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## Original Article

# Patchwork of oil and gas facilities in Saudi waters of the Arabian Gulf has the potential to enhance local fisheries production

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Because of the increasing oil industry development in the Arabian Gulf, hundreds of oil and gas facilities have been installed in both offshore and inshore areas during the last few decades. However, no studies have been conducted till now on the influence of these platforms on the structure and composition of marine faunal assemblages. The present work addresses this issue to propose environmental management measures connected to the utilization of fishery resources. Offshore and inshore surveys were carried out along the Saudi Gulf waters using trawl and beach-seine nets, respectively. Data relative to only fish (offshore) and fish and invertebrates (inshore) were collected concurrently with several factors: density of oil and gas facilities (offshore), distance to the nearest coastal platform (inshore), oceanographic variables, and habitat characteristics. Results of offshore surveys indicated higher fish density—both total and of fishery resources—in locations with a higher number of oil and gas facilities within a 5 km radius, whereas biomass density was not significantly different. Hence, oil and gas facilities seem to serve as nursery areas for small fish. For inshore communities, more species and diversity were found in stations closer to coastal oil and gas facilities. In addition, among the five coastal embayments sampled, those with more oil and gas facilities had more species. The findings of the present work support the hypothesis of a positive net ecological role of oil and gas platforms of the Saudi Arabian Gulf, with the implication that this effect could be extended to improve the sustainability of important fishery resources.

**Keywords:** Arabian Gulf, artificial reefs, faunal assemblages, fishery production, marine protected areas, Saudi Arabia.

## Introduction

The extraction of oil and gas from marine fields has increased considerably during the last decades and it has become one of the main activities for the exploitation of marine resources (Ghisel, 1997; Terlizzi *et al.*, 2008). The number of oil industry structures built in marine areas is now exceeding 7500 in 53 countries (Parente *et al.*, 2006). Along the Saudi coast in the Arabian Gulf (hereafter "the Gulf"), the fossil fuel industries have deployed many oil and gas facilities, mainly on the northern part, to drill wells, extract and process oil and natural gas, and/or for temporary storage. Some of those structures have been set in coastal areas and have caused a certain degree of coastal modification, whereas others have been located in offshore areas.

Many authors have reported that the installation of marine oil and gas facilities generates some negative consequences on the environment through oil spill accidents, hazards of shipping, and facilitation of the introduction of alien species (Olsgard and Gray, 1995; Page *et al.*, 2006). However, since the exploitation of marine oil and gas resources continues regardless of those environmental concerns, marine scientists have started to turn their attention to the net positive effects of marine oil/gas structures as additional hard substrata, acting as artificial reefs which may provide habitat, food, protection from predation and spawning substrata to marine organisms (Scarborough-Bull, 1989; Atchison *et al.*, 2008; Claisse *et al.*, 2014; Friedlander *et al.*, 2014) and through the exclusion of certain fishery activities, in particular trawling (Schroeder and Love, 2004). Despite their direct impacts on the surrounding natural environment, especially during construction, it has been argued that offshore oil and gas platforms provide, through their associated fouling organisms, favourable habitats for many fish species in different areas (Stanley and Wilson, 1997; Love *et al.*, 2003; Love and York, 2005; Scarcella *et al.*, 2011; Consoli *et al.*, 2013; Pradella *et al.*, 2014). In fact, these artificial structures were found to support high abundances of reef-dwelling or partially reef-dwelling species and are considered to act as artificial reefs (Helvey, 2002; Love and York, 2005; Love *et al.*, 2005; Consoli *et al.*, 2013). They attract marine species including pelagic fish and contribute locally and regionally to the enhancement of fish production (Polovina and Sakai, 1989; Page *et al.*, 1999; Friedlander *et al.*, 2014). Claisse *et al.* (2014) found that oil and gas platforms off the coast of California have the highest secondary fish production per unit area of seabed of any marine habitat that has been studied, about an order of magnitude higher than fish communities from other marine ecosystems. In the Gulf, coastal and offshore oil and gas structures interfere with other human activities that have their own impacts, most importantly commercial fishing, because a ban on human activities is enforced within a safety perimeter. This has incidentally created a patchwork of hundreds of small, partially marine protected areas (MPAs) with varying degrees of spatial concentration.

Inshore areas may play the role of nurseries, where the juveniles of both fish and shellfish species can feed, grow, and survive (Beck *et al.*, 2003). However, unlike offshore structures, studies regarding the effects of these coastal oil facilities on surrounding faunal assemblages are very few or even absent. In our case, the presence of a coastal oil or gas facility introduces restrictions to access into the surrounding areas. Thus, it is reasonable to hypothesize that these coastal facilities may also play a positive ecological role by reducing levels of other human activities. Potential coastal nurseries areas of the Saudi Arabian Gulf are mainly represented by seagrass meadows, algal beds, and mangrove forests, mostly in coastal shallow embayments (Figure 1).

The specific objectives of this work are, on the one side, to determine the net effect of the distance to coastal and offshore oil and gas facilities on the faunal assemblages (density, biomass, number of species, and diversity) and, on the other side, the influence of several human and environmental factors, such as urban pressure, substratum type, habitat type, and depth. The conceptual framework guiding these specific objectives is to explore the feasibility to improve the sustainability of Saudi fisheries via the creation of zones of special protection in the areas of high concentration of oil and gas facilities.

## Material and methods

### General features of the study sites

The Saudi waters in the Gulf extend from the border with Kuwait to the gulf of Salwah, covering a territorial area of 27 050 km$^2$ (Figure 1). The coastline is characterized by gently sloping dunes, many shallow bays and beaches, and a series of offshore, low and small sandy islands, and patches of reefs of coralline origin (Sheppard *et al.*, 1992). The offshore areas are characterized by a shallow depth (mostly $<50$ m) where primary productivity is among the highest in the Indian Ocean (Longhurst *et al.*, 1995), in particular along the coastal regions but also around several sandy offshore islands (Sheppard *et al.*, 1992). The Saudi waters in the Gulf support a wide variety of tropical Indo-Pacific flora and fauna (Carpenter *et al.*, 1997), and the coastal region has diverse habitats, including saline lagoons, sheltered bays, shallow exposed coastal waters, and offshore open waters.

