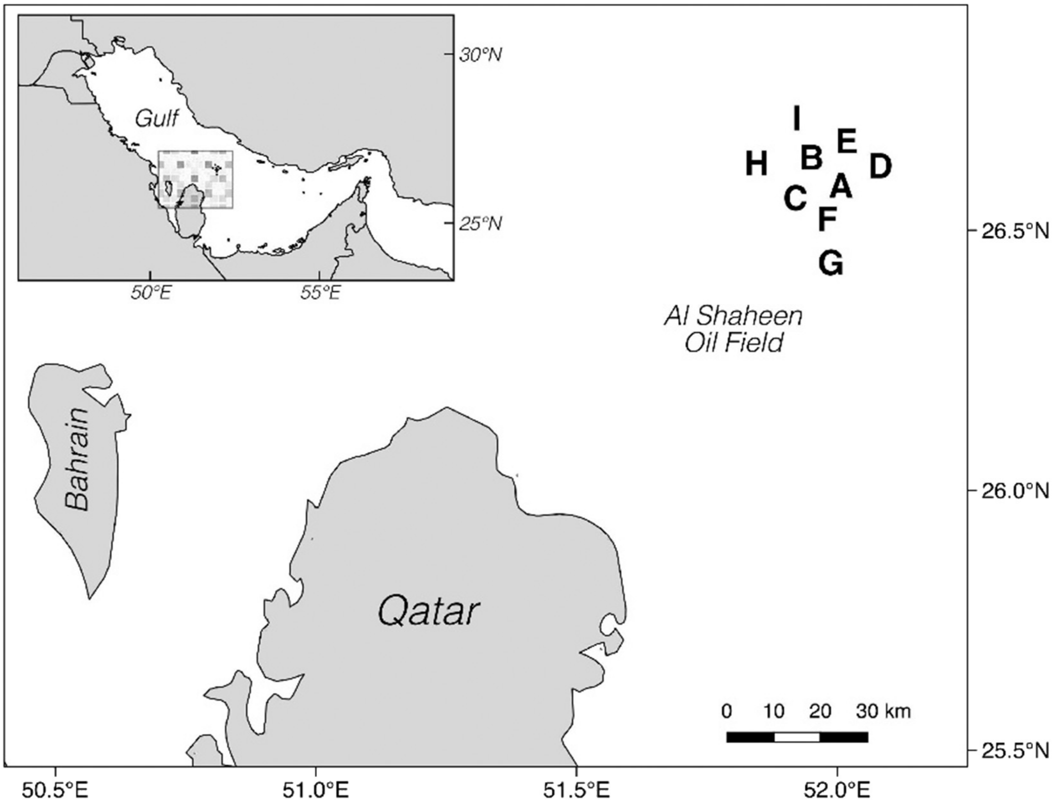

Fig. 1. Map of platform locations (A-I) in the Al Shaheen oil field in northeast of Qatari exclusive economic zone.

Table 1
Oil and gas platforms in the Al Shaheen oil field in the Qatari exclusive economic zone included in the study.

Location	Platform	Year of	Max. Depth	Weight	Sampling year				
		Installation	(m)	(MT)	2007	2009	2010	2011	2014
A	C	1997	60	774					+
	D	1998	62	2078					+
B	A	1998	61	3610	+	+	+		+
	B	1997	61	671					+
	C	2004	61	1098					+
	G	2009	61	7986					+
C	A	1998	56.5	3590		+		+	
D	B	2004	65	941					+
E	B	2004	66.5	958					+
	F	2009	66.5	913					+
F	A	2004	55	4440	+		+		
H	A	2007	57	3407		+		+	+
	B	2009	57	–					+
I	A	2007	69.5	4139		+		+	+

2.3. Statistical analysis

Minor functional groups (< 5%) in total footage were not considered for the analyses, and thus thirteen functional groups remained for the multivariate analyses. Resemblance patterns among both depth ranges and age of platforms were observed in a two-dimensional non-metric multidimensional scaling (nMDS) plot using Bray–Curtis index of dissimilarity. Next, we tested potential difference across the spatial or temporal group depicted in the nMDS according to depth ranges, age of platforms and interaction depth * age, through permutational analysis of variance (PERMANOVA) with 5000 permutations. We also performed a similarity permutation analysis (SIMPER) to determine the average contribution of functional groups driving differences between both the depth intervals and the age of platforms. All previous multivariate analyses were run using the *vegan* package in R (Oksanen et al., 2020). Moreover, the association of the most prominent species to both the depth range and the age of platforms were assessed by the indicator value index (IndVal; Dufrêne and Legendre, 1997) and its posterior statistical significance ($p < 0.05$) was obtained by a randomization procedure (5000 permutations). The IndVal quantifies the fidelity and specificity of species in relation to groups of sites. This analysis was performed with the *labdsv* package in R (Roberts, 2019).

3. Results

Cirripedia and Encrusting were ubiquitous (> 99% occurrence in the 468 samples), while Turf was highly frequent (> 75% samples). In contrast, four functional groups were rare (< 5%) and thereby excluded from multivariate analyses, namely, Urchins (3.2%), Anemones (< 2%), Bryozoans (< 1%) and Massive sponges (< 1%).

3.1. Depth range

The numbers of functional groups generally increased from the surface to the sea bottom, peaking at depths exceeding 35 m (Fig. 2a). Cirripedia, Encrusting and Turf were present throughout the entire depth range, whilst Bivalves were absent in the deepest layer (55-60 m; Fig. 3). Some functional groups were exclusively present in shallow layers, whereas others restricted to deep ones. For example, Bryozoa was restricted to 0–20 m range, in contrast to Branching that first appeared at 20-25 m; Anemone at 25-30 m; Fan complex, Foliaceous, Bushy and Hard coral at 35-40 m; and Whip at 40–45 m.

Twelve functional groups had their highest frequency of occurrence in the 35-60 m range, whereas, for the remaining five groups the maximum frequency of occurrence was in the 0-20 m range. Among the functional groups that were present at all depth ranges, Cirripedia and Encrusting did not change their frequency of occurrence from the surface to the bottom, on the other hand, Bivalves decreased its frequency as depth increased while Turf increased its frequency with depth (Table 2).

The depth gradient also affected the abundance of the groups. For example, median abundance of Encrusting and Turf decreased from the surface to the bottom, while Fleshy arborescent increased its median abundance as depth increased. The other groups did not change their medians along the depths where they were recorded (Fig. 3). Vertical stratification was evident and clearly sighted in the first axis of nMDS (Fig. 4a). In addition, species composition differed significantly among depth strata (PERMANOVA, $p < 0.001$). PERMANOVA showed that depth alone explained 54% of the model variance (Table 3). Pairwise comparisons of depth intervals with SIMPER analysis indicated that Turf was the group contributing with the highest dissimilarity between upper and lower strata, followed by Fleshy arborescent and Hard corals (Fig. 5). This corroborates with the results depicted in Fig. 3, which shows that the abundance of these groups increases from the surface to the sea bottom.

