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Benthic surveys of the historic pearl oyster beds of Qatar reveal a dramatic ecological change

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A B S T R A C T

The study aimed to confirm the presence of historic oyster banks of Qatar and code the biotopes present. The research also collated historical records and scientific publications to create a timeline of fishery activity. The oyster banks where once an extremely productive economic resource however, intense overfishing, extreme environmental conditions and anthropogenic impacts caused a fishery collapse. The timeline highlighted the vulnerability of ecosystem engineering bivalves if overexploited. The current status of the oyster banks meant only one site could be described as oyster dominant. This was unexpected as the sites were located in areas which once supported a highly productive oyster fishery. The research revealed the devastating effect that anthropogenic impacts can have on a relatively robust marine habitat like an oyster bed and it is hoped these findings will act as a driver to investigate and map other vulnerable habitats within the region before they too become compromised.

1. Introduction

The mapping and classification of marine benthic habitats into specific biotopes is now a recognised procedure for the comparative analysis of ecological data which can be used to monitor environmental change (Olenin and Ducrotoy, 2006; Costello, 2009). The concept of describing marine and terrestrial habitats in association with substratum and associated species is not novel and has been in practice since the mid 1800's (Tillin et al., 2008; Costello, 2009). Southern (1915) stated that the classification of marine habitats based on their associated flora and fauna, their intertidal/subtidal zonation, benthic/pelagic nature, substratum type and salinity were all excellent descriptive parameters when accurately defining a specific marine environment. The correct documentation of habitat characteristics is crucial when managing and monitoring the spatial and temporal changes of marine ecosystem components and the resources they provide (Connor et al., 2004; Costello, 2009). In the western Arabian Gulf one of the most recognised marine ecosystem components has been the pearl oyster assemblages (Al-Khayat and Al-Ansi, 2008; Smyth et al., 2016a).

The large oyster beds on the western Gulf have acted as bio-engineers for centuries with many of the marine habitats throughout the region formed as a result of the services provided by these assemblages (Bouma et al., 2009; Smyth et al., 2016a). These accumulations of oysters have been primary components in the stabilisation of sediments, water filtration, the provision of hard substratum for sessile species and the subsequent reef matrix complexes for mobile fauna (Bouma et al., 2009; Smyth et al., 2016a).

The oyster beds of the Gulf have been exposed to anthropogenic impacts since as far back as 1050 CE when they were harvested for food and pearls (Carter, 2005). They were fished intensely for pearls from the late 1700's up until the early 1900's (Bowen, 1951). The scale of the fishing activity was immense and Captain Durand of the East India Trading Company in 1878 estimated that over 4000 pearling boats were working the oyster banks of the Gulf (Carter, 2005; Hightower, 2012). However, concerns about the over-exploitation of the oyster beds were raised as early as 1770 by a pearl trader called Justamond who described the beds as being overfished and exhausted (Carter, 2005). Durand reinforced this concern about overfishing a century later in 1878 when he described the yield of pearls and oysters as having decreased considerably. These reductions in the pearl as a commodity lead to an almost doubling of prices which subsequently lead to an increase in exploitation (Hightower, 2012). In the early 1900's pearling boat captains were reporting a drop of 40% in landings with the catch per unit effort of the fishery considered not economically viable (Burdett, 1995). In 1905 Mr. James Hornell, an officer of the Madras Fisheries Bureau proposed a scientific survey of the beds be undertaken to establish the true status of the standing stocks, however this investigation never came to fruition with the onset of the First World War (Carter, 2005). Interest in the pearl industry within the Gulf diminished after the war with the introduction of cultured pearls from Japan in the 1930's. The discovery of oil in the western Arabian Gulf during the

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1940's marked the end of the commercial fishery as more economic benefit was available from employment with the oil companies than could be obtained from the harvesting of pearls (Burdett, 1995; Mohammed and YASSIEN, 2003).

During the pearl fishing epoch the offshore oyster banks within Qatari waters were considered particularly productive (Carter, 2005). Numerous research studies have been conducted on the oyster beds of Qatar in regards to topographical features, heavy metal contamination and population dynamics (Al-Madfa et al., 1998; Al-Khayat and Al-Ansi, 2008). However, these survey sites have not been investigated in relation to their environmental status and the density of the associated oyster assemblages.