### Offshore trawl surveys

We conducted two trawl surveys during spring and summer of 2013 (March and July 2013) on a chartered commercial outrigger with a total of 84 stations covering almost all territorial waters of Saudi Arabia in the Gulf. The trawling net had a mesh size of 15 mm and a headrope length of 35 m long. The outrigger was fitted with two such nets operating in parallel. We conducted trawling during the daytime and trawling duration was around 30 min. All trawling activities were done within a distance of at least 500 m from any offshore facility to avoid possible damage following the security regulation of the oil industries. Once the catch was on the deck, the weight (kg) of large animals (sharks, rays, and turtles) was measured individually and these animals were immediately released to the sea. The rest of the catch was weighted (kg) in bulk and a sample of 5–40% was preserved with ice on deck for further analysis in the laboratory. At each station, we also recorded environmental variables such as water temperature (°C), salinity (‰), pH, dissolved oxygen (DO, mg l$^{-1}$), and total dissolved solids (mg l$^{-1}$) in the surface and bottom using CTD (650MDS, YSI Incorporated, USA). The GPS coordinates, weather condition (calm, medium, or windy), depth (m) in the initial and end position of each haul, duration (min), and speed (knots) of each haul and bottom type (sand, mud, rocky, or seagrass) were also recorded. In the laboratory, fish were identified to the nearest taxonomical level according to Randall (1995) and Carpenter *et al.* (1997) and grouped into commercial vs. non-commercial groups based on official catch statistics (FAO, 2014). Total length and body weight were measured to the lowest millimetre and gramme, respectively. Total fish biomass ($B$, kg km$^{-2}$) and abundance (ind. km$^{-2}$) were estimated by total fish weight and fish number divided by area swept (km$^2$). Species richness ($R$) was represented by the total species number in the sample, and Shannon–Wiener diversity index ($H'$) of the fish was calculated using R (R Core Team, 2013) with package *vegan* 2.0–10 (Oksanen *et al.*, 2013).

### Inshore surveys

Beach seining has been proposed as a suitable method to sample beaches and other very shallow locations to determine inshore nursery grounds (e.g. Jarrin and Shanks, 2010; De Raedemaecker *et al.*, 2011). We carried out a beach-seine survey totalling 106 samples from 53 stations on five major embayments in the east coast of Saudi Arabia: Half-Moon, Tarut, Khursaniya, Manifa, and Safaniya (Figure 1) during autumns of 2012 and 2013. The seine net was 30 m long and 1.5 m deep, made of nylon multifilament with a stretched mesh size of 10 mm, with an upper rope fitted with 25 plastic floats, and a lower rope with iron chain having a weight of 11.5 kg. The seining operation was oriented to capture juvenile individuals and was carried out in a standardized manner. In the laboratory, all samples were examined to separate the specimens into main taxonomical groups, identified to the nearest level (species or genus) according to Randall (1995) and Carpenter *et al.* (1997) and then counted and weighted. Groups were also classified according to fishery interest (commercial and