According to the IndVal index, the most prominent functional groups in the first depth ranges were Cirripedia (0-5 m), Encrusting (5-10 m), Bivalve (15–20 m); in middle layers Turf (35–40 m); and in deep layers Hard coral, Fan complex, Bushy (45–50 m), Foliaceous (50–55 m), Fan simple, Fleshy arborescent, Crinoids and Whip (55–60 m; Table 4).

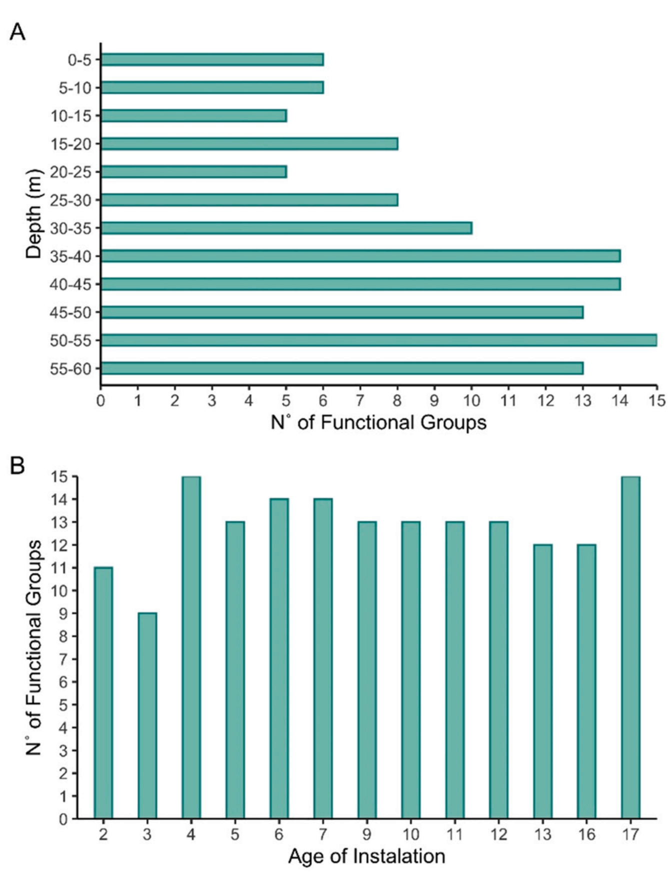

Fig. 2. Count of functional groups by 5 m depth strata along the vertical profile of platforms (A) and by age of the community (B).

3.2. Age of platforms installation

Regarding the age of the platforms, 11 of 17 groups were present in the platform's legs since the second year of installation. Of these groups, Bryozoa, Massive sponge, Fan complex and Whip were not recorded within the three first years, with the two last groups appearing in the fourth and fifth years, respectively. In turn, Bryozoa and Massive sponge were not recorded in the first years likely because they had very low overall frequency of occurrence throughout the years. Interestingly, Hard coral progressively increased its frequency along the years with peaks from the twelfth year (Fig. 2b and Table 5).

For most of the groups, the median abundance throughout the years was zero, except for Cirripedia, Encrusting and Turf (Fig. 6). Looking at the upper quartile, however, Hard coral steeply increased its abundance as time passed by. The nMDS analysis showed a slight temporal pattern in the fouling community across the years (Fig. 4b), especially when considering depth ranges >35 m (Supplementary Information; Fig. S1). PERMANOVA showed that age was a significant factor ($p < 0.01$), though it explained only 0.08% of the variance (Table 3). The age * depth interaction was also significant ($p < 0.01$) and explained 17% of the variance. Pairwise comparisons of platform ages using SIMPER analysis showed that Turf was the group contributing with the highest dissimilarity between ages, though the pairwise dissimilarity did not show a clear temporal trend for this group. Hard coral, in turn, indicated that dissimilarity tended to increase as the platforms became older (Fig. 7). The IndVal analysis showed that Turf (2 years), Bivalve (4), Foliaceous and Branching (5), as the most prominent functional groups in the first years. Whereas, Fleshy arborescent (7) in intermediate ages, and Fan complex and Hard Coral in older platforms (17; Table 6).

4. Discussion

The recurrent loss of natural reef habitat in The Gulf, due to both bleaching events and widespread urban coastal development, brings an unavoidable debate on whether platform foundations in The Gulf should be removed after decommissioning or converted in place as artificial reefs for marine organisms (i.e., RTR approach). Hence, describing communities inhabiting these submerged structures provides pivotal information to foster the debate and make decisions, in addition to providing baseline data to compare this community against neighboring natural reefs. Nevertheless, biological information of organisms in offshore artificial habitats is still fairly scarce in the region. Here, we took advantage of opportunistic data to generate this information that otherwise would not be known. The ROV survey used in this study represents the first assessment of fouling assemblages on a major oil field deployed in the EEZ of Qatar and the first in deep waters (>20 m) of The Gulf. In this region, previous studies were only carried out off Abu Dhabi (Stachowitsch et al., 2002) and off Iran (Amini et al., 2016), in areas as deep as 20 and 10 m, respectively, using conventional SCUBA diving.

The RTR approach does not consider retaining the whole vertical relief of the standing platforms (Ajemian et al., 2015). Thus, an assessment of how the functional groups may change with depth is important to estimate future impacts of these programs when selecting heights of platform jackets cutoff. Although the methods used here to assess the epigrowth on platform were semi-quantitative, it was clear that faunal composition on the jacket changed with depth. The cluster analysis depicted a sharp vertical structure in the distribution of the fouling

