Regional Studies in Marine Science 5 (2016) 87–96

Contents lists available at ScienceDirect

Regional Studies in Marine Science

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

Anthropogenic related variations in the epibiotic biodiversity and age structure of the "Pearl Oyster" *Pinctada radiata* within the eulittoral zone of Qatar

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form
10 February 2016
Accepted 10 February 2016
Available online 16 February 2016

Keywords:
Pinctada radiata
Anthropogenic disturbance
Epibiota
Age structure
Eulittoral

ABSTRACT

Oyster aggregations provide critical habitat that contain diverse communities, with epibiota and oysters sensitive to environmental disturbance. The monitoring of oysters and associated organisms has become an important tool in gauging change within the marine environment. The research aimed to investigate the population structure of the *Pinctada radiata* and its epibiota in relation to anthropogenic disturbance within the eulittoral zone of Qatar. Oysters were recorded at six sites along the east coast but were absent from the west and southeast. The absence of oysters in the west was attributed to high salinity and temperature combined with the low flush hydrodynamic regimen of the region. The southeast sites absent of oysters were a result of unsuitable settlement substrate. In sites where *P. radiata* was recorded, significant inter-site differences existed between epibionts. These differences became significant when epibiota was divided into vagile and sessile species. Sites situated in close proximity to coastal land reclamation activities showed a significantly lower number of vagile taxa. It would appear that sedimentation from coastal development is having a significant effect on epibiont species associated with *P. radiata*.

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1. Introduction

The pearl oyster *Pinctada radiata* is a marine bivalve indigenous to the Arabian Gulf. It comprises 95% of pearl oyster stocks found naturally on 80 designated beds within Qatari waters (Payne, 2013). The gregarious settlement of oysters such as *P. radiata* when combined with the appropriate hydrodynamics and settlement material can lead to reef forming densities. These reefs provide large areas of hard substrate in the form of living and dead shell. The consequential oyster assemblages can be habitats in their own right acting as benthic-pelagic couplers while providing crucial ecosystem services (Lenihan and Peterson, 1998; Coen et al. 2007; La Peyre et al. 2014). Previous research into oyster shell habitats has been conducted from a fisheries perspective and as a consequence the associated epibiont species have been regarded as bio-fouling or spoiling factors of a market commodity (Walne, 1974; Breitburg et al., 1995; Lenihan and Micheli, 2000; Wronski, 2010). However recent research carried out under the remit of habitat enhancement using bioengineering species like *Crassostrea gigas* and *C. virginica* in North America and *Ostrea edulis* in Northern Ireland, has challenged the concept of epibiotic organisms as being bio-foulers (Smyth and Roberts, 2010; Wronski, 2010). These studies suggest that epibiont communities on live and dead oyster shells should be regarded as integral members of a complex benthic matrix. The contribution of oyster assemblages in regards to marine biodiversity within benthic communities becomes apparent when the numbers of epifaunal species recorded are examined. Mobius (1893) listed 86 species on German oyster beds. Hagmeier and Kändler (1927) recorded 105 species on the same oyster grounds; Mistakidis (1951) recorded 121 species at the Essex oyster grounds in the South of England and Larsen (1985) 142 species from Chesapeake Bay in the USA. The offshore oyster beds in Qatari waters are known to accommodate highly diverse communities, with between 111 and 189 benthic faunal species

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http://dx.doi.org/10.1016/j.rsma.2016.02.004
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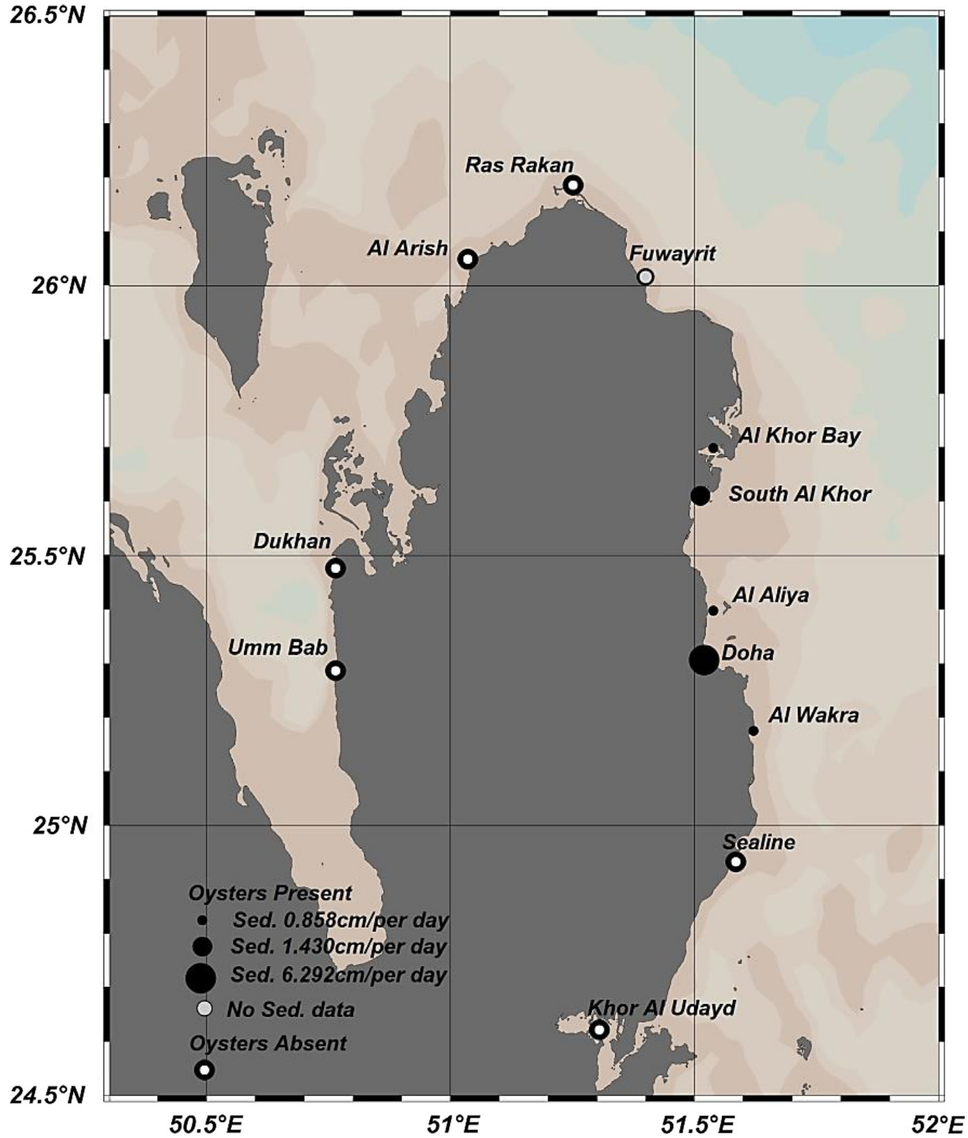