Over the past decade Qatar is one of the countries within the Gulf, which has experienced unprecedented economic growth and development (Sheppard et al., 2010; Feary et al., 2011; Smyth et al., 2016a). An increase in real estate and infrastructure expansion has been accompanied by an equivalent rise in the number of people living in the country. The national residency of Qatar was recorded as being 470,000 in 1990 the estimate rose to over 2.2 million by 2014 (Kamrava, 2015). This exponential population climb has placed extreme pressure on natural resources, particularly those within the marine environment. The increase in food demands from a growing population has concentrated significant stress on the fishing sector (Price, 1993; Sheppard et al., 2010). Unfortunately, the marine habitats within the Gulf not only have to accommodate anthropogenic stressors but also the naturally occurring extremes in environmental conditions. The Arabian Gulf is a small semi-enclosed sea which experiences extreme ranges of temperature and salinity on an annual basis (Riegl and Purkis, 2012; Smyth et al., 2016a). The west coast of Qatar for example regularly has salinities recorded at >60 ppt and sea temperatures at >35 °C. When increases in fishing activity are combined with the loss of intertidal and subtidal habitats and an increased input of pollutants from a growing population the status of marine ecosystems become a matter for concern (Munawar et al., 2002; Sheppard et al., 2010).

As previously discussed the classification of biota in both the terrestrial and marine environments into easily recognisable biotopes was developed as a practical tool to assist in the preservation and management of habitats (Connor et al., 1997a, 2003; Bartsch and Tittley, 2004). The use of baseline biotope classification codes has been used successfully to monitor and evaluate the recovery and demise of marine environments which have been exposed to extreme stresses such as; oil spills, tsunami, algal blooms and fishing impact (Tyler-Walters and Jackson, 1999; Zacharias and Gregr, 2005). When marine habitat classification is combined with ecological descriptions of a biotope a very powerful monitoring device is created which can be rapidly employed to identify site specific changes (Bartsch and Tittley, 2004).

The oyster beds of Qatar have experienced centuries of overexploitation and have been exposed to a significant increase in environmental pressure and anthropogenic disturbances over the last 15 years (Carter, 2005; Al-Khayat and Al-Ansi, 2008; Smyth et al., 2016a). It was therefore considered necessary to evaluate the current environmental status of the historical oyster beds with a methodology that would be suitable for their long term ecological monitoring.

The primary aim of this study was to assess the presence of the historic offshore pearl oyster beds and identify the biotopes present at the sites by employing a coding system based on that used by the Joint Nature Conservation Committee (JNCC) as described by Connor et al. (1997a, 1997b, 2003). A secondary aim was to compare descriptive ecological data from previous studies and historical records so that a temporal perspective on the stability of the oyster bed biotopes could be obtained.

2. Materials and methods

2.1. Study area

Qatar is situated on the west coast of the Arabian Gulf 25°30′N and 51°15′E (Fig. 1A) located on the peninsula bordering Saudi Arabia and the United Arab Emirates. It has a total coastline of 563 km. The hydrodynamic regimen in Qatari waters is typified by a south easterly surface current 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). The survey focused on five sites which would be representative of the historically renowned oyster banks (Fig. 1A & B) and this research was undertaken in October 2014 and all sites were located subtidally at depths of between 12 and 25 m (Fig. 1B).

2.2. Methodology

A Qatari oyster bank is recognised on a nautical chart as a raised mound known locally as a *hairãt* and is surrounded by neighboring deep water topography. A team of scientific divers were used to collect biotope data from five historical renowned pearl oyster banks and the five neighboring deep water sites. The divers employed video and digital still transect survey methodologies along four 100 m transect lines as outlined in Smyth et al. (2009) and Giraldes et al. (2015). The start and finish of each survey transect was marked by a diver deployed surface marker buoy. The longitudinal and latitudinal co-ordinates of each surface marker were recorded by topside using a Garmin ® GPS plotter. The transects ran parallel to each other separated by a 10 m band either side of each transect. At each site one diver recorded the substratum type and noted key species on a dive slate, the second recorded video footage of each transect and the third diver collected quantitative biotope data by taking 25 digital stills of randomly placed frame (1 m) mounted 0.25 m^{-2} quadrats. If oysters were recorded at any site a sample was taken to ascertain which oyster species were present and to identify age classes.