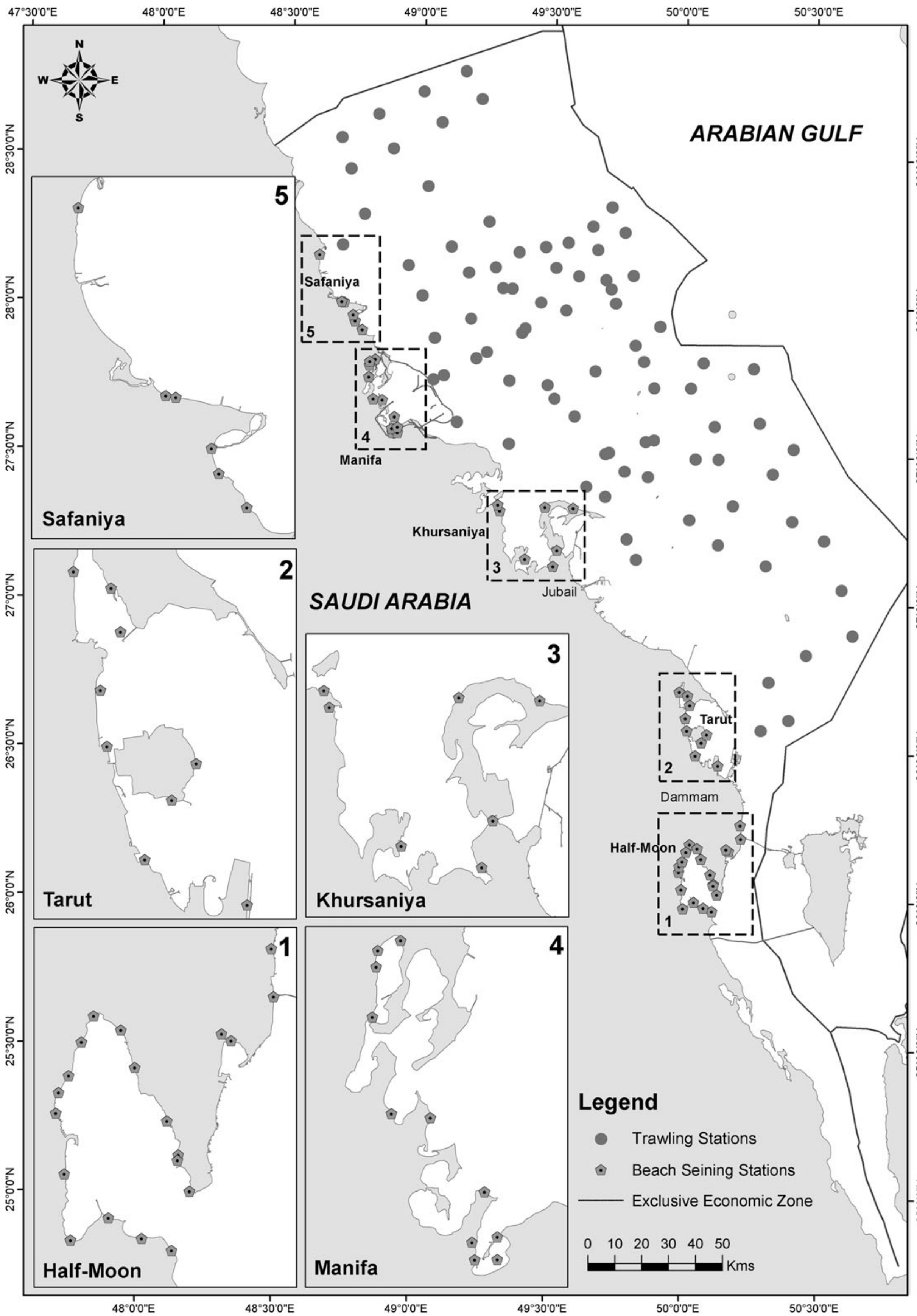


**Figure 1.** Location of the offshore trawling stations and inshore beach seining stations along the coast of the Saudi Arabian Gulf.

non-commercial). The variables describing the faunal assemblages were the biomass (*B*) and the number of individuals (*N*) per volume of water filtered ($m^3$), the species richness (*R*), and the Shannon–Wiener diversity index ($H'$). The environmental variables recorded at stations included water temperature (°C), salinity (‰), dissolved oxygen ($mg\,l^{-1}$), GPS coordinates, substratum type (sandy, muddy, sandy–muddy), substratum cover (bare, algae, seagrass, mangroves), and habitat type (open sea, lagoon). One additional factor related to each sample was urban pressure (high, average, low), determined visually based on the proximity of each sampling station to urban areas.

## Data analysis and modelling

Generalized linear models were applied to extract the effects of proximity to oil and gas facilities on the status of faunal communities (fish for trawling stations and fish and invertebrates for beach seining stations) while accounting for the effects of other potential predictors. For offshore facilities, the coordinates of each installation, including water discharges, gas oil separation plants, clusters, and wells, were collected and then pairwise great circle distance (km) between each trawling station and each facility was calculated using R package *Imap* 1.32 (Wallace, 2012). With these data, we calculated a predictor representing the effect of proximity, which was defined as the number of facilities within two concentric rings around each trawl station (Figure 2a). The inner ring covered between 500 m and 5 km and the outer ring between 5 and 10 km (Figure 2b). Out of the 84 trawling stations, 58 and 31 had no installations within the inner and outer ring, respectively. These stations served as controls to evaluate the effect of increased number of facilities around the trawling stations. For coastal facilities, the predictor representing the effect of proximity was the straight-line shortest distance from each beach-seine station to the nearest coastal oil or gas structure.

The statistical distribution of total biomass and Shannon–Wiener diversity index was assumed to be γ, based on the fact that these data are continuous and can only take positive values. Abundance and species richness data were assumed to be distributed as negative binomial, considering that these data are counts and may present a certain degree of overdispersion. Preliminary models with different combinations of potential predictors were fitted, and the variables that showed significant effects on one of the four response variables (total biomass, abundance, species number, and diversity index) were retained for further analysis. Model estimation was done in R using function *glm* (R Core Team, 2013) and significance level was set at 0.05.

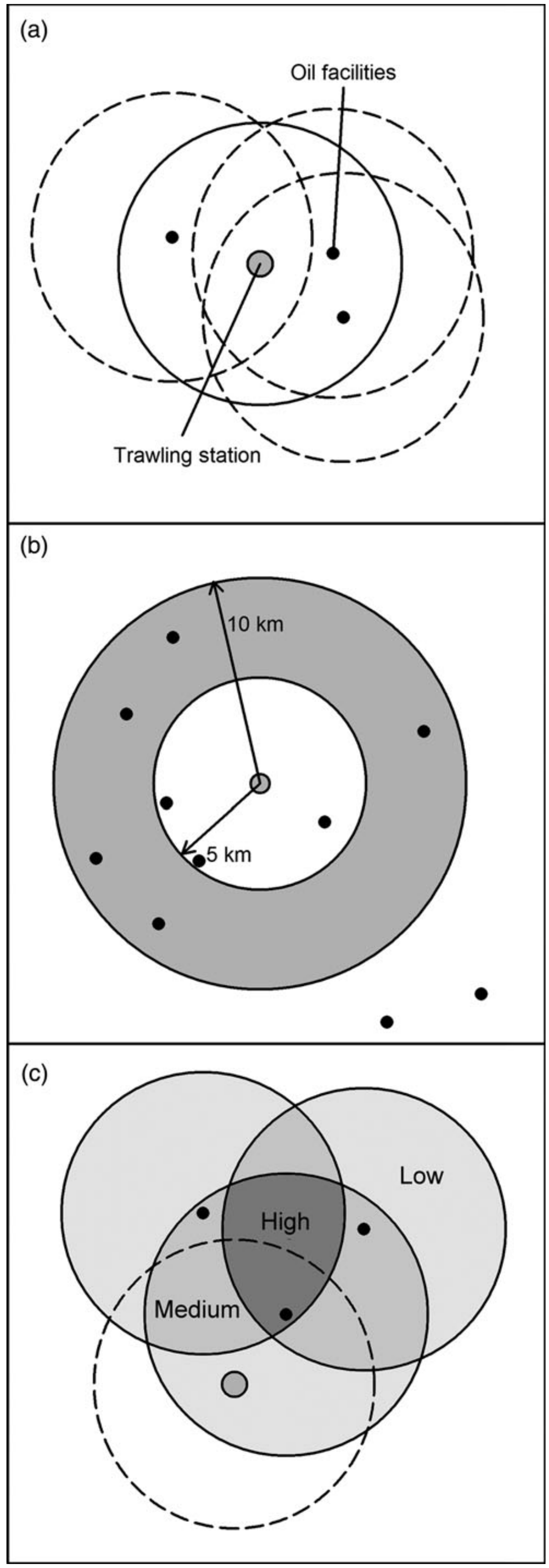


**Figure 2.** (a) Diagram showing the overlap between fishing banning areas around facilities (broken line circles) and the area within a 5 km radius of trawling stations (solid circle). (b) Diagram showing concentric area counting of facilities at two distance levels from trawling stations. (c) Conceptual diagram showing how the positive effects of one facility can be reduced by the existence of nearby facilities. See the Discussion section for detailed explanation.