Fig. 1. Location of survey sites around the coast of Qatar. Sedimentation data at sites where oyster assemblages existed are denoted by graduated sizes of solid filled spheres. Sites where no oyster assemblages were found and had no sedimentation data are represented by grey filled spheres.

being recorded on 18 randomly selected *P. radiata* sites (Al-Khayat and Al-Maslamani, 2001; Al-Khayat and Al-Ansi, 2008).

The nations of the Arabian Gulf have experienced extensive development in recent years. Qatar is currently the fastest growing Gulf State and as a result is undergoing a rapid period of growth around its shallow coastal zones many of which are settlement areas for *P. radiata*. An example of the scale of coastal development was revealed during the construction of the newly established Pearl City situated on the central east coast of Qatar. The project required 400 hectares of land reclamation with approximately 13.5 million m^3 of landfill (Rezai et al. 2004). There are numerous coastal development projects presently on-going in Qatar with most of the construction and land reclamation work focused on the delicate intertidal zone. This benthic zone is finely balanced and extremely susceptible to disturbance and a robust *in-situ* biological monitoring program for the eulittoral is essential if irreparable environmental damage is to be avoided (Bishop, 2002; Khan et al., 2002; Munawar et al., 2002; Jones et al., 2007; Khan, 2007). Long lived marine bivalves such as *P. radiata* have been used on many occasions as bio-indicators of environmental stressors (Depledge et al., 1994; Markich et al., 2001). The oyster and its epibiota have varying sensitivities to environmental disturbance and the integrity of the oyster benthic matrices has become an important tool in gauging change within the marine environment (Breitburg et al., 1995; Lenihan and Peterson, 1998; Hargis and Haven, 1999; Grandcourt et al., 2011; Henglong, 2011).

The need for *in-situ* biological monitoring protocols within Qatar's coastal zone was the driver behind this current research into eulittoral *P. radiata* assemblages and its associated epibiota. The study aimed to compare population dynamics and the associated epibiota of *P. radiata* at different eulittoral sites. The working hypothesis was that oyster assemblages from less anthropogenically disturbed sites along Qatar's eulittoral zone would present a broad oyster population age structure with a high epifaunal biodiversity.

2. Materials and methods

2.1. Study area

Qatar is a small country centrally located on the west coast of the Arabian Gulf 25°30′N and 51°15′E (Fig. 1) located on the peninsula bordering the Gulf and Saudi Arabia. It has a total coastline of

563 km which is subjected to a south easterly surface circulation (Kampi and Sadrinasab, 2006). The average sea temperature ranges from 18.7 to 32.0 °C and salinities vary from 35.5 to 44.5 ppt (Al-Maslamani et al., 2009). In an attempt to ascertain the current geographical distribution of eulittoral *P. radiata* around the coast of Qatar twelve sites were visited during October 2014 (Fig. 1). The selection of survey sites was intended to be representative of the entire coast of Qatar and included areas where *P. radiata* populations would be expected to occur based on local knowledge and also areas where oysters had not been recorded previously. All sites were located in the lower eulittoral/upper infralitterol zone just below the chart datum low water mark, experiencing a tidal range of up to 2.7 m but were never fully exposed even on a spring tide. All of the east coast survey sites had been exposed to some form of coastal development with the exception of the most northerly site at Fuwayrit.

2.2. Methodology

Logistical challenges and ease of access to the survey site dictated the use of a timed search technique within a fixed area rather than a conventional fixed transect line. This methodology is considered suitable for surveying discrete bivalve assemblages located within demanding environments (Smyth et al., 2009). Previous studies have shown a high degree of correlation between data sets for both fixed area timed searches and transect survey methods (Smyth et al., 2009). To quantify the density and biodiversity of epibiota we employed a timed shore walk search of 10 min at each site on a low tide within a 10 m × 10 m plot and repeated it four times. A maximum collection quota of 65 oysters was set per site to limit the impact of the research. The individual oysters were collected sub-surface, and placed *in-situ* into individual zip-lock sample bags. The water surrounding the oyster was retained during the collection process within the closed zip-lock bag to ensure the maximum retention of epibionts during the sampling procedure. On return to the laboratory, oyster samples were rinsed using seawater over a 0.5 mm meshed sieve to collect associated vagile species. The species were preserved in 5% buffered formalin in seawater. Vagile specimens were sorted according to their taxonomic rank and identified to species level (where possible). The oysters were relaxed in 5% ethanol and preserved in 70% ethanol as per Mann et al. (1991). Individual oysters were placed in a white photographic tray and the sessile species were identified using ×10 Nikon© SMZ 2B stereo microscope.