2.3. Biotope data analysis

The subtidal biotope classification of the survey sites followed the protocol developed by Foster-Smith and Sotheran (2003). The protocol allocates biotope codes to sites according to the heterogeneity of the substratum type as viewed from the video recordings and digital still images. The still imagery collected during the survey was analysed using Coral Point Count© software with an Excel extension (CPCe). The images were calibrated in CPCe to the known distance at which the photos were taken (1 m). The program randomly overlaid a pre-determined number of points on each photo and whatever was present at each point was identified. A total of 50 overlay points were used for each image a methodology recommended by Carleton and Done (1995). The software quantified the quadrat epifauna to class level as per Kohler and Gill (2006). CPCe software then calculated Shannon-Weaver and Simpson Diversity Index for each oyster bank surveyed.

2.4. Construction of biotope codes

Identification of biotopes and the allocation of lettered codes followed that described by Connor et al. (1997a and 2003) whereby the primary divisions of biotope classification concern physical features, firstly rock or sediment substratum and secondly zonation. The largest unit of biological feature is the 'habitat complex' which can contain one or more biotopes. Within the biotope sub-biotopes can also be described.

The use of a lettered coding system enables the construction of intuitive codes which can be related to their respective biotope features. The codes are defined for each level in the classification. Each unit of the classification is given a lettered code with each letter representing physical and biological features. Habitat factor codes for, higher taxa and descriptive community features are derived from the lexicon created by Connor (1997). Codes for names of genera are derived using the first three letters of a genus or higher taxon name. Codes for species names are derived using the first letter of the genus and the first three letters of the specific name. Within the code each new element of the code

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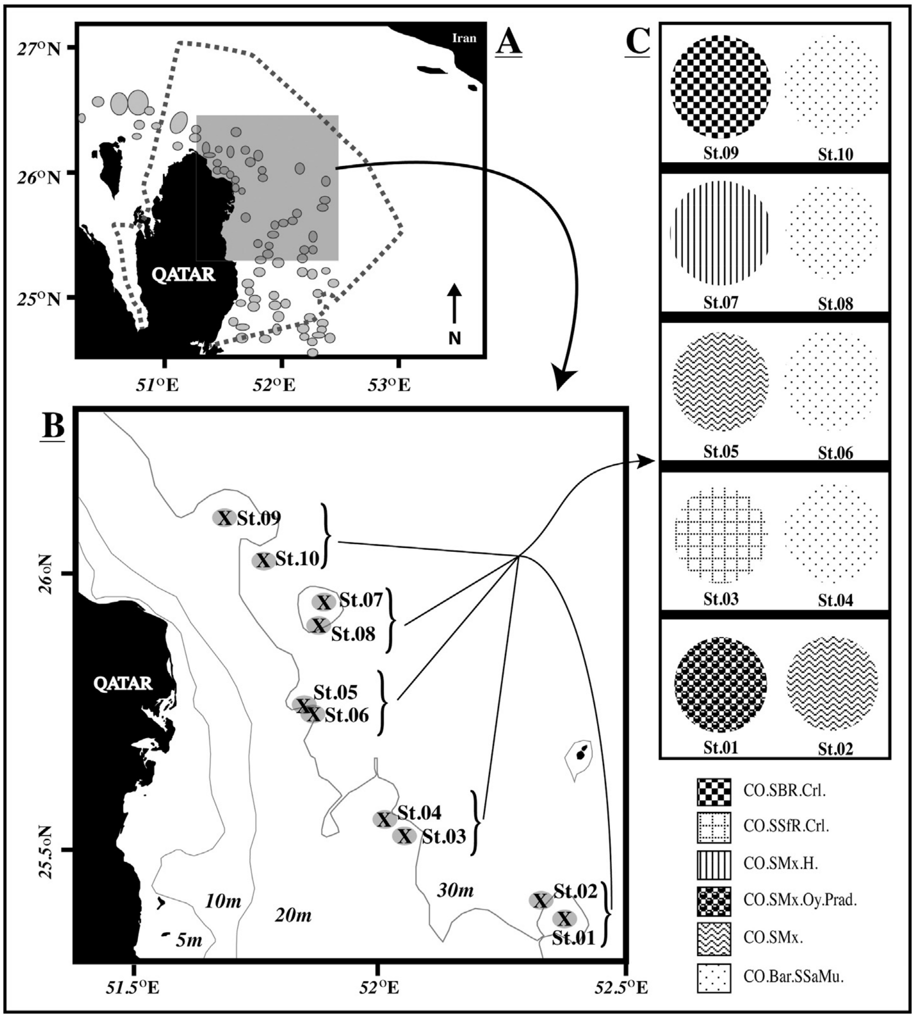