# Results

## Offshore trawl surveys

The stations with sandy and muddy (or sandy–muddy) bottom types were predominant (43 and 37%, respectively). It was common to observe seagrasses (67% of stations) and their presence was the predominant bottom feature in 10 stations (12%), so for further analyses, the seagrass category was included as a bottom type along with muddy, sandy, and rocky. The stations examined were generally located in shallow areas of the Gulf with a depth ranging from 3.8 to 66 m. They were characterized by high water temperature and high salinity, as well as high mean fish biomass, number abundance, and species richness, although the Shannon–Wiener diversity index was generally not high ranging between 0.89 and

**Table 1.** Summary statistics of environmental conditions and fish community composition at the offshore trawling stations in the Saudi waters of the Arabian Gulf during spring and summer of 2013.

| **Substrate** | | |
|---|---|---|
| Mud | 31 | |
| Sand | 46 | |
| Rock | 7 | |
| | Mean ± s.d. | Range |
| Environmental parameters | | |
| Depth (m) | 36.3 ± 16.0 | 3.8–66.0 |
| Temperature (°C) | 24.5 ± 4.4 | 19.22–33.28 |
| Salinity (‰) | 44.0 ± 11.3 | 39.62–69.36 |
| Bottom pH | 7.7 ± 0.1 | 7.54–7.81 |
| Bottom DO (mg $l^{-1}$) | 6.3 ± 0.8 | 4.95–7.84 |
| Bottom TDS (mg $l^{-1}$) | 60.7 ± 19.1 | 41.4–122.3 |
| | Mean ± s.d. | Range |
| Fish catch statistics | | |
| Biomass (kg $km^{-2}$) | 3333 ± 2667 | 402–15 172 |
| Abundance ($10^3$ ind. $km^{-2}$) | 127.8 ± 156.8 | 2.8–1144.0 |
| Species number | 21 ± 6 | 10–37 |
| Diversity index | 1.995 ± 0.506 | 0.895–3.082 |

3.08 (Table 1). All the species collected during the trawling survey are given in Supplementary Appendix SI.

Among the environmental variables measured as potential predictors, only bottom type, weather condition, and station depth showed significant effects on either fish biomass, abundance, species richness, or diversity index and therefore, they were retained for subsequent analysis of the effects of offshore oil facilities. Estimates of effects and corresponding $p$-values are shown in Table 2. The number of offshore oil facilities within a 5 km radius had a highly significant positive effect on fish abundance ($p = 0.007$ all species, $p = 0.015$ commercial species), but not on fish biomass, species richness, nor $H'$ diversity index (all $p > 0.125$). The number of offshore oil facilities inside the region between 5 and 10 km radii was not found to affect any of the response variables considered (all $p > 0.152$). However, the interaction between the numbers of facilities within a 5 km radius and 5–10 km concentric area on fish abundance was found to be significantly negative ($p = 0.021$ all species, $p = 0.043$ commercial species).

## Inshore surveys

A total of 19 561 individuals, weighing 94.0 kg, and belonging to 126 fish and invertebrate species (Supplementary Appendix SII) were collected from the sampled embayment systems. The vast majority of individuals were early juveniles, supporting the hypothesis that the sampled embayment systems constitute nursery areas. Fish species predominated in terms of number of species, number of individuals and biomass, followed by crustaceans and molluscs and then other zoological groups (Figure 3a–c). Non-commercial fish and shellfish species predominated in total number of species over commercial ones (Figure 3d), whereas commercial species were quantitatively more important in number of individuals and biomass (Figure 3e and f).

Figure 4 presents the raw data relating the four response variables to distance to nearest oil or gas facility, implying a decreasing trend in abundance and diversity with increasing distance to nearshore oil or gas facility even before statistical analysis. Compared with muddy bottom, stations with sandy bottom had significantly

**Table 2.** Maximum likelihood estimates of the parameters and corresponding $p$-values for faunal analysis of offshore locations.

| | **Response variable** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Biomass** | | **Abundance** | | **Biomass.C** | | **Abundance.C** | | **Species richness** | | **$H'$ diversity index** | |
| **Covariates** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** |
| Substratum type: rock | $3.16 \times 10^{-4}$ | 0.048 | −1.28 | <0.001 | $4.66 \times 10^{-4}$ | 0.069 | −1.40 | <0.001 | 0.08 | 0.461 | −0.11 | 0.045 |
| Substratum type: sand | $8.93 \times 10^{-5}$ | 0.082 | −0.25 | 0.192 | $1.61 \times 10^{-4}$ | 0.607 | −0.32 | 0.116 | $2.98 \times 10^{-3}$ | 0.962 | −0.01 | 0.686 |
| Substratum type: seagrass | $-2.26 \times 10^{-5}$ | 0.703 | −0.38 | 0.206 | $-5.26 \times 10^{-5}$ | 0.551 | −0.30 | 0.340 | 0.10 | 0.305 | −0.10 | 0.031 |
| Depth | $7.05 \times 10^{-7}$ | 0.638 | −0.02 | <0.001 | $2.36 \times 10^{-6}$ | 0.292 | −0.03 | <0.001 | $-1.35 \times 10^{-3}$ | 0.452 | $-3.99 \times 10^{-4}$ | 0.670 |
| Weather: medium–calm | $3.69 \times 10^{-4}$ | 0.051 | −1.10 | <0.001 | $5.68 \times 10^{-4}$ | 0.079 | −1.06 | 0.002 | 0.22 | 0.032 | −0.10 | 0.041 |
| Weather: windy | $-4.33 \times 10^{-5}$ | 0.335 | 0.21 | 0.286 | $-8.30 \times 10^{-5}$ | 0.253 | 0.25 | 0.235 | 0.11 | 0.078 | −0.03 | 0.331 |
| Num.5 km | $-2.84 \times 10^{-5}$ | 0.125 | 0.23 | 0.007 | $-3.45 \times 10^{-5}$ | 0.232 | 0.23 | 0.015 | 0.01 | 0.674 | $-7.69 \times 10^{-4}$ | 0.959 |
| Num.5–10 km | $-2.26 \times 10^{-7}$ | 0.979 | −0.01 | 0.758 | $2.59 \times 10^{-6}$ | 0.854 | −0.01 | 0.653 | 0.01 | 0.152 | $-3.89 \times 10^{-4}$ | 0.411 |
| Num.5 km × Num.5–10 km | $5.31 \times 10^{-6}$ | 0.156 | −0.02 | 0.021 | $6.31 \times 10^{-6}$ | 0.278 | −0.02 | 0.043 | $-8.66 \times 10^{-4}$ | 0.765 | $3.06 \times 10^{-3}$ | 0.830 |