2.3. Age determination in Pinctada radiata

In order to ascertain the size and age frequency of the oysters the 20 largest *P. radiata* collected from Al-Wakra, Al Aliyah and South Al-Khor were selected. These sites presented a good geographical representation of the oyster assemblages along the coast of Qatar and kept the removal of mature broodstock to a minimum (Fig. 1). The shell ageing methodology was as per that described by Mohannadi (2001). Single shell valves were chosen and the umbo region was cut off using a diamond saw (Fig. 2 labelled A–B) and then embedded in Metaset© resin before cutting the shell along the axis X–Y (Fig. 2). Ages were determined using shell growth ring counts from the resin embedded samples and age–size relationships established for *P. radiata* in as per Mohannadi (2001). To investigate the link between biodiversity and oyster population age structure, shell measurements for each oyster were taken to the nearest 0.1 mm using Vernier calipers. Shell height (umbo to the shell margin) and width (anterior–posterior axis) were taken for each oyster (Gibson et al. 2001).

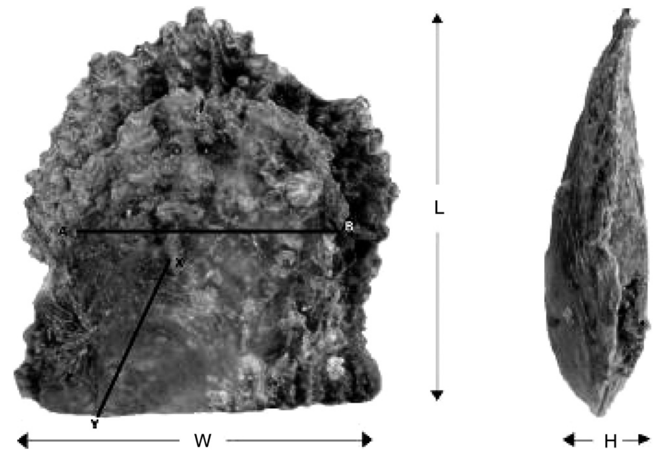

Fig. 2. Shell of *Pinctada radiata* showing shell measurements and structures, H = shell height, L = shell length, W = width. A–B marks the dissection made in preparation of the umbo region X–Y cut orientation used for shell ageing.

2.4. Data analysis

The epibiont community comparisons between sites were based on numbers of both species and individuals. The PAST© statistical package was employed for univariate analysis. Normality and homoscedasticity were ascertained prior to testing each dependent variable using the Levene's test, respectively, and all assumptions were met prior to using the one-way Analysis of Variance (ANOVA) procedure. One-way ANOVA was used to test differences between vagile and sessile epibiotont numbers in relation to species Richness and Abundance at the surveyed sites. If significant differences were found, a *post-hoc* test (Tukey's HSD) was run to determine where the differences existed.

Multivariate analyses was carried out using the PRIMER 6© statistical package (Clarke and Gorley, 2001) to create a Bray–Curtis similarity coefficient to construct a similarity matrix from the fourth-root transformed densities of the vagile and sessile epibiont species recorded at each site. Sites were catagorised in regards to the volume of sedimentation load recorded from previous studies in their locality (Fig. 1). This matrix was then subjected to non-metric multidimensional scaling (nMDS) ordination. An analysis of similarities (ANOSIM) was applied to test the difference between vagile and sessile epibionts at each site all of which were allocated their sedimentation load in cm per day as related to the area of sampling.

3. Results

3.1. Population structure and age

The survey revealed that the assemblages of *P. radiata* were confined to six sites on the east coast (Fig. 1). The abundance of oysters at the sites was considered low with an average density of <0.55 m^{-2}. The lowest oyster density was recorded at Al-Khor Bay 0.37 m^{-2} and the highest at Al-Wakra 0.64 m^{-2} (Fig. 3). The size frequency investigation revealed the largest oyster sampled was recorded at Al-Khor Bay and measured 94.2 mm in shell height and the smallest was at Fuwayrit and measured 10.3 mm (Fig. 4). The height frequency data showed the Fuwayrit assemblage to be comprised of the youngest oysters with the majority of individuals in the 0–1 year age bracket. The assemblages at Al Aliya and Doha were made up of individuals within the year two, three and four age ranges. The assemblage at the Al-Wakra site comprised of oysters within the year one, two and three age range, while those at Al-Khor Bay and South Al-Khor included oysters in all four age ranges (1–4 years) (Fig. 5). No site displayed the full (0–4 year) comprehensive age structure within its population.

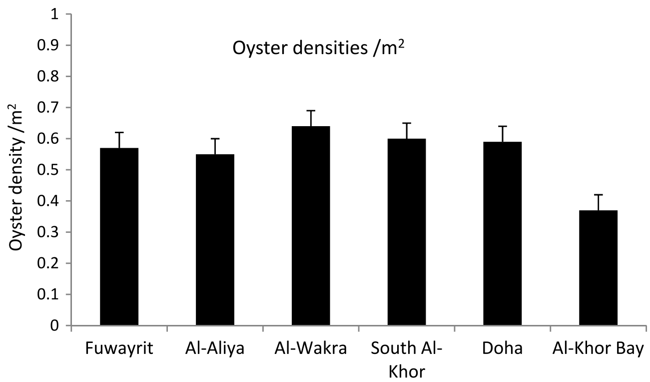

Fig. 3. Oyster densities per m^2 at sites on the east coast of Qatar.

3.2. Analysis of vagile and sessile species composition

A total of 1583 individuals were collected during the study comprising of a total of 148 species, which were represented in 14 phyla. The data showed a greater abundance of vagile (110) than sessile (38) species associated. The species richness differed between individual sites. The lowest species richness was recorded at Doha which produced a total of 38 species, 18 sessile and 20 vagile (Fig. 6). The site which recorded the highest species richness was Al Alyia with a total of 85 species, 16 sessile and 69 vagile. South Al-Khor, Al-Wakra and Al-Khor Bay had between 60 and 68 species. Fuwayrit produced a total of 44 species 5 sessile and 39 vagile (Fig. 6).