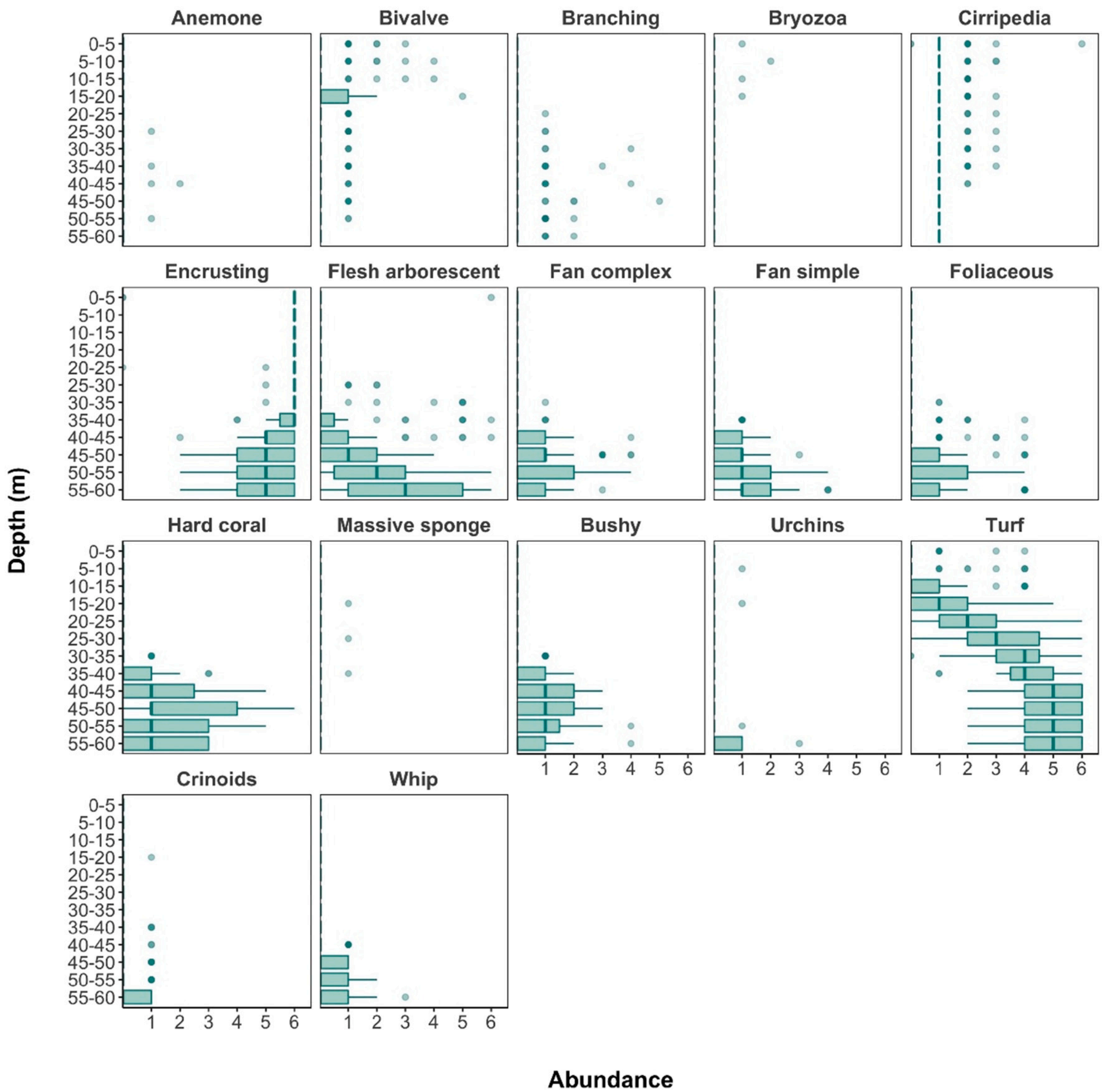

Fig. 3. Abundance boxplot by 5 m depth strata for each functional group.

Table 2
Frequency of occurrence (%) by 5 m depth interval for each functional.

	Depth ranges (m)											
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60
Anemone	0	0	0	0	0	2.6	0	2.6	5.1	0	2.6	0
Bivalve	20.5	20.5	15.4	30.8	12.8	15.4	7.7	12.8	7.7	10.3	5.1	0
Branching	0	0	0	0	2.6	5.1	7.7	12.8	12.8	12.8	20.5	10.3
Bryozoa	2.6	2.6	2.6	2.6	0	0	0	0	0	0	0	0
Cirripedia	94.9	100	100	100	100	100	100	100	100	100	100	84.6
Encrusting	94.9	100	100	100	97.4	100	100	100	100	100	100	84.6
Fleshy arborescent	2.6	0	0	0	0	12.8	15.4	25.6	33.3	53.8	74.4	71.8
Fan complex	0	0	0	0	0	0	2.6	7.7	28.2	59	43.6	35.9
Fan simple	0	0	0	0	0	0	0	12.8	38.5	51.3	69.2	71.8
Foliaceous	0	0	0	0	0	0	5.1	20.5	23.1	35.9	46.2	38.5
Hard coral	0	0	0	0	0	0	10.3	43.6	69.2	76.9	69.2	53.8
Massive sponge	0	0	0	2.6	0	2.6	0	2.6	0	0	0	0
Bushy	0	0	0	0	0	0	15.4	38.5	59	64.1	59	41
Urchins	0	2.6	0	2.6	0	0	0	0	0	0	2.6	30.8
Turf	15.4	23.1	41	64.1	87.2	92.3	94.9	100	100	100	100	84.6
Crinoids	0	0	0	2.6	0	0	0	7.7	5.1	12.8	12.8	28.2
Whip	0	0	0	0	0	0	0	0	17.9	46.2	43.6	35.9

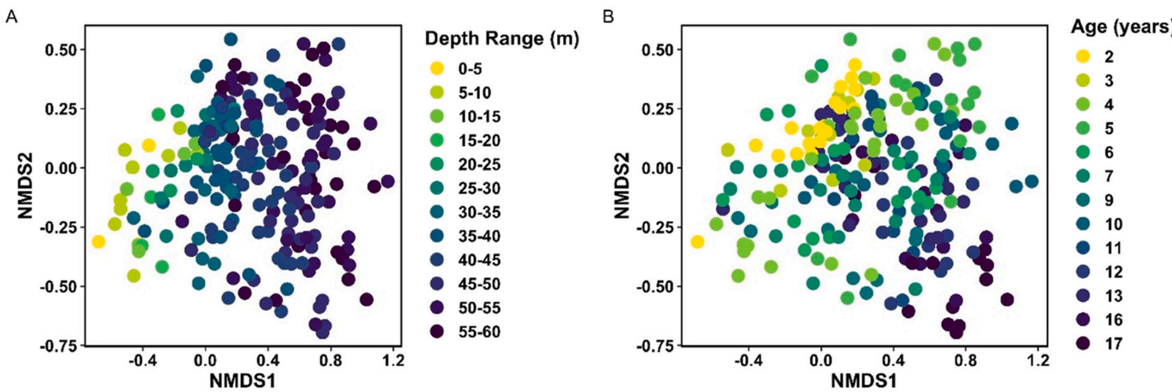

Fig. 4. nMDS ordination (Stress: 0.11) of fouling communities (A) at each depth range and (B) at each age.

Table 3
PERMANOVA table of results.