Tested predictors are: "bottom type" (compared with muddy), "station depth", "weather condition" (compared with calm), number of offshore oil facilities within 5 km (Num.5 km) and between 5 and 10 km (Num.5–10 km), and their interaction (Num.5km × Num.5–10 km). Response variables are: fish biomass, abundance, biomass of commercial species (Biomass.C), abundance of commercial species (Abundance.C), species richness, and Shannon's diversity index ($H'$).

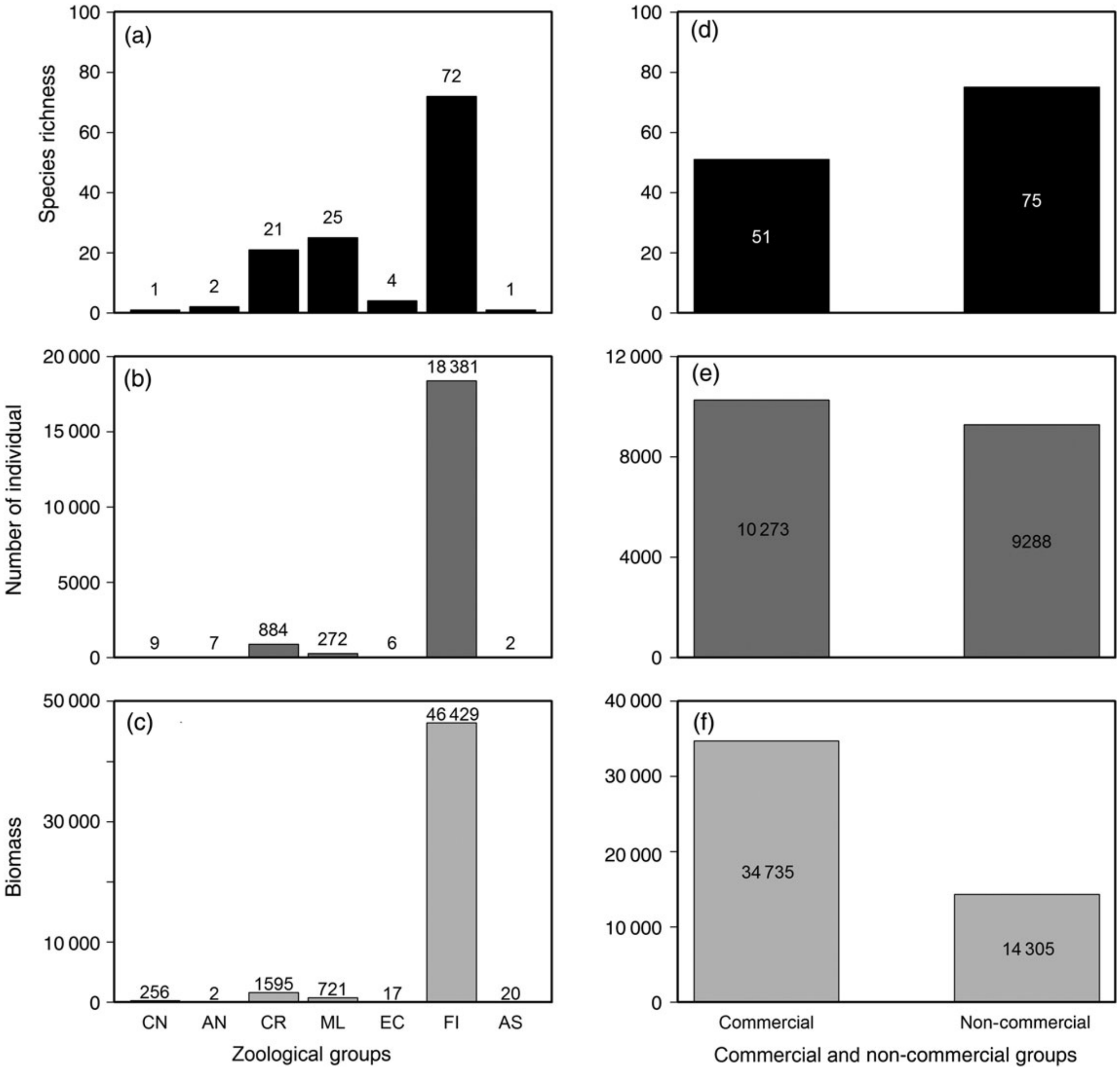


**Figure 3.** Distribution of the total number of species (a and d), total number of individuals (b and e), and total biomass "kg" (c and f) among the different zoological groups and among the commercial and non-commercial groups sampled during the inshore surveys. CN, Cnidarians; AN, Annelids; CR, Crustaceans; ML, Molluscs; EC, Echinoderms; FI, Fish; AS, Ascidians.

lower biomass, abundance, and species richness with $p < 0.002$ (Table 3). In terms of station coverage, stations with bare cover had significantly higher biomass ($p = 0.019$) and stations with a seagrass cover had higher species richness ($p = 0.008$). Stations with low urban pressure had significantly a lower diversity index than those with medium urban pressure ($p = 0.04$). The effect of distance to oil and gas facilities is significant and strong in relation to richness and diversity ($p < 0.001$ for all tests) and affects the ecosystem in the sense that as distance increases, both richness and diversity decrease.