Fig. 1. A. Location of historical eastern oyster banks (Burdett, 1995). B. Survey stations on the eastern banks of Qatar St. 1,3,5,7 and 9 historical oyster banks, St. 2,4,6,8 and 10 non-oyster sites. C. List of biotope codes for each survey station with associated biotope label.

starts with a capital letter. Each biotope code is accompanied by a full ecological description of the habitat complex, biotope, or sub-biotope. The characterising species, abundance, and associated species are listed (Table 1).

The final full coding allocated to each station was compiled using the code for each level in the hierarchy, separated from the next level by a full stop, starting with the broad habitat, followed by the main habitat, biotope complex and so on. For example (CO.SMx.Oy.Prad) was a code allocated to the biotope found at station one. The code starts with CO. which is the JNCC recognised coding for offshore, next is S. which is the coding used to describe the sublittoral zone. The next component of the code represents the biotope complex which in this case was Mx. mixed which refers to the mixed sediments which make up the substratum. The next portion of the code is Oy. This notifies oysters as the most visually dominant taxon within the biotope and finally Prad which refers to the species of oyster *Pinctada radiata*. Therefore station 1 can be identified as an offshore oyster biotope dominated by *P. radiata* on a sublittoral mixed sediment substrate. Each biotope code was also given a black and white textured label which can be overlaid on a map to allow for the quick visual identification of the biotope type (Fig. 1C).

2.5. Historical timeline of oyster fishery

Past information on marine ecology and related species associated with the oyster banks and their surrounding sites is relatively sparse with most descriptions being anecdotal and published in non-peer reviewed articles. A literature review of scientific publications, official government reports and historical accounts for sites in close proximity to those investigated during this research was undertaken. The collated data was examined closely and wherever possible an interpreted biotope description was allocated. This material was used to present a historic timeline of the oyster banks and the fishery status (Table 2).

3. Results

3.1. Biotope classification and ecological descriptions

The biotope allocations for the offshore oyster banks and neighboring deep water sites are listed in Table 1 and Fig. 2. The table gives an overview of the biotope name and a breakdown of the code allocated to each survey station as per the Connor et al. (2003). A brief description of the biotope and the visually dominant species is also included (Table 1). Video capture images of each biotope and biotope complex are presented in Fig. 2. This survey represents the first biotope mapping of any offshore benthic marine habitats in Qatar and as such all of the six biotope classifications are new.

3.1.1. Station 1. (St.1) CO.SMx.Oy.Prad.

Station 1. 25 23.001 N, 52 22.700 E average depth was 16 m and was considered an oyster bank or *hairãt* since the early 1700's. The habitat

Table 1
The offshore subtidal biotopes of the historic pearl oyster banks and associated visually dominant species. Biotope codes and names are based on the categorisations used by Connor et al. (1997b, 2003).