	Df	Sum of squares	Mean of squares	F. Model	R2	Pr (>F)
Depth range	11	27.724	2.52034	68.993	0.53865	2e-04
Age of installation	12	3.989	0.33240	9.099	0.07750	2e-04
Depth * Age	130	8.541	0.06570	1.799	0.16595	2e-04
Residuals	307	11.215	0.03653		0.21790	
Total	460	51.469			1.00000	

assemblage, with the highest number of functional groups found in deep portions of the structures, as well as the abundance of most groups. The results showed that removal of the first layers would mainly affect Cirripedes, Encrusting, Turf, Bivalves and Bryozoans. Actually, the three first were ubiquitous throughout the vertical profile, but the Bryozoans, besides rare, were restricted to 20 m depth.

Importantly, contrary to what one might expect due to the reduced light penetration, Hard coral was both frequent and abundant in deeper layers such that removing only the top layers of the platforms will not affect this group. Azooxanthellate scleractinian corals and soft corals (Alcyonacea) were commonly observed at depths greater than 30 m. The abundance of both groups increased with depth and the hard corals also tended to be more abundant on older platforms. The fact that azooxanthellate reef building corals are recruiting and growing on these oil platforms is highly significant, given that this type of corals had not previously been reported in Qatari waters. It further raises the question of whether their regional distribution extends beyond artificial substrates.

Our ROV survey supports previous worldwide literature documenting vertical trends in community structure, with different taxonomic groups contributing to each depth range: The Gulf (Amini et al., 2016; Stachowitsch et al., 2002), North Sea (Forteath et al., 1982; Whomersley and Picken, 2003), Gulf of Mexico (Lewbel et al., 1987) and Gulf of China (Yan et al., 2006). We also showed that the deepest zone was the most diverse with the highest number of functional groups occurring at 50-55 m ($n = 15$) followed by 35-40 m and 40-45 m ($n = 13$). Also in the Gulf region off Iran, samples from 10 m contained more fouling organisms than at 2 m (Amini et al., 2016). These trends corroborate investigations in the North Sea, where the bottom zones of platforms harbour a higher species richness and diversity compared to the surface layers (Schutter et al., 2019; Whomersley and Picken, 2003). In our study area, vertical structure was also observed for fish with a peak of species richness between 20 and 50 m depth (Torquato et al., 2017).

Thermocline position and turbulence from wave action may be important factors to explain the vertical structure. The thermocline in the study area is located around 18 m (Reynolds, 1993), in the Al Shaheen oil field above the thermocline temperature varies from 20 °C to 35 °C while below typically ranges from 20 °C to 27 °C, with occasional peaks over 30 °C (S. Bach, *pers. comm.*). Additionally, it has been suggested that impact of higher wave action near the surface decreases species richness (van der Stap et al., 2016), and may also dislodge recently coral recruits (Gass and Roberts, 2006; Roberts, 2002).

The ROV survey showed that the lowest number of functional groups occurred at early ages (2-3 years old), and the highest numbers were observed from the fourth year onwards. A slight temporal tendency of changing was observed in multivariate analyses, and some fouling groups either increased or decreased their frequency and abundance along the years. For example, coral colonies were maximized in older structures. Most studies that evaluate the temporal patterns of colonization and succession of the benthic assemblages on platforms were temporally limited. In The Gulf, Amini et al. (2016) showed that after a one-year survey cirripedes and bivalves were the dominant organisms in Iranian platforms. Forteath et al. (1982) and Whomersley and Picken (2003) showed that in platforms from the North Sea, fouling assemblages still changed in composition even after 5 and 11 years of survey, respectively. Likewise, comparing platforms with different years of installation in the same region, van der Stap et al. (2016) showed that species richness was positively correlated with platform age.

Studies carried out in natural areas of The Gulf showed that turf algae, sponges and bivalves dominated the youngest artificial structures, whereas coral cover dominated the oldest breakwaters (≥ 25 years) (Burt et al., 2009a). Furthermore, benthic communities on breakwaters became more similar to those on natural reefs with increasing age (Burt et al., 2011a), though coral coverage on mature breakwaters can be higher relative to natural reefs (Burt et al., 2009a, 2011a). Likewise, Perkol-Finkel et al. (2006) observed that after a century, fouling assemblages in artificial habitats from the Red Sea did not differ from adjacent natural reefs when structural features were similar.

Although the aim of this study was not to compare the platforms with other habitats (natural or artificial), it is very likely that the Al Shaheen oil field is a distinct habitat. In The Gulf, site is an important variable determining the benthic community composition in both natural and artificial habitats. For example, among natural habitats in Qatari waters, sand and dead coral may cover up to 80% of the near-shore substrate, whereas live coral and algae covered over 75% of the substrate at offshore sites (Burt et al., 2016). Within Abu Dhabi waters, Stachowitsch et al. (2002) found that taxonomic groups contributing to the biomass and abundance differed between two offshore oil fields. In the same country, coral recruitment was spatially variable among onshore artificial reefs and breakwaters (Burt et al., 2009b). Among natural habitats in Abu Dhabi, a benthic survey conducted in shallow waters (5 - 7 m) showed that live coral was the most common benthic category, while all other living benthos made up relatively minor components of reef communities (Burt et al., 2011b). Burt et al. (2016) suggest that spatial differences of benthic composition among coral reef habitat in the