## Discussion

The main finding reported in this study is that the presence of oil and gas facilities in offshore and coastal areas of Saudi waters in the Gulf currently has positive net ecological effects on fish and invertebrate communities. The positive effect in offshore locations is of increased number of individuals, whereas the positive effect in coastal locations is increased species richness and diversity. Specifically, for any given offshore point, more offshore oil and gas facilities within a 5 km radius lead to higher fish abundance in numbers; in coastal areas, closer proximity to a facility results in higher species richness and diversity of very early juveniles. These results are robust to potential effects of other factors such as substratum type, substratum cover, and urban pressure because their separate effects were accounted for in the statistical analysis. Access to the areas surrounding coastal facilities is physically restricted and fishing and navigation within a 500 m radius around offshore facilities is banned for security reasons. In addition, the positive effect on fish numbers is not accompanied by a significant and positive effect on fish biomass. Therefore, the most likely proximate

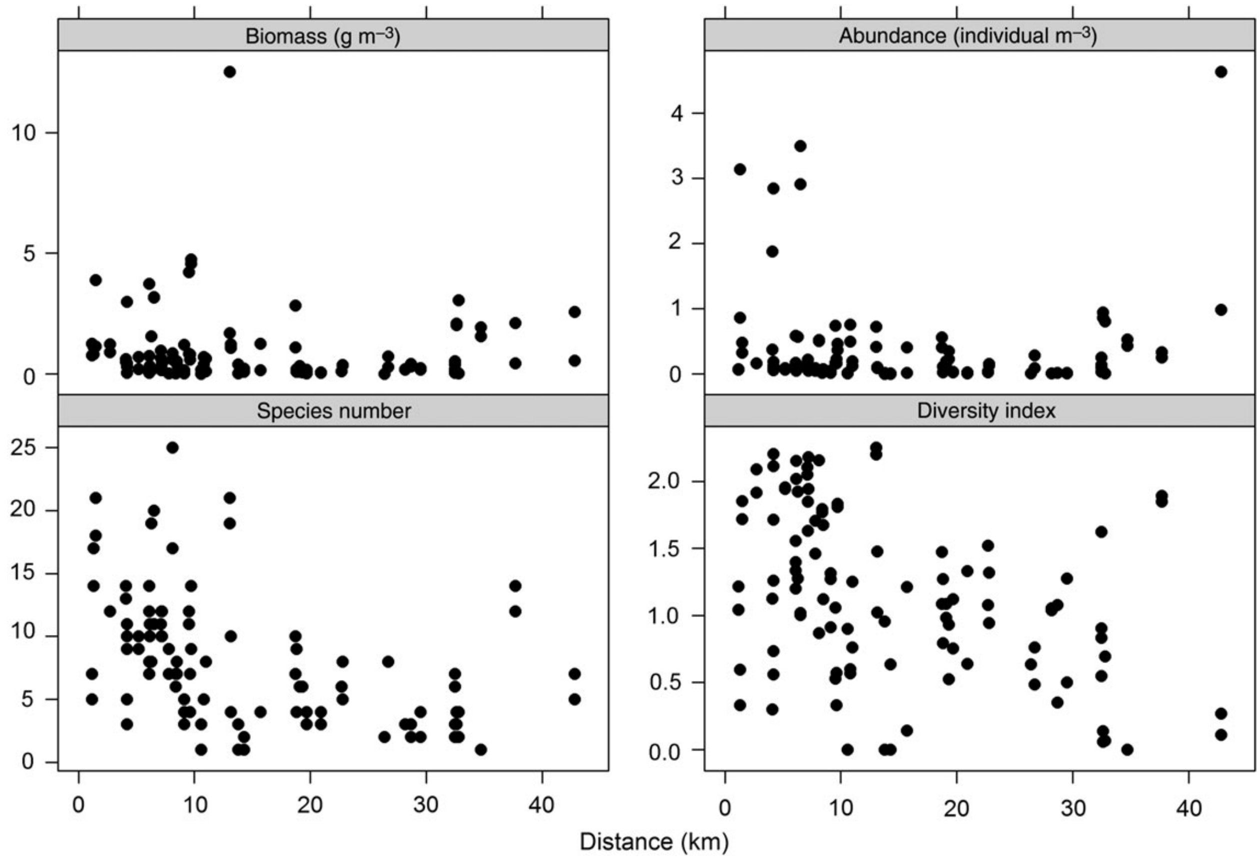


**Figure 4.** Plot of the biomass (kg $m^{-3}$), abundance (ind. $m^{-3}$), number of species, and Shannon–Wiener diversity index ($H'$) estimated in the samples collected from nursery areas, with respect to distance from the sampling stations to the nearest coastal oil/gas industry structure (km).