A one-way ANOVA was used to compare the differences in the pooled data for the species Abundance of vagile, and sessile epibionts. No significant differences were detected with F value = 2.51 and $p > 0.05$. The pooled data for species Richness of vagile and sessile species was then analysed using a one-way ANOVA. A highly significant difference was detected with an F value = 24.65 and $p < 0.005$ (Table 1). A comparison of vagile and sessile species Richness was carried out using a Tukey's post-hoc test which identified the vagile species as being significantly different with a $p < 0.005$ (Table 2).

3.3. Multivariate analysis

A Multi-Dimensional Scaling plot, based on the Bray–Curtis similarity matrix for the species Richness of sessile epibionts related to the corresponding sedimentation load associated with sites from the region was plotted. Groupings were clear in relation to sediment load and site with no overlapping of sites. A stress value of 0.16 represented a good interpretation of the data (Fig. 7).

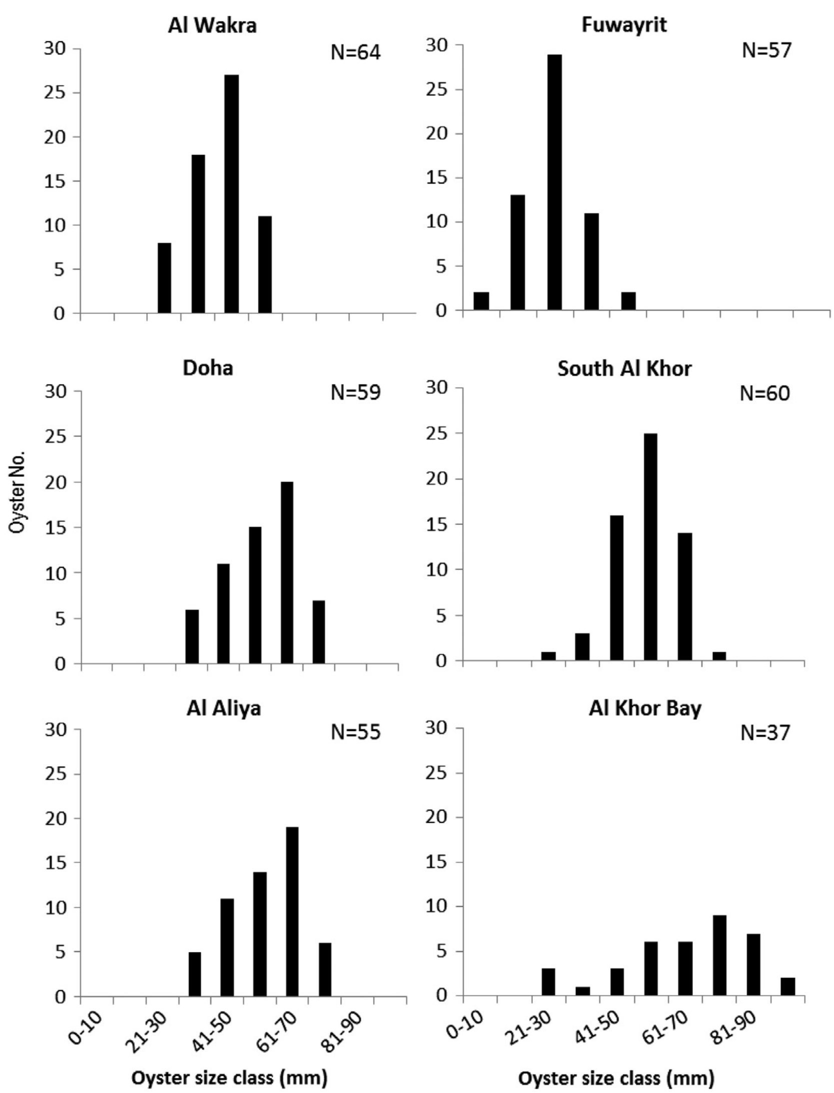

Fig. 4. Size frequency of *Pinctada radiata* from sites on the east coast of Qatar. Classes were fitted in 10 mm cohorts based on shell height measurements.