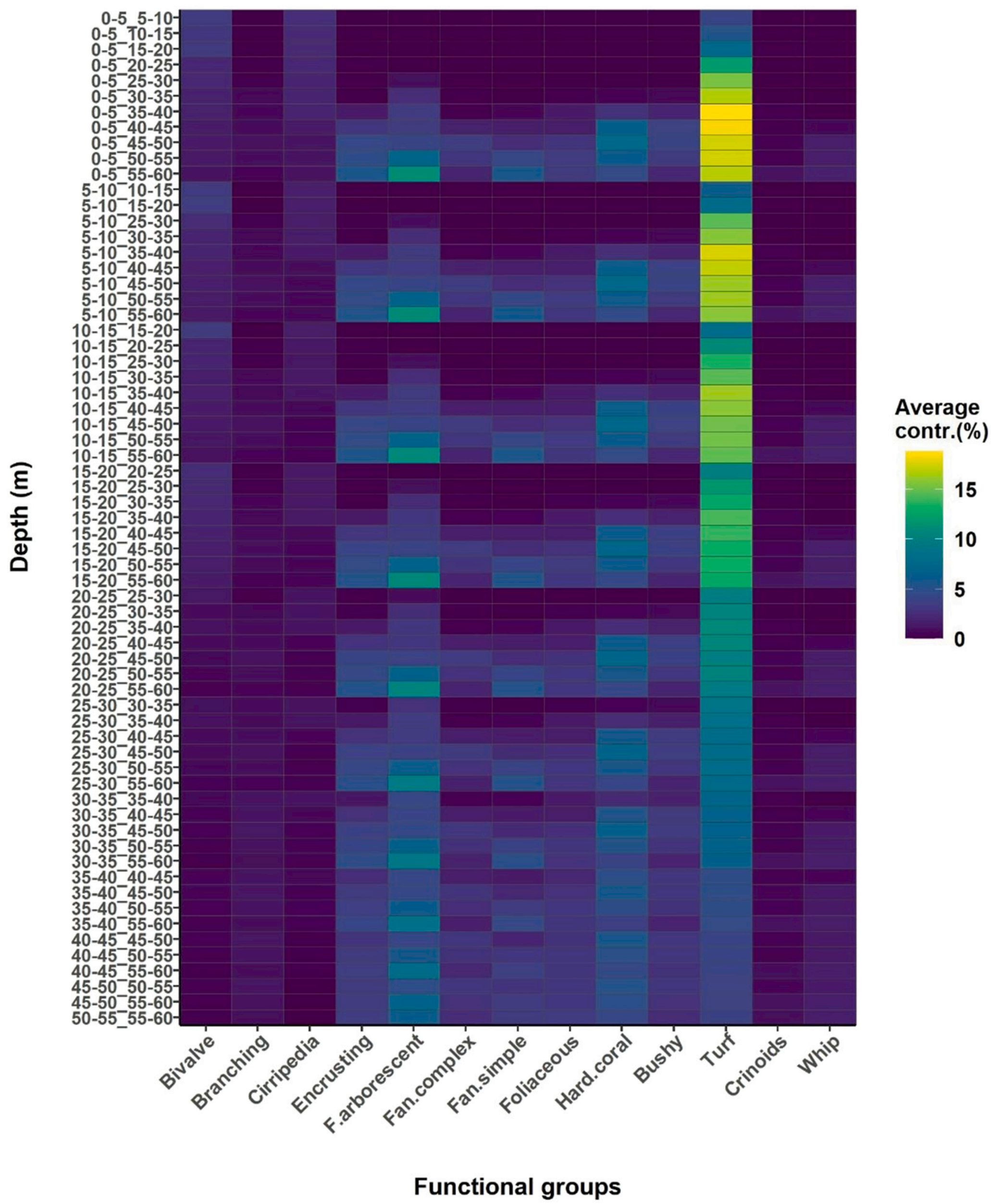

Fig. 5. Average contribution of functional groups in pairwise comparisons (SIMPER) between depth intervals. F. arborescent denotes Fleshy arborescent.

Table 4
Numerical summary of Indicator Value index (IndVal) by depth.

Functional groups	Depth range	IndVal index	*p*-Value	Frequency
Cirripedia	0–5	0.1258	0.001	460
Encrusting	5–10	0.1247	0.001	459
Bivalve	15–20	0.0603	0.018	62
Turf	35–40	0.1277	0.001	352
Hard coral	45–50	0.2014	0.001	126
Fan complex	45–50	0.1883	0.001	69
Bushy	45–50	0.1530	0.001	108
Foliaceous	50–55	0.1180	0.001	67
Fan simple	55–60	0.3188	0.001	95
F. arborescent	55–60	0.2516	0.001	113
Crinoids	55–60	0.1372	0.001	27
Whip	55–60	0.1322	0.001	56

region likely occurs because the impacts caused by bleaching events were not spatially homogeneous.

4.1. Future research directions

Presently, the management of marine ecosystems in The Gulf is constrained by mapping and habitat characterization. This work, together with Torquato et al. (2017) highlighted a previously undescribed major oilfield as an important marine habitat in The Gulf. However, these studies focused only on the ecological benefits of these artificial habitats, namely, biological productivity. These exploratory studies constitute the first step to characterize biological communities associated with these underwater structures. The results clearly illustrate the potential of this type of offshore infrastructure to support the establishment of functional reef ecosystems, suggesting that the conversion of decommissioned oil platforms into artificial reefs may be a valid alternative in this region. A step further is now required for a better comprehension of the role played by the decommissioned rigs in the

Table 5
Frequency of occurrence (%) by age for each functional.

	Age of installation												
	2	3	4	5	6	7	9	10	11	12	13	16	17
Anemone	2.8	0	8.3	0	2.8	0	0	0	0	0	0	0	0
Bivalve	2.8	16.7	33.3	11.1	27.8	11.1	11.1	11.1	0	11.1	30.6	2.8	2.8
Branching	16.7	2.8	5.6	16.7	11.1	2.8	0	8.3	8.3	2.8	16.7	0	0
Bryozoa	0	0	2.8	0	0	0	2.8	0	0	0	0	0	5.6
Cirripedia	100	91.7	100	100	88.9	97.2	100	100	100	100	100	100	100
Encrusting	100	91.7	100	100	88.9	97.2	100	100	100	100	97.2	100	100
Fleshy arborescent	2.8	0,0	47.2	44.4	8.3	55.6	16.7	30.6	22.2	22.2	19.4	25	19.4
Fan complex	0	0,0	5.6	16.7	11.1	22.2	19.4	16.7	5.6	19.4	16.7	19.4	38.9
Fan simple	0	2.8	30.6	27.8	19.4	25	25	13.9	30.6	33.3	22.2	16.7	16.7
Foliaceous	5.6	8.3	25	33.3	5.6	16.7	22.2	30.6	2.8	0	5.6	22.2	5.6
Hard coral	0	2.8	16.7	19.4	25	36.1	27.8	36.1	22.2	41.7	38.9	41.7	41.7
Massive sponge	0	0	0	0	0	0	0	0	0	0	2.8	0	5.6
Bushy	2.8	13.9	27.8	13.9	25	38.9	25	22.2	25	19.4	25	25	36.1
Urchins	5.6	0	2.8	0	0	5.6	0	0	5.6	11.1	0	5.6	5.6
Turf	97.2	75	86.1	69.4	69.4	66.7	61.1	61.1	80.6	75	75	77.8	83.3
Crinoids	8.3	0	13.9	5.6	11.1	8.3	11.1	5.6	2.8	2.8	0	0	5.6
Whip	0	0	0	2.8	16.7	2.8	16.7	19.4	11.1	16.7	19.4	25	25