**Table 3.** Maximum likelihood estimates of the parameters and corresponding *p*-values for faunal analysis of coastal locations.

| | **Response variable** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Biomass** | | **Abundance** | | **Species richness** | | **$H'$ diversity index** | |
| **Covariates** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** | **Estimate** | ***p*-value** |
| Substratum type: sandy | −1.20 | $2.31 \times 10^{-3}$ | −1.81 | $3.5 \times 10^{-8}$ | −0.59 | $1.85 \times 10^{-6}$ | 0.10 | 0.532 |
| Substratum type: sandy–*muddy* | −0.30 | 0.516 | −0.21 | 0.582 | −0.31 | 0.030 | 0.25 | 0.179 |
| Substratum cover: bare | 0.92 | 0.019 | 0.59 | 0.072 | 0.03 | 0.816 | 0.14 | 0.387 |
| Substratum cover: mangroves | 1.03 | 0.098 | −0.07 | 0.899 | −0.12 | 0.535 | 0.14 | 0.586 |
| Substratum cover: *seagrass* | 0.47 | 0.356 | 0.35 | 0.421 | 0.41 | 0.008 | 0.31 | 0.143 |
| Habitat type: *open sea* | 0.05 | 0.904 | −0.36 | 0.339 | −0.17 | 0.227 | −0.23 | 0.215 |
| Urban pressure: *high* | −0.38 | 0.389 | −0.43 | 0.248 | −0.30 | 0.054 | −0.34 | 0.061 |
| Urban pressure: *low* | 0.33 | 0.409 | 0.02 | 0.942 | −0.17 | 0.183 | −0.34 | 0.040 |
| Distance to the nearest oil/gas facility (km) | 0.02 | 0.384 | 0.01 | 0.347 | −0.03 | $1.76 \times 10^{-5}$ | −0.03 | $5.99 \times 10^{-4}$ |

Tested predictors are: "Substratum type" (compared with muddy), "Substratum cover" (compared with algae), "Habitat type" (compared with lagoon), "Urban pressure" (compared with average), and distance to the nearest oil/gas facility. Response variables are: number of species, number of individuals, biomass, and Shannon–Wiener diversity index ($H'$).

cause for the net positive effects is that the presence of oil and gas facilities creates a patchwork of small zones of special protection that act as nurseries for small fish and habitat for small-bodied species and that the spillover of their biological enrichment affects the surrounding areas.

The Saudi territorial waters in the Gulf are mainly dominated by soft bottoms; rocky areas are scarce particularly in the northern part (Table 1). Therefore, hard substratum can be a limiting resource for sessile macro-invertebrates and algae species in this area, and the oil and gas industry structures may contribute to alleviate the scarcity. According to Bohnsack *et al.* (1991), oil and gas platforms provide habitat that potentially increases the growth and survival of individuals, affording shelter for protection from predation and spawning substrate, and acting as a visual attractant for organisms not otherwise dependent on hard bottom, such as pelagic species. All these properties could be attracting factors for many fish species from surrounding habitats, in particular reef-associated fish (Laborel, 1974; Gallaway and Lewbel, 1981; Bohnsack *et al.*, 1991; Scarborough-Bull and Kendall, 1994) leading to an increase in the ecological connectivity (Cowen and Sponaugle, 2009). Moreover, these artificial structures may be suitable substrata for spawning of some species and additional habitats that ultimately lead to an increase in the biotope size and therefore to an increase in the biomass production of fish populations (Laborel, 1974; Bohnsack *et al.*, 1991) which in turn supports fisheries production. Within this context, Page *et al.* (1999) reported higher catch per unit effort of the commercially important crab species *Cancer antennarius* and *Cancer anthonyi* close to an offshore oil platform and explained that while the former species remained primarily near the platform, females of the latter species were attracted to the platform from surrounding habitat and that the habitat selection in this species is related to reproduction. In Japan, an increase in the catch per unit effort of the Pacific giant Octopus (*Octopus dofleini*) was reported after the addition of artificial reefs, supporting therefore the fisheries production (Polovina and Sakai, 1989). Fish attraction occurs in the first few years after the installation of artificial reefs leading to increases in abundance (Bohnsack and Sutherland, 1985) and subsequently the process of increased production occur over several decades (Macreadie *et al.*, 2011). In our case, even if it was confirmed only with fish abundance (and not with biomass), we suggest that the oil and gas facilities of the Saudi waters in the Gulf contribute directly and indirectly to the enhancement of local production by providing suitable areas for the settlement and reproduction of fish species and through the fisheries exclusion which may in turn contribute to the decrease in fishing mortality (Friedlander *et al.*, 2014). Consequently, the opportunity exists to improve the long-term sustainability of Saudi fisheries by amplifying this effect with the establishment of official zones of special protection, merging the fishing exclusion zones of each individual installation and the surrounding waters in the region of highest concentration of oil and gas facilities, the northern part of Saudi territorial waters. This management proposal is directly supported by our empirical, statistically oriented approach. It can also be supported by considering recent theoretical work. Brochier *et al.* (2015) developed a system of ordinary differential equations to model the effect of artificial habitats inside MPAs, vs. situations in which the artificial habitats are located outside MPAs, within the context of the attraction/production hypothesis and fisheries production. Their model demonstrates that locating the artificial structures inside MPAs leads to an equilibrium with higher biomass and landings in the areas outside the MPAs. Our proposal involves the reverse operation of setting the zone of special protection such that it surrounds pre-existing artificial structures, but it can be reasonably assumed that the net effect will be the same as that obtained by Brochier *et al.* (2015). Spillover effects that may occur from a major zone of special protection surrounding the area of highest concentration of offshore oil and gas structures could also help alleviate the ongoing decline of fisheries production in neighbouring countries (Al-Zaidan *et al.*, 2013). Spillover effects of MPAs spanning larger spatial scales have already been demonstrated (Christie *et al.*, 2010). Our main result contributes to a body of knowledge indicating that offshore oil facilities are complex habitat-building structures. They provide suitable settlement for sessile invertebrates such as mussels, barnacles, sponges, oysters, and corals (Bull *et al.*, 2006), creating further structure that acts as nursery ground for juvenile fish (Love *et al.*, 2001; Helvey, 2002).

The significant and negative effect of the interaction between the number of offshore oil and gas facilities within a 5 km radius and the number of facilities between 5 and 10 km on fish abundance is very small, ten times smaller than the main effect of the number of facilities within a 5 km radius. The most reasonable interpretation of this effect is that there is a small "dilution effect" of the number of oil and gas facilities within the 5–10 km ring on the positive effect of the number of facilities within a 5 km radius. This also means that isolated facilities within a 5 km radius tend to slightly increase the crowding in of fish when compared with facilities within a 5 km radius that are surrounded by many other facilities within the 5–10 km ring.