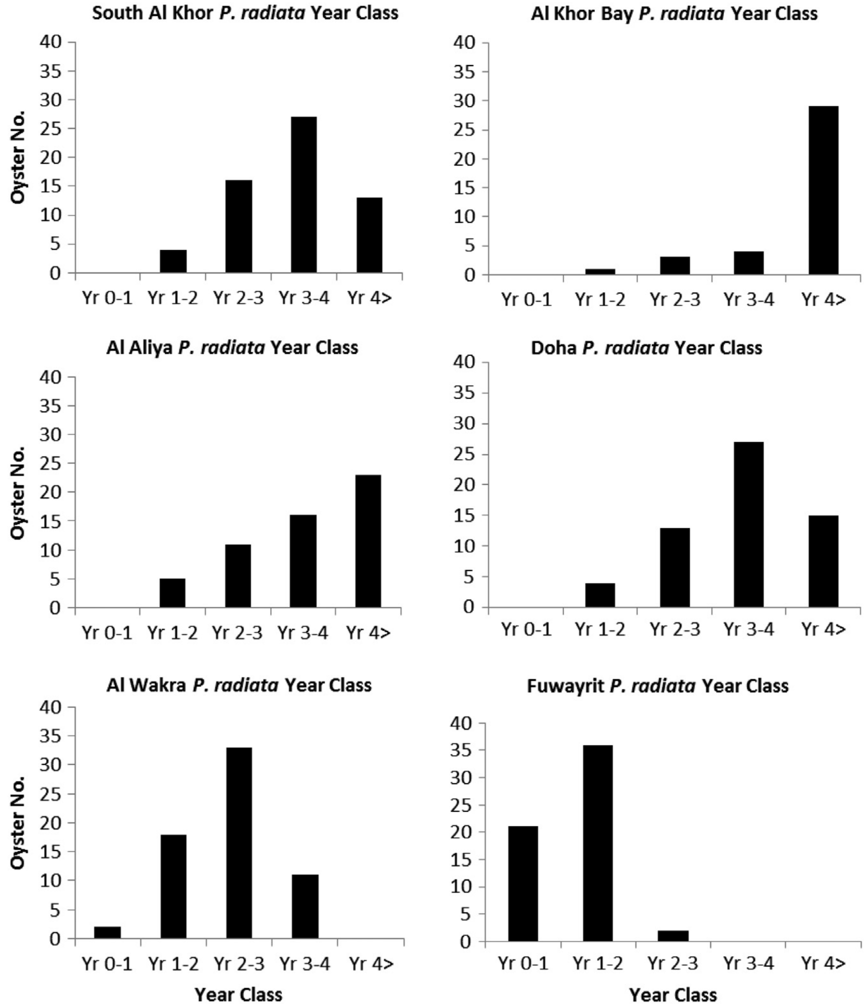

Fig. 5. *Pinctada radiata* size classes at each site based on acetate peel growth line counts.

Table 1
One-way ANOVA of pooled data for species richness between vagile and sessile species recorded on *P. radaita* assemblages. Significant *p* value is presented in bold font for $p < 0.005$.

Species richness Sessile and vagile	*df*	MS	*F*	*p*
Between groups	1	3300.08	24.65	**0.00056**
Within groups	10	1338.83		
Total	11			

Table 2
Post-hoc Tukey tests for unequal *n* were performed for subsequent multiple comparisons between the pooled vagile and sessile groups. Significant *p* value is presented in bold font for $p < 0.005$.

	Sessile	Vagile
Sessile		**0.00071**
Vagile	7.021	

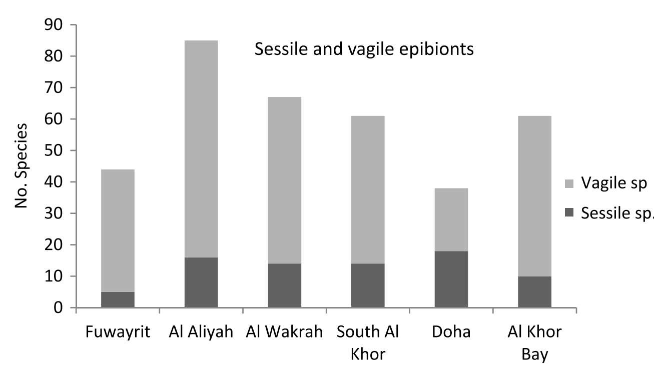

Fig. 6. Species richness of sessile and vagile epibiotic taxa found on *P. radiata* at sites around the coast of Qatar.

A Multi-Dimensional Scaling plot, based on the Bray–Curtis similarity matrix for site specific vagile epibiont species Richness data in relation to sediment load was plotted. Sites were clearly grouped in relation to sedimentation (Fig. 8). Doha was orientated to the periphery of the plot displaying a clear difference from the other five sites. The analysis produced a stress value of 0.1 which is indicative of a good two-dimensional representation of the data.

An analysis of similarity test ANOSIM was used to detect statistically significant differences for both vagile and sessile species Richness in relation to specific sedimentation load. The ANOSIM tests revealed significant differences between the above-mentioned groups. The ANOSIM for sessile species presented a Global R value $= 0.433$ indicating a non-significant separation between groups (Table 3). The ANOSIM for vagile species presented a Global R value $= 0.806$ indicating a significant difference between groups (Table 4). The ANOSIM pairwise test showed a highly significant difference ($p < 0.005$) between vagile species Richness for the low vs. medium and high vs. low sedimentation groups. A significant difference ($p < 0.05$) was also shown between medium and high groups (Table 4).

Table 3
ANOSIM results for sessile species richness and associated daily sediment load.

Global test			
Sample statistic (Global *R*): 0.433 Significance level of sample statistic: 0.1% Number of permutations: 999 (Random sample from a large number) Number of permuted statistics greater than or equal to Global *R*: 0			
Pairwise test			
Sessile species group comparison Sediment load per site (cm/day)	*R*-value	Significance level % (*p*)	Possible permutations
Low (0.85), Med (1.43)	0.14	0.137	1820
Low (0.85), High (6.29)	0.032	0.35	1820
Med (1.43), High (6.29)	0.18	0.25	1820

Table 4
ANOSIM results for vagile species richness and associated daily sediment load.

Global test			
Sample statistic (Global *R*): 0.806 Significance level of sample statistic: 0.1% Number of permutations: 999 (Random sample from a large number) Number of permuted statistics greater than or equal to Global *R*: 0			
Pairwise test			
Vagile species group comparison Sediment load per site (cm/day)	*R*-value	Significance level % (*p*)	Possible permutations
Low (0.85), Med (1.43)	0.435	0.001	1820
Low (0.85), High (6.29)	1	0.002	1820
Med (1.43), High (6.29)	1	0.029	1820