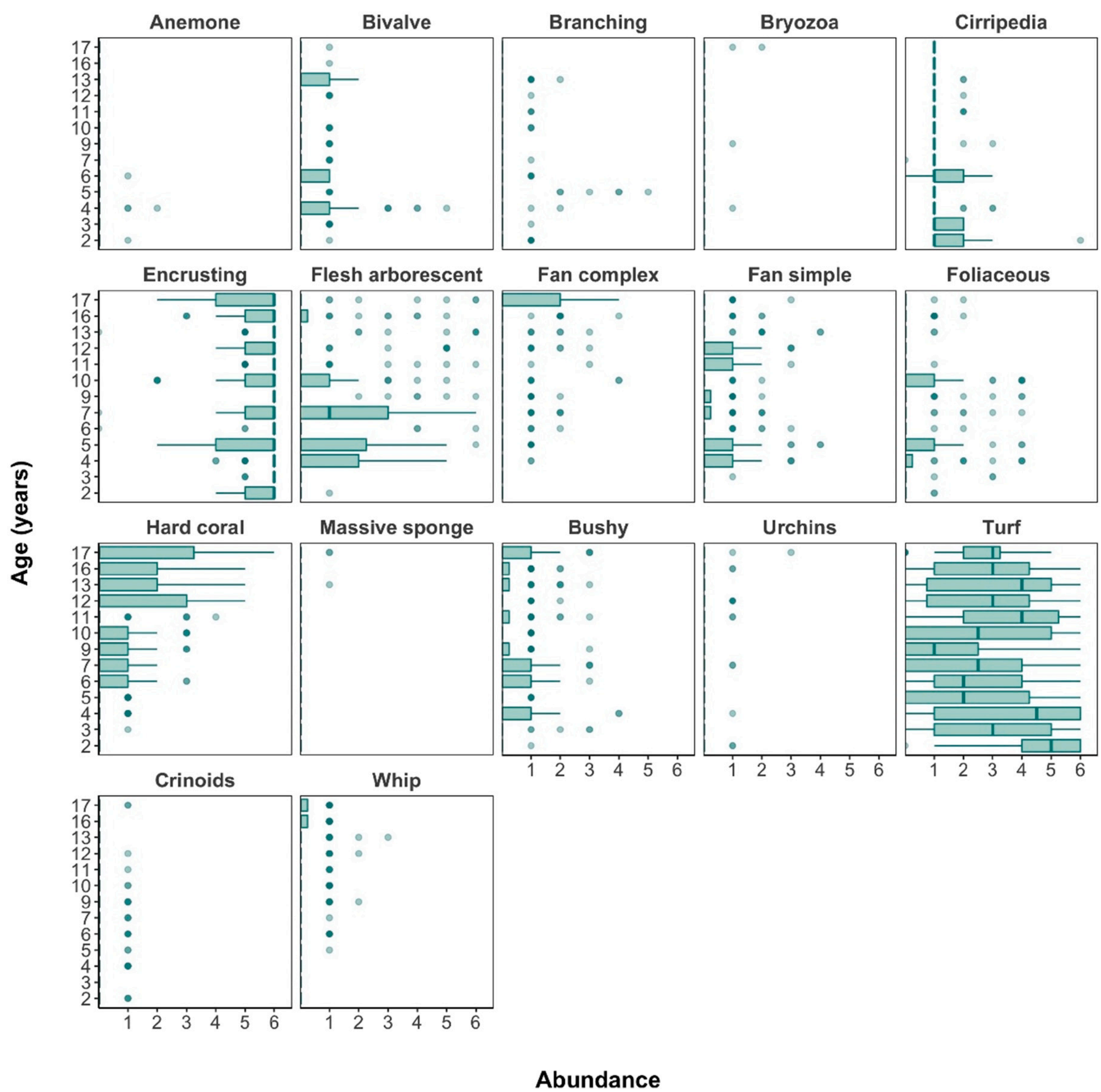

Fig. 6. Abundance boxplot by age of the community for each functional group.

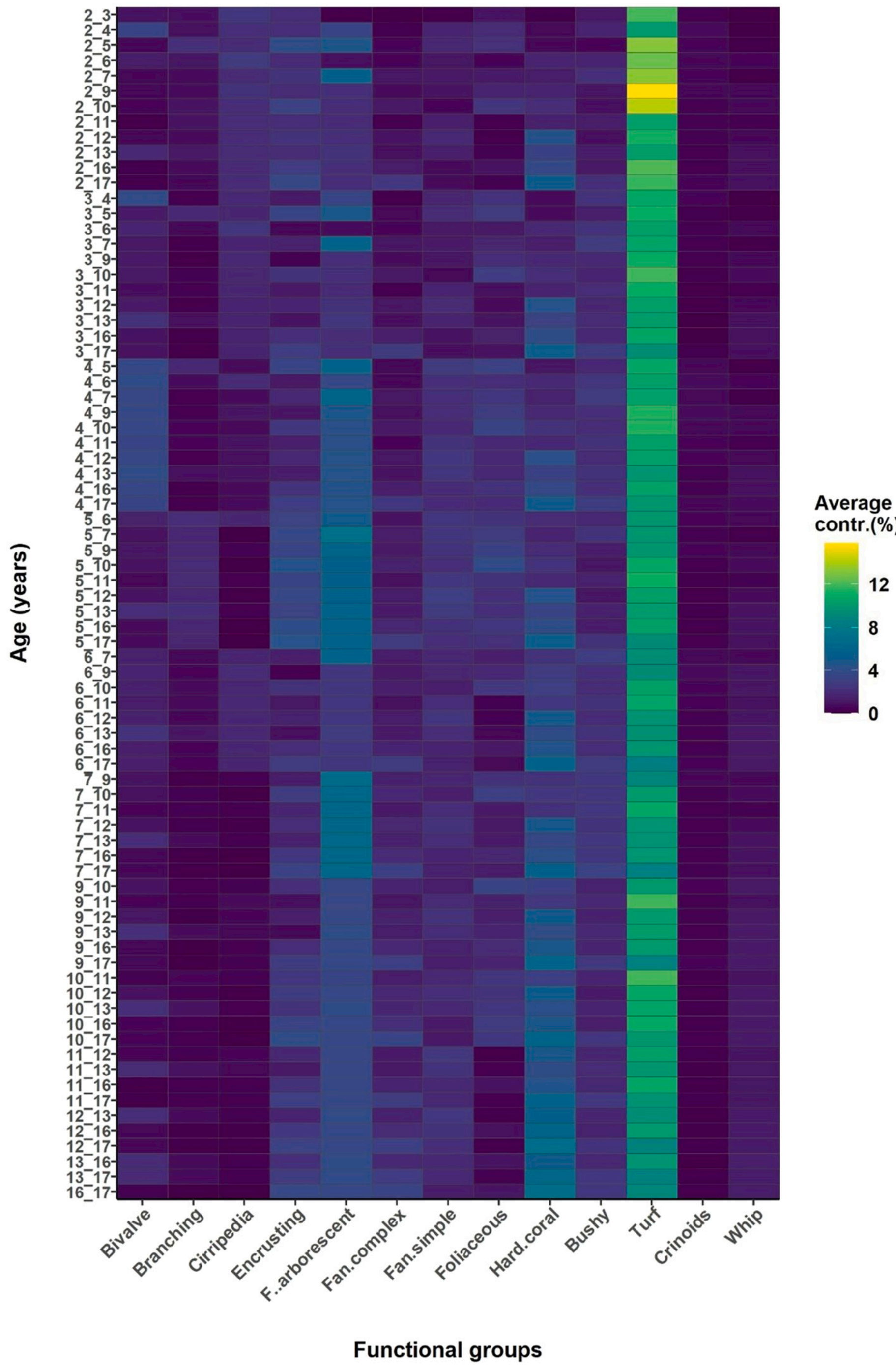

Fig. 7. Average contribution of functional groups in pairwise comparisons (SIMPER) between platform ages. F. arborescent denotes Fleshy arborescent.