St.	Biotope code 1700–1900	Biotope code 2016	Biotope description	Dominant species	Occasional species
1	CO. SSBR.Oy	CO. SSMx.Oy.Prad	Habitat; offshore sublittoral mixed sediment. Main biotope is oyster represented exclusively by *Pinctada radiata*.	*Pinctada radiata* predominately juveniles in the 0–1 age cohort. Bryozoan species on the surface of dead shell fragments.	*Chama aspersa*, *Leiaster coriaceus*, *Ophiothrix savignyi* and *Metalia sternalis*.
2	CO. SSMx	CO. SSMx.	Habitat; is offshore sublittoral mixed sediments a combination of fine coral and shell fragments.	No visually dominant species recorded. Needs further investigation.	Patches of dead Mussidae and Faviidae.
3	CO. SSBR.Oy	CO. SSfR.Mx.Crl. OY.Prad	Habitat; offshore sublittoral soft rock with a biotope complex of mixed sediment. Main biotope is a mix of coral species	Patchy areas of mixed coral and low density clusters of 2–4 year *cohorts of P. radiata*.	*Echinometra mathaei* and *Ophiothrix savignyi*.
4	CO. SSaMu	CO. Bar.SSaMu.	Habitat and biotope is offshore barren sublittoral sandy mud.	A barren community feature with no species recorded. Evidence of *endo*-benthic species.	Barren substrate no epibiota recorded.
5	CO. SSBR.Oy	CO. SSMx.	Habitat and biotope is offshore sublittoral mixed sediment; fine coral and shell fragments.	No visually dominant species recorded.	*Echinometra mathaei*, *Linckia guildingi* and *Heteropsammia cochlea*.
6	CO. SSaMu	CO. Bar.SSaMu.	Habitat and biotope offshore sublittoral sandy mud.	A barren community feature with no species recorded.	Barren substrate no epibiota recorded.
7	CO. SSBR.Oy	CO. SMx.H	Habitat offshore sublittoral mixed sediments. Biotope complex represented by hydroid species	Hydroid species on small shell fragments on a mixed sediment substrate.	*Amphipholis squamata*, *Ophiothrix savignyi*, *Clypeaster reticulatus*, *Obelia* sp., live and dead Mussidae sp.
8	CO. SSMx.	CO. Bar.SSaMu.	Habitat and biotope offshore sublittoral sandy mud.	A barren community feature with no species recorded.	Barren substrate no epibiota recorded.
9	CO. SSBR.Oy	CO. SBR.Crl.	Habitat offshore sublittoral biogenic reef. Biotope a mix of coral species	Dominant patches of coral species interspersed with mixed sediment, porifera and bryozoan species.	Callyspongidae, Halicondriidae, *Linckia multiflora* and *Astropecten polyacanthus*.
10	CO. SMx.	CO. Bar.SSaMu.	Habitat and biotope offshore sublittoral sandy mud.	A barren community feature with no visually obvious species recorded.	Barren substrate no epibiota recorded.

Table 2
Historical timeline of the pearl oyster fishery on the western banks of the Arabian Gulf from 1700 to 2002.

Year	Events	Biotope	Reference
1700	"Extremely rich and bountiful in pearls"	CO. BR.Oy.	Hightower (2012)
1750	"Eastern oyster banks highly productive"	CO. BR.Oy.	Carter (2005)
Oyster stocks supporting intensive fishing effort			
1770	Eastern oyster banks are "overfished"	CO. BR.Oy.	Burdett (1995)
1790	"The banks are not as productive"	CO. BR.Oy.	Hightower (2012)
1800	Increase in price of pearls leads to increased fishing	CO. BR.Oy.	Burdett (1995)
Oyster banks show signs of overfishing			
1813	Regeneration of eastern oyster banks	CO. BR.Oy.	Carter (2005)
Oyster banks show signs of recovery			
1815	Oyster banks continue to be productive	CO. BR.Oy.	Hightower (2012)
1878	Decrease in pearl yield.	CO. BR.Oy.	Burdett (1995), Carter (2005)
Oyster banks show signs of overfishing			
1900	A 40% decrease in oysters landed.	CO. BR.Oy.	Burdett (1995), Carter (2005)
1905	"Unrestrained overfishing and removal of shell, further decline in landings"	CO. SMx.Oy.	Burdett (1995), Carter (2005)
Large removal of oyster shell from reef matrix lead to a change in biotope code			
1950	Pearling remains with <100 boats	CO. SMx.Oy.	Carter (2005)
1950	Extremely bad pearl harvest reported	CO. SMx.Oy.	Burdett (1995)
Pearl diving not economically viable – fishery collapse			
1992	*P. radiata* densities recorded; 21–85 m^{-2}	CO. SMx.Oy.Prad.	Al-Madfa et al. (1998)
P. radiata identified as the visually dominant biotope species			
2001	*P. radiata* densities of 4–6 m^{-2}	CO. SMx.Oy.Prad.	Al-Khayat and Al-Maslamani (2001)
	P. radiata no longer the dominant bivalve	CO. SMx.Bv.	
P. radiata in low densities results in a new biotope classification at sites			
2002	*P. radiata* densities of 12–17 m^{-2} Two new biotopes described	CO. SMx. CO.SfR.Crl.	Al-Mohannadi (2002)