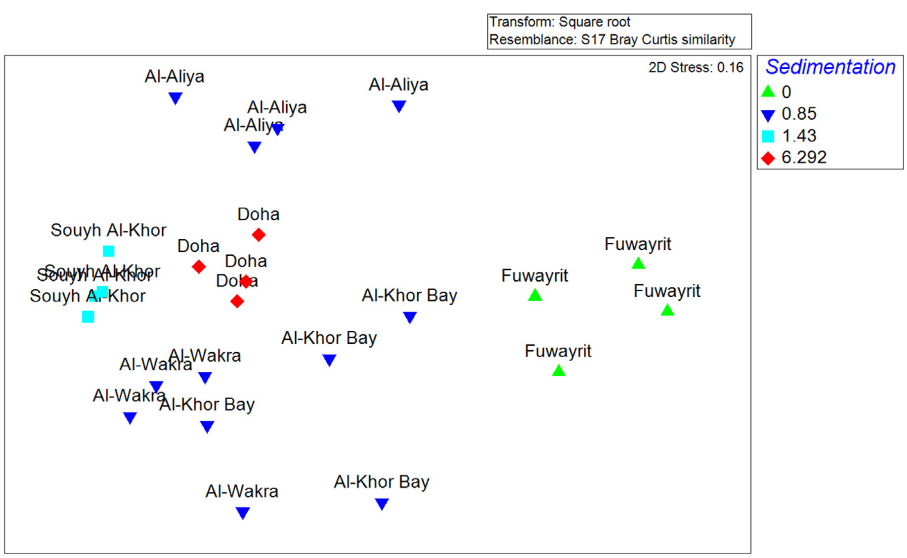

Fig. 7. MDS plot based on Bray–Curtis similarity matrix for species richness of sessile epibionts of *P. radiata* at sites on the east coast of Qatar. Sites were catagorised in regards to the daily sedimentation load of the region; low (0.858 cm), medium (1.430 cm) and high (6.292 cm).

4. Discussion

The study detected significant differences between the vagile and sessile taxa of *P. radiata* epibiota at sites in the eulittoral zone which were in close proximity to coastal development projects. A major component of coastal construction in Qatar relies on land reclamation through dredging. Studies carried out in 2012–13 by Qatar University showed that the sediment load in the water column can be substantial with sediment traps close to dredging activities collecting between 21.71 and 46.76 cm in a year (ESC, 2014). The effects of suspended sediments from dredging activity can physically smother benthic habitats leading to a deoxygenation of underlying substrata (Newell et al. 1998; Allen et al. 2008). The resulting physical and chemical alterations can lead to a reduction in biodiversity, richness, abundance and biomass of the associated macro-benthos (Smith and Rule 2001). The population dynamics and associated species for offshore oyster assemblages in Qatar have been documented in several studies (Al-Madfa et al., 1998; Al-Khayat and Al-Maslamani, 2001; Al-Khayat and Al-Ansi, 2008). However a comprehensive understanding of *P. radiata* in the eulittoral zone has been absent from peer reviewed literature. The current research was instigated as a preliminary investigation to address this lack of information in regards to *P. radiata* assemblages within the eulittoral zone.

The hydrodynamic and environmental parameters are influencing factors in the marine benthic habitats of the Arabian Gulf. Pous et al. (2012) used a shallow water model coupled with a 3-dimensional hydrostatic ocean model to study wind induced circulation along the western Arabian Gulf and discovered the presence

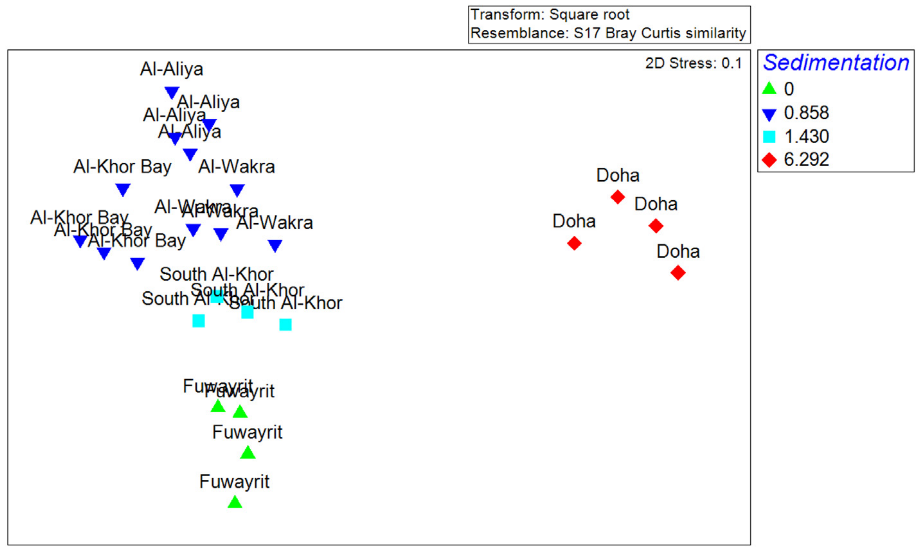

Fig. 8. MDS plot based on Bray–Curtis similarity matrix for the species richness of vagile epifauna of *P. radiata* at sites on the east coast of Qatar. Sites were catagorised in regards to the daily sedimentation load of the region; low (0.858 cm), medium (1.430 cm) and high (6.292 cm).

of a double surface water gyre formed by northwesterly winds. The study revealed that this wind induced gyre influenced the south-easterly current which flowed along the western coast of the Arabian Gulf. The eastern coast of Qatar is subjected to this south-easterly surface circulation and the region supports a high density of offshore oyster beds (Kampi and Sadrinasab, 2006). The abundance of these beds has been acknowledged in numerous historical texts as far back as the 4th/3rd and 1st century (Williamson, 1973; Coles and McCain, 1990; Carter, 2005). It is probable that the eastern eulittoral assemblages recorded during this study are a consequence of the hydrodynamic conditions, available settlement substrate and concentrated larval supply from the eastern offshore beds.

No oysters were recorded at the two most southerly sites on the east coast, Sealine and Khor Al Udayd. These sites benefit from the same environmental conditions as the other eastern assemblages therefore the supply of *P. radiata* larvae is unlikely to be a limiting factor (Pous et al., 2012). The southeasterly prevailing wind of Qatar carries wind borne sand particles in a southerly direction. The influence of this wind has resulted in the southeast corner of the country having large areas of soft sandy substratum (Coles and McCain, 1990). The absence of oysters from these two most southerly sites is probably a result of the soft sand substratum covering any available hard settlement materials (Burt et al. 2013).