We obtained a significant increase in the number of individuals at any given location with increasing number of offshore facilities within a 5 km radius, but no significant effect was found with the other response variables. This disagrees with the findings of other authors who reported higher species richness, abundance, and diversity at areas close to offshore oil and/or gas facilities (Stanley and Wilson, 1990, 1997; Love *et al.*, 1994; Consoli *et al.*, 2013). The higher abundances of fish recorded in stations close to oil and gas facilities could be due to the prohibited or at least reduced fishing activities around these facilities compared with more remote areas. This probably implies a direct increase in fish abundances that could act as a source of fish to the surroundings (i.e. spillover effect, Russ *et al.*, 2004). In addition, offshore oil and gas facilities seem to provide habitats to a few rare species, such as *Apistus carinatus*, *Arnoglossus aspilos*, *Champsodon nudivittis*, and *Psettodes erumei* that are scarce in numbers. This agrees with previous observations in the Southern California Bight and Gulf of Mexico, where the snapper (genus *Lutjanus*) and rockfish (genus *Sebastes*) are two species groups found highly associated with offshore oil facilities, but are either sparse or overfished in the natural habitats (Love *et al.*, 2003; Love and York, 2005).

Similar results on the ecological effect of artificial structures have been reported also with marine renewable energy installations. These latter structures have been considered to have both positive and negative effects on the environment, as well as variable effects at different stages of their life from construction to decommissioning (Gill, 2005; Inger *et al.*, 2009; Grecian *et al.*, 2010). Some previous reviews came to the idea that these installations can play the role of MPAs by providing artificial reefs, fish aggregating devices, and exclusion zones to destructive fishing activities therefore augmenting fisheries and benefiting coastal areas (Linley *et al.*, 2007; Inger *et al.*, 2009). In addition, the deployment of such artificial structures in marine environments has been found to have an influence on the specific functional groups and also on species composition (Ashley *et al.*, 2014) by attracting fish and sessile invertebrates. According to Anderson and Öhman (2010), the introduction of offshore wind turbines in marine waters could have a positive effect on fish numbers and the presence of sessile invertebrates. Hunter and Sayer (2009) and Langhamer and Wilhelmsson (2009) reported an increase in the occurrence of some fish species including the commercial gadoids, Pollock (*Pollachius pollachius*) and cod (*Gadus morhua*) close to offshore wind farms. Similarly, the abundance of the economically important species *Cancer pagurus* (Brown crab) was found to increase close to these artificial structures (Langhamer and Wilhelmsson, 2009).

To our knowledge, the effect of oil and gas facilities on the structure and composition of coastal nurseries has not been studied previously. We attribute our finding of increased number of species and diversity near facilities to the fact that these artificial structures are often located in areas relatively undisturbed by human activities other than operational activities related to the platform which are rarely frequented by humans, and that the presence of the structures further reinforces the location as a protected nursery ground for several species inhabiting coastal and offshore habitats. We also found that the structure and composition of coastal nursery communities were shaped by substratum type, substratum cover, and urban pressure. The significant effect of substratum type on the biomass, number of species, and individuals is probably due to the different affinities of species to different types of substrata. For the substratum cover, the higher number of species found in seagrass meadows compared with bare areas or close to mangrove forests argues in favour of the important ecological role played by seagrass meadows in the Gulf (Sheppard *et al.*, 1992; Price, 1998; Jones *et al.*, 2002). In fact, these habitats are considered as a critical marine resource in the Gulf, which offers various ecological benefits including a sustainable and high primary productivity, a high biodiversity of associated species, and crucial nursery grounds for penaeid shrimps, pearl oysters, and other organisms of importance to the Gulf's commercial and artisanal fisheries (Sheppard *et al.*, 1992; Jones *et al.*, 2002). In addition, seagrass beds are considered as a major source for detrital food chains, which provide an indirect source of food for many marine organisms (Erftemeijer and Shuail, 2012). In this connection, significantly higher densities and biomass of benthic fauna were reported in seagrass beds relative to unvegetated sandy and muddy habitats (Orth *et al.*, 1984; Coles and McCain, 1990). The number of benthic species occurring in seagrass meadows of the Gulf have been reported to range between 530 (Basson *et al.*, 1977) and 835 (Coles and McCain, 1990). The high densities and biomass of benthic fauna in these habitats would favour fish assemblages by providing higher trophic resources.

Regarding the urban pressure factor, we found marginally non-significant or marginally significant negative effects of low and high urban pressure on the number of species and the $H'$ diversity index when compared with intermediate urban pressure. This result could be explained by the intermediate disturbance hypothesis (IDH) (Connell, 1978). According to this hypothesis, the species richness and diversity of competing species are should peak at intermediate levels of disturbance or environmental change. However, this diversity-disturbance relationship was judged to be quite variable due to the possible influence of environmental factors (see Randall Hughes *et al.*, 2007 for review). Within this context, it was demonstrated that although the number of species and abundance, and hence diversity, are supposed to decrease with decreasing habitat quality, they however might not be linearly correlated with the environment deterioration (Whitfield and Elliott, 2002; Coates *et al.*, 2007).

Despite the highlighted positive ecological effects of marine oil and gas facilities, surrounding areas cannot be considered as full MPAs but only as partially protected areas, since activities carried out in these artificial structures may represent themselves a potential risk for the marine life. Within this context, previous oil spills in the Arabian Gulf have generated high mortality of many invertebrates, including crabs, bivalves, and gastropods and many fish species, although mangroves trees as well as coral reefs and their associated faunal assemblages were less affected and the recovery of the ecosystems was considered satisfactory (Spooner, 1970; Jones *et al.*, 1998). Although we found a net positive aggregate effect on certain important ecological variables, a better knowledge of the detailed population and ecosystem dynamics around these artificial structures is still necessary.

## Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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