complex was distinguishable by offshore sublittoral mixed sediment (CO,SMx) the biotope complex was an oyster assemblage (Oy.) and the dominant visual species was *Pinctada radiata* (Prad.) (Table 1 and Fig. 2). Oysters were visually dominant and two 0.25 m^{-2} quadrats were removed with *P. radiata* confirmed as the principal species. Morphometric measurements were taken of all oysters within the quadrat samples and measurements compared to age determination findings of Smyth et al. (2016a). All oysters were found to be within the 0–2 yr age cohort (Table 2). Video analysis revealed four other species present in relatively high densities; Bivalvia *Chama aspersa*, Asteroidea *Leiaster coriaceus*, Ophiurida *Ophiothrix savignyi* and the flattened urchin *Metalia sternalis*.

3.1.2. Station 2. (St. 2). CO.SMx.

Station 2. 25 24.520 N, 52 20.060 E had an average depth of 24 m and with no history of supporting an oyster assemblage. The habitat complex was distinguishable by offshore sublittoral mixed sediments (CO,SMx) no specific biotope allocation could be added to the complex code as no visually dominant species were present. Patches of dead Mussidae and Faviidae coral fragments were recorded at irregular intervals throughout the survey (Table 1 and Fig. 2).

3.1.3. Station 3. (St. 3). CO.SSfR.Mx.Crl.Oy.Prad.

Station 3. 25 31.147 N, 52 03.041 E average depth 17 m and was considered an active oyster bank in the past. The habitat complex was distinguishable by offshore soft rock and mixed sediments (CO,SSfR.Mx.) the biotope complex (Crl.) was made up of a number of live coral species from the Mussidae and Acroporidae families (Table 1 and Fig. 2). Oy.Prad. was used to identify the considerable patchy assemblages of *P. radiata* in the 4–5 yr age cohort which were recorded as occasional (Table 2). Video analysis revealed two species which were identified occasionally; the boring urchin *Echinometra mathaei* and the Ophiurida *Ophiothrix savignyi* none were considered dominant.