At the four westerly sites no assemblages or individual *P. radiata* were recorded. The marine environmental conditions experienced along the west coast of Qatar are considered challenging for even the hardiest of species. The region has an average depth between 4 and 7 m, a water temperature of between 26.8 and 35.2 °C and an average salinity of 56.5 ppt, (John and George, 2006). Dissolved inorganic nutrients on the western coast of Qatar are in low concentrations (Kampi and Sadrinasab, 2006). The area also experiences a low flush regime with currents being tidally generated. This results in long periods of water retention which can lead to high levels of evaporation and subsequently salinities can reach 70 ppt in the region (Sheppard et al., 1992). Clarke and Keij (1973) emphasized the fact that in the Western Gulf there is an observable reduction in benthic diversity when salinities exceeded 45 ppt. The combination of no larval supply, hydrographical and physio-chemical conditions can explain the absence of *P. radiata* from the west coast sites of Umm Bab, Dukhan, Al Arish and Ras Rakan (Fig. 1). In contrast, the eastern coastal waters experience a salinity range of between 35 and 44 ppt and a temperature range of 15–32 °C with high plankton densities making the region more favorable for *P. radiata* settlement (Al-Maslamani et al., 2009). The environmental suitability to oyster populations on the eastern coast has been confirmed from the results presented within this study.

No significant inter-site differences in *P. radiata* densities were noted between the assemblages (Fig. 3). The densities of 0.12 individual's m^{-2} and 0.21 m^{-2} recorded during the study can be considered low when compared to 9.0–50.0 individual's m^{-2} in offshore oyster beds (Al-Khayat and Al-Ansi, 2008). The differences in densities could be the result of a combination of factors such as: the lack of suitable settlement substrate, extreme environmental stressors and anthropogenic disturbance.

Tolley et al. (2005) showed how seasonal variations in salinity levels in Southwest Florida could influence the densities of both oyster and epibiota. An increase in fresh water input during winter months and increased evaporation in summer months was substantial enough to increase mortalities. This could be the case in Qatar as the offshore oyster assemblages experience a more constant salinity level than those of the coastal zones where salinities can fluctuate between 35 and 55 ppt during summer months (Al-Maslamani et al., 2009).

Offshore sites tend to experience a more constant environmental balance. The locale of these benthic zones means they are not exposed to the same intensity of stressors derived from temperature and salinity fluctuation, air exposure, mechanical disturbance and pollution experienced by ecosystems at inshore sites. This lack of exposure to stressors allows offshore ecosystem components to function more efficiently and as a result the communities within these ecoregions tend to be more productive accommodating both a higher biomass and species diversity than is found within the coastal zones (Koch et al., 2009; Frélichová and Fanta, 2015). The difference between offshore and coastal densities within *P. radiata* assemblages in Qatar confirms this research.

The influence of unregulated harvesting of oysters may also be a factor contributing to *P. radiata* density differences between offshore and coastal sites. Although the offshore oyster fishery is considered no longer operational (Carter, 2005) it is quite possible that unregulated harvesting still exists particularly within easily accessible intertidal marks. Smyth et al. (2009) showed that even low impact hand gathering of oysters can have a devastating effect on vulnerable intertidal populations. This may be the case at the intertidal sites around the Qatari coastline however further investigation would be required to confirm this.

Inter-site differences in *P. radiata* size frequency were detected, with variations in maximum shell heights ranging from 41 to 50 mm at Fuwayrit and 91–100 mm at Al Khor Bay. The findings suggest that the Fuwayrit, oyster assemblage was relatively recent. It was noted during the survey that oysters were recorded settled on scrap metal deposits which had provided a hard settlement substrate on an otherwise sandy substratum.

The availability of suitable settlement substrata has long been recognized as a governing factor in oyster bed formation (Hatcher et al., 1989; Northbridge, 1991; Dayton et al., 1995; Peterson et al., 2003). In the nearby Gulf State of Bahrain the large expanse of hard substratum within its coastal zone has accounted for the prolific oyster bed coverage in the region (Sheppard et al., 1992). It would appear that the dumping of scrap at Fuwayrit inadvertently expanded the infralittoral range of *P. radiata* in Qatar.

The shell heights recorded at Al-Khor Bay in contrast to those of Fuwayrit are suggestive of a well-established assemblage of oysters. The oyster assemblage at Al-Khor Bay has been protected from anthropogenic disturbance as it is within an isolated area with a low population density and, to date, limited coastal development.

Oyster assemblages have often been defined as critical habitat areas with high biodiversity indices (Breitburg 1995; Bartol and Mann, 1997 and Borja et al., 2009). Age and shell size are important parameters to consider when investigating the abundance of vagile and sessile species which contribute to oyster bed biodiversity (Korringa, 1951; Waugh, 1972; Walne, 1974). The abundance of species associated with oysters has been shown to be influenced by shell characteristics. Studies have revealed that the periostracum of bivalve molluscs such as oysters form a natural defense against epibionts (Korringa, 1951; Guenther et al., 2006; Guenther and De Nys, 2006). The periostracum consists of a thin, flexible, sclerotinized protective protein layer which becomes reduced as an individual bivalve grows older due to environmental abrasion and decay (Mao-che et al., 1996; Harper, 1997; Guenther et al., 2006).