Table 6
Numerical summary of Indicator Value index (IndVal) by age.

Functional groups	Age	IndVal index	*p*-Value	Frequency
Turf	2	0.1466	0.001	352
Bivalve	4	0.1043	0.002	62
Foliaceous	5	0.0728	0.005	67
Branching	5	0.0563	0.018	33
Fleshy arborescent	7	0.1129	0.001	113
Fan complex	17	0.1069	0.001	69
Hard coral	17	0.0798	0.013	126

maintenance of metapopulations, however, it requires implementation of inter- and/or multidisciplinary research. Hence, future studies using molecular markers, biophysical modeling or stable isotopes might be able to respond to how the platforms are connected with natural habitats, and also if they work as stepping-stone systems between natural habitats that otherwise would not be connected.

CRediT authorship contribution statement

Felipe Torquato: Formal analysis, Writing – original draft, Writing – review & editing. **Mustafa H. Omerspahic:** Data curation, Writing – original draft, Writing – review & editing. **Pedro Range:** Conceptualization, Writing – review & editing, Supervision. **Steffen S. Bach:** Data curation, Writing – review & editing. **Rodrigo Riera:** Funding acquisition, Writing – original draft, Writing – review & editing. **Radhouane Ben-Hamadou:** Funding acquisition, Project administration, Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to Mærsk Oil, Qatar for providing access to the ROV videos. This work was conducted within the framework of the NPRP projects 'Connectivity, diversity and genetics between offshore natural coral reefs and oil platforms—NPRP7-1129-1-201' and 'Assessing the contribution of oil platforms and the impact of decommissioning scenarios to marine biodiversity, productivity and connectivity (PlatDecom)— NPRP13S-0208-200302' both funded by the Qatar National Research Fund (a member of The Qatar Foundation). Open Access funding provided by the Qatar National Library.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112935.

References

Airoldi, L., Balata, D., Beck, M.W., 2008. The gray zone: relationships between habitat loss and marine diversity and their applications in conservation. J. Exp. Mar. Biol. Ecol. 366, 8–15.

Ajemian, M.J., Wetz, J.J., Shipley-Lozano, B.J., Shively, D., Stunz, G.W., 2015. An analysis of artificial reef fish community structure along the northwestern Gulf of Mexico shelf: potential impacts of "rigs-to-reefs" programs. PLoS One 10, e0126354.

Althaus, F., Hill, N., Ferrari, R., Edwards, L., Przeslawski, R., Schönberg, C.H.L., Stuart-Smith, R., Barrett, N., Edgar, G., Colquhoun, J., Tran, M., Jordan, A., Rees, T., Gowlett-Holmes, K., 2015. A standardised vocabulary for identifying benthic biota and substrata from underwater imagery: the CATAMI classification scheme. PLoS One 10, e0141039.

Amini, N., Rezai, H., Pourjomeh, F., Ardalan, A.A., 2016. Spatial and temporal variations of biofouling on the oil platforms around Khark Island, Persian gulf. Indian J. Geo Mar. Sci. 45, 1714–1718.

Bailey-Brock, J.H., 1989. Fouling community development on an artificial reef in Hawaiian waters. Bull. Mar. Sci. 44, 580–591.

Baine, M., 2001. Artificial reefs: a review of their design, application, management and performance. Ocean Coast. Manag. 44, 241–259.

Bartholomew, A., Feary, D., 2012. Man-made structures as artificial reefs in the gulf. In: Riegl, B., Purkis, S. (Eds.), Coral Reefs of the Gulf Adaptation to Climatic Extremes. Springer, Netherlands, pp. 171–186.

Bishop, M.J., Mayer-Pinto, M., Airoldi, L., Firth, L.B., Morris, R.L., Loke, L.H.L., Hawkins, S.J., Naylor, L.A., Coleman, R.A., Chee, S.Y., Dafforn, K.A., 2017. Effects of ocean sprawl on ecological connectivity: impacts and solutions. J. Exp. Mar. Biol. Ecol. 492, 7–30.

Bram, J.B., Page, H.M., Dugan, J.E., 2005. Spatial and temporal variability in early successional patterns of an invertebrate assemblage at an offshore oil platform. J. Exp. Mar. Biol. Ecol. 317, 223–237.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at Risk, Revisited. World Resources Institute, Washington, DC.

Burt, J., Bartholomew, A., Usseglio, P., Bauman, A., Sale, P.F., 2009a. Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs 28, 663–675.

Burt, J., Bartholomew, A., Bauman, A., Saif, A., Sale, P.F., 2009b. Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. J. Exp. Mar. Biol. Ecol. 373, 72–78.

Burt, J., Bartholomew, A., Sale, P.F., 2011a. Benthic development on large-scale engineered reefs: a comparison of communities among breakwaters of different age and natural reefs. Ecol. Eng. 37, 191–198.

Burt, J., Al-Harthi, S., Al-Cibahy, A., 2011b. Long-term impacts of coral bleaching events on the world's warmest reefs. Mar. Environ. Res. 72, 225–229.

Burt, J.A., Smith, E.G., Warren, C., Dupont, J., 2016. An assessment of Qatar's coral communities in a regional context. Mar. Pollut. Bull. 105, 473–479.

Coles, S., 2003. Coral species diversity and environmental factors in the Arabian gulf and the 444 Gulf of Oman: a comparison to the indo-Pacific region. Atoll Res. Bull. 507, 1–19.

Connell, J.H., Slatyer, R.O., 1977. Mechanisms of succession in natural communities and their role in community stability and organization. Am. Nat. 111, 1119–1144.

Dufrêne, M., Legendre, P., 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol. Monogr. 67, 345–366.

Feary, D.A., Burt, J.A., Bartholomew, A., 2011. Artificial marine habitats in the Arabian gulf: review of current use, benefits and management implications. Ocean Coast. Manag. 54, 742–749.

Forteath, G., Picken, B., Ralph, R., Williams, J., 1982. Marine growth studies on the North Sea oil. Mar. Ecol. Prog. Ser. 8, 61–68.