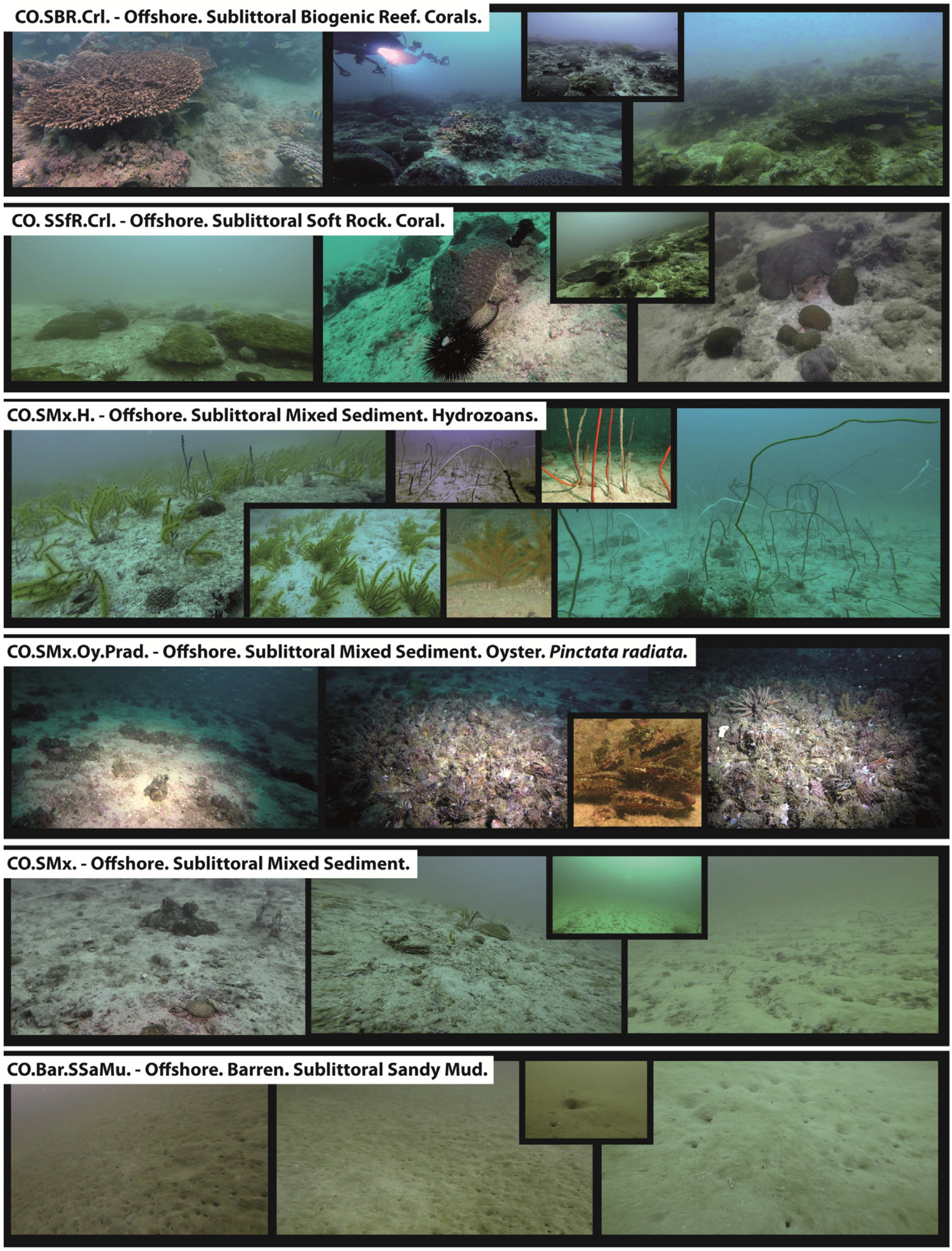

Fig. 2. Complete biotope codes with associated video captures for each habitat complex, biotope and sub-biotope.

3.1.4. Station 4. (St. 4). CO.Bar.SSaMu.

Station 4. 25 33.509 N, 52 01.220 E had an average depth of 24 m and had no history of supporting an oyster assemblage. The habitat complex was distinguishable by an offshore sublittoral sandy mud substrate and the complex was considered barren as no visible species were recorded (CO.Bar.SSaMu). Evidence of *endo*-benthic species was apparent throughout with syphon holes or burrow entrances covering large areas (Table 1 and Fig. 2) further investigation is required to confirm which species are responsible.

3.1.5. Station 5. (St. 5). CO.SMx.

Station 5. 25 45.550 N, 51 52.310 E had an average depth of 16 m and was considered an active oyster bank in the past. The habitat complex was similar to that described for station 2 offshore mixed sediments

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(CO,SMx) no specific biotope allocation could be added to the complex code as no visually dominant species were visible (Table 1 and Fig. 2). Video analysis recorded the occasional *Echinometra mathaei*, Asteroidea *Linckia guildingi* and the walking coral *Heteropsammia cochlea* the species were not present in high enough densities to be considered dominant.

3.1.6. Station 6. (St. 6). CO. Bar.SSaMu.

Station 6. 25 44.000 N, 51 53.018 E had an average depth of 19 m and no history of supporting an oyster assemblage. The habitat complex was as described for St. 4 (Table 1 and Fig. 2).

3.1.7. Station 7. (St. 7). CO.SMx.H

Station 7. 25 57.000 N, 51 54.000 E had an average depth of 14 m and was considered an active oyster bank in the past. The habitat complex was distinguishable by a sublittoral offshore mixed sediment substrate (CO.SMx.) the biotope complex (H) was made up of a number of hydroid species (Table 1 and Fig. 2). Video analysis recorded a number of species which were considered occasional but not dominant they included; the Ophiuridae *Amphipholis squamata* and *Ophiothrix savignyi*, the Echinoidea *Clypeaster reticulatus*, an *Obelia* sp. of sponge and live and dead Mussidae coral species (Fig. 2).

3.1.8. Station 8. (St. 8). CO.Bar.SSaMu.

Station 8. 25 54.000 N, 51 54.000 E had an average depth of 24 m and no history of supporting an oyster assemblage. The habitat complex was as described for St. 4 and 6 (Table 1 and Fig. 2).

3.1.9. Station 9. (St. 9). CO.SBR.Crl.

Station 9. 26 07.901 N, 51 42.050 E had an average depth of 12 m and was considered an active oyster bank in the past. The habitat complex was distinguishable as a sublittoral offshore biogenic reef (CO.SBR.) the biotope complex (Crl.) was made up of a variety of live coral species from the Mussidae, Acroporidae and Poritidae (Table 1 and Fig. 2). Video analysis revealed a number of sponge species which could be considered common but not dominant; the Callyspongidae and Halicondriidae and the Asteroidea *Linckia multiflora* and *Astropecten polyacanthus*.

3.1.10. Station 10. (St. 10). CO.Bar.SSaMu.

Station 10. 26 02.490 N, 51 46.072 E had an average depth of 21 m and no history of supporting an oyster assemblage. The habitat complex was as described for St. 4, 6 and 8 (Table 1 and Fig. 2).

3.2. Diversity indices

The CPCe software calculated two measures of diversity the Shannon Weaver (SW) and Simpson Diversity Index (SI) for the five oyster bank survey stations. It was considered not necessary to analyse the five deep water sites associated with the oyster bank topography as no records of oyster assemblages existed and all were classified as CO.Bar.SSa.Mu. The analysis carried out for St. 5 (CO.SSMx.) would be a good representation of indices for St. 2,4,6,8 and 10 as it had a comparable habitat complex (Table 1). Station 1 was the one oyster bank site that could be classified as an oyster biotope. It presented the third highest SW (0.73) and SI (0.39) indices (Fig. 3). The soft rock mixed sediment with coral biotope at station 3 produced relatively low SW (0.68) and SI (0.32) indices in comparison to stations 1, 7 and 9 (Fig. 3). The indices were a reflection of the patchy coverage of coral (Fig. 2) and the subsequent reduction in associated species.

Station 5 had the lowest Indices of diversity SW (0.12) and SI (0.11) (Fig. 3) of the five oyster banks, reflecting the low species richness and low species abundance recorded on the featureless mixed sediment substrate. Station 7 mixed sediment substrate with a hydroid dominated biotope (Fig. 2) accommodated a high diversity of species. This was displayed in an SW index of 1.12 and the second highest SI index of 0.56 which was a reflection of the high abundance of hydroid species (Fig. 3). Station 9 biogenic reef habitat with the coral dominated biotope produced the highest SI index of 0.58 (Fig. 3) which was a statistical representation of the high species evenness of the coral species making up the reef matrix (Fig. 2). The SW index was 0.79 (Fig. 3) was a lower value than that of station 7 an indication of the low number of species recorded.

4. Discussion

The biotope classification of the historical offshore oyster banks of Qatar is the first to be undertaken in the region. The study of five representative oyster banks revealed only one site (St.1 CO.SMx.Oy.Prad) which could warrant the allocation of a sub-biotope classification dominated by oyster (Table 1 and Fig. 2). The oysters which made up the biotope were all within a 0–1 yr age cohort, indicating that the assemblage had only recently been established. No adult oysters where recorded suggesting that a spawning broodstock from another site supplied the larvae.

Oysters were also recorded at survey station 3 but not in sufficient numbers to be categorised as a sub-biotope but were allocated a species specific code of Oy.Prad. The oysters were within the 4–5 yr size cohort and therefore sexually mature. As previously mentioned the east coast of Qatar is subjected to south easterly surface current circulation (Kampi and Sadrinasab, 2006). It is quite possible that as a result of the north easterly position of St.3 in relation to St 1. (Fig. 1B) that spawning oysters from the site could have provided larvae for the newly settled assemblage. It has been shown that a relatively small spawning stock of Ostreidae oysters can successfully provide larvae to