The age and size of the shell can therefore become a governing factor in the number of sessile and vagile species associated with the oyster (Harper and Skelton, 1993; Scardino et al., 2003; Guenther et al., 2006). The increased settlement of sessile organisms on abraded periostracum has been demonstrated for *Mytilus edulis* (Wahl et al., 1998), *Mytilus galloprovincialis* (Scardino et al., 2003) and *Ostrea edulis* (Smyth et al., 2009). Colgan and Ponder (2002) and Scardino et al. (2003) reported a positive correlation between age of the individual and area of periostracum shell coverage in relation to the density of sessile species on the oyster *Pinctada imbricata*. Guenther et al. (2006) and Smyth and Roberts (2010) suggested that an intact periostracum on the shell of young oysters contributed to the lack of settlement of sessile species and a loss of the protective periostracum led to an increase in the settlement of sessile species. The accurate ageing of an oyster can therefore be a valuable tool when describing variations in associated epifauna. For example the majority of oysters at Fuwayrit were in the 0–1 year bracket (Fig. 5) with only five sessile species recorded on an intact periostracum.

The presence or absence of sessile species is normally the main component when quantifying benthic biodiversity indices during habitat assessments, with vagile species regularly neglected (Sax and Gaines, 2003; Tlig-Zouari et al., 2009; Grandcourt et al., 2011). However the exclusive use of sessile fauna may result in bias (Giacobbe, 2012), as vagile taxa form an integral component within the functioning complexity of any biogenic reef community (Grall and Glémarec, 1997; Tlig-Zouari et al., 2009). In the present study there was a highly significant difference between the number of vagile and sessile taxa (Table 2). These differences cannot be attributed to oyster age or size as all sites displayed similar size frequency distributions, with the exception of Fuwayrit where the smallest and youngest oysters were found. However, a 7:1 vagile to sessile species ratio was still observed at that site. The oyster community sampled at Al Aliyah is six nautical miles (Fig. 1) from Doha and included 69 vagile species (Fig. 6). This site benefits from the protection of a Qatari government nature reserve classification and as a result there is minimal exposure to anthropogenic disturbance and coastal development. In contrast, the unprotected site at Doha is close to numerous on-going coastal infrastructure development projects and exhibited lower species diversity and low number of individuals, indicative of a response to stressful environmental conditions (Gervis and Sims, 1992). Large-scale dredging activity and sediment re-suspension from nearby shipping and land reclamation projects were the likely source of the observed high level of sedimentation on the oysters collected from Doha. An environmental impact assessment carried out by the Environmental Science Centre at Qatar University recorded a daily sedimentation rate during 2012–13 of 6.292 cm (Fig. 1) close to the Doha site (ESC, 2014).

The volume of coastal development around the Doha region has increased considerably since 2012–13 with the construction of a new commercial shipping port and it is likely that the sedimentation rate has increased however further research is required to confirm this. Turbidity created during dredging activity can be an influencing factor in species diversity with suspended sediment and silted layers on substrata of <1 mm limiting the presence of many epifaunal species (Moore, 1977; Gosling, 2003). Al-Madfa et al. (1998) observed dead *P. radiata* beds close to Doha harbor and attributed the deaths to biological stress caused by suffocation from a high sedimentation load in the water column as a result of continuous dredging activity and ship traffic. An oyster reef community impacted by sediment will display a reduction in biodiversity leaving only a few inconspicuous stress tolerant taxa (Bohnsack et al., 1991; Ginn et al., 2000). D'Anna et al. (2000) observed that a high rate of silt deposition led to a slowing down of the successional colonisation rate within intertidal bivalve communities. The findings of this study would concur with the previous researchers as the multivariate analysis carried out during the research clearly showed a separation of sites based on epibiota composition and sediment loads (Figs. 7 and 8). The ANOSIM analysis results (Tables 3 and 4) highlighted the differing effects sedimentation had on both type of epibiont species Richness. No significant differences were detected amongst the sessile epibiont species Richness between sites throughout the range of sediment loads. However highly significant differences ($p < 0.005$) were detected for vagile species Richness at low to high and low to medium load sites and significant differences ($p < 0.05$) were shown between medium and high load sites (Table 4). The results show that even at sites which are considered to experience low sediment loads by Qatari standards vagile species Richness was affected.

At the Doha site there was a reduction in vagile species, while sessile taxa were still diverse (Fig. 6). It was noted during analysis that the Doha samples had a high percentage cover of the sessile species *Acetabularia calyculus, Cladophoropsis* sp. and *Cystoseira* sp. recognized indicators of anthropogenic disturbance (Al-Khayat and Al-Ansi, 2008). This suggests that the inclusion of vagile species diversity associated with oyster assemblages may be a more sensitive and accurate indicator of environmental stress when conducting ecological monitoring.

The coastal region of Qatar has been exposed to substantial large scale modifications to accommodate the development of the country with projects such as: Ras Laffan industrial city, Qatari Diar Lusail city; the four million m^{-2} artificial islands of the Pearl, the Katara village project and the New Port of Doha. All have required land reclamation and modification through dredging (Rehan and Quiton, 2003; Barth et al., 2008; Sheppard et al., 2010; Burt, 2011). These engineering projects are influential factors on the biodiversity in the eulittoral zone along the east coast of Qatar. The results from this research suggest that the working hypotheses should be accepted that oyster assemblages from less anthropogenically disturbed sites along Qatar's eulittoral zone present a broad oyster population age structure with a high epifaunal biodiversity.

5. Conclusion

The eulittoral zone is considered highly vulnerable when exposed to physical and biological stressors. The majority of the east coast of Qatar is under severe pressure from coastal development and as a result the eulittoral zone is being constantly exposed to environmental risks. This study suggests that the oyster reefs and their associated epifauna, including vagile species, could be employed as an effective *in-situ* monitoring tool of environmental disturbance in Qatar.

Acknowledgments

The authors express their thanks to Mr. Hassan Hassan for his contribution of archived material, Ms. Aisha Ahmed Al-Ashwel for help with sorting and identifying samples and Mr. Ghulam Usman and Mr. Faisal Muthar Al-Quaiti for the collection of samples.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.rsma.2016.02.004.

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