Gass, S.E., Roberts, J.M., 2006. The occurrence of the cold-water coral Lophelia Pertusa (Scleractinia) on oil and gas platforms in the North Sea: colony growth, recruitment and environmental controls on distribution. Mar. Pollut. Bull. 52, 549–559.

Granneman, J.E., Steele, M.A., 2015. Effects of reef attributes on fish assemblage similarity between artificial and natural reefs. ICES J. Mar. Sci. 72, 2385–2397.

Hiscock, K., 1990. Marine Nature Conservation Review: Methods. Joint Nature Conservation Committee. CSD Report (No. 1072).

Jagerroos, S., Krause, P.R., 2016. Rigs-to-reef; impact or enhancement on marine biodiversity. J. Ecosyst. Ecogr. 6, 1000187.

Lewbel, G.S., Howard, R.L., Gallaway, B.J., 1987. Zonation of dominant fouling organisms on the northern Gulf of Mexico petroleum platforms. Mar. Environ. Res. 21, 199–224.

Nesterov, O., Temimi, M., Fonseca, R., Nelli, N.R., Addad, Y., Bosc, E., Abida, R., 2021. Validation and statistical analysis of the Group for High Resolution sea Surface Temperature data in the arabian gulf. Oceanologia. https://doi.org/10.1016/j.oceano.2021.07.001.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2020. vegan: community ecology package. R package version 2.5-7. https://CRAN.R-project.org/package=vegan.

Perkol-Finkel, S., Benayahu, Y., 2005. Recruitment of benthic organisms onto a planned artificial reef: shifts in community structure one decade post-deployment. Mar. Environ. Res. 59, 79–99.

Perkol-Finkel, S., Shashar, N., Benayahu, Y., 2006. Can artificial reefs mimic natural reef communities? The roles of structural features and age. Mar. Environ. Res. 61, 121–135.

Ponti, M., Abbiati, M., Ceccherelli, V.U., 2002. Drilling platforms as artificial reefs: distribution of macrobenthic assemblages of the "Paguro" wreck (northern Adriatic Sea). ICES J. Mar. Sci. 59, S316–S323.

Range, P., Riera, R., Omerspahic, M., Bouwmeester, J., Bach, S.S., Møller, P.R., Ben-Hamadou, R., 2018. Fouling assemblages on offshore oil platforms: diverse vertical reefs in the Arabian Gulf. In: Qatar Foundation Annual Research Conference Proceedings. https://doi.org/10.5339/qfarc.2018.EEPP894 p. EEPP894.

Reynolds, R.M., 1993. Physical oceanography of the Persian Gulf, Strait of Hormuz and the Gulf of Oman – results from the Mt. Mitchell expedition. Mar. Pollut. Bull. 27, 35–59.

Roberts, J.M., 2002. The occurrence of the coral Lophelia Pertusa and other conspicuous epifauna around an oil platform in the North Sea. Underw. Technol. 25, 83–92.

Roberts, D.W., 2019. labdsv: ordination and multivariate analysis for ecology. R package version 2.0-1. https://CRAN.R-project.org/package=labdsv.

Sanabria-Fernandez, J.A., Lazzari, N., Riera, R., Becerro, M.A., 2018. Building up marine biodiversity loss: artificial substrates hold lower number and abundance of low occupancy benthic and sessile species. Mar. Environ. Res. 140, 190–199.

Schutter, M., Dorenbosch, M., Driessen, F.M., Lengkeek, W., Bos, O.G., Coolen, J.W., 2019. Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: effects of location and depth. J. Sea Res. 153, 101782.

Seaman, W., 2007. Artificial habitats and the restoration of degraded marine ecosystems and fisheries. Hydrobiologia 580, 143–155.

Sheppard, C., Al-Husaini, M., Al-Jamali, F., Al-Yamani, F., Baldwin, R., Bishop, J., Benzoni, F., Dutrieux, E., Dulvy, N.K., Durvasula, S.R.V., Jones, D.A., Loughland, R., Medio, D., Nithyanandan, M., Pilling, G.M., Polikarpov, I., Price, A.R.G., Purkis, S., Riegl, B., Saburova, M., Namin, K.S., Taylor, O., Wilson, S., Zainal, K., 2010. The Gulf: a young sea in decline. Mar. Pollut. Bull. 60, 13–38.

Siebold, E., 1973. Biogenic sedimentation of the Persian Gulf. In: Zeitschel, B. (Ed.), The Biology of the Indian Ocean. Springer-Verlag, New York, pp. 103–114.

Stachowitsch, M., Kikinger, R., Herler, J., Zolda, P., Geutebrück, E., 2002. Offshore oil platforms and fouling communities in the southern arabian gulf (Abu Dhabi). Mar. Pollut. Bull. 44, 853–860.

Stone, R.B., McGurrin, J.M., Sprague, L.M., Seaman, W., 1991. Artificial habitats of the world: synopsis and major trends. In: Seaman, J.R.W., Sprague, L. (Eds.), Artificial Habitats for Marine and Freshwater Fisheries. Academic Press Inc., San Diego, pp. 31–57.

Swift, S.A., Bower, A.S., 2003. Formation and circulation of dense water in the Persian/Arabian Gulf. J. Geophys. Res. 108 (C1), 4-1-4-21.

Thomasen, J., Al-Emadi, I.A., Noman, R., Damgaard, A., 2005. Realizing the Potential of Marginal Reservoirs: The Al Shaheen Field Offshore Qatar. International Petroleum Technology Conference, 10854.

Torquato, F., Jensen, H.M., Range, P., Bach, S.S., Ben-Hamadou, R., Sigsgaard, E.E., Thomsen, P.F., Møller, P.R., Riera, R., 2017. Vertical zonation and functional diversity of fish assemblages revealed by ROV videos at oil platforms in the Gulf. J. Fish Biol. 91, 947–967.

van der Stap, T., Coolen, J.W., Lindeboom, H.J., 2016. Marine fouling assemblages on offshore gas platforms in the southern North Sea: effects of depth and distance from shore on biodiversity. PLoS One 11, e0146324.

Vaughan, G.O., Al-Mansoori, N., Burt, J.A., 2016. The changing dynamics of coral reef science in Arabia. Mar. Pollut. Bull. 105, 441–458.
Whomersley, P., Picken, G.B., 2003. Long-term dynamics of fouling communities found on offshore installations in the North Sea. J. Mar. Biol. Assoc. U. K. 83, 897.
Yan, T., Yan, W., Dong, Y., Wang, H., Yan, Y., Liang, G., 2006. Marine fouling of offshore installations in the northern beibu gulf of China. Int. Biodeterior. Biodegradation 58, 99–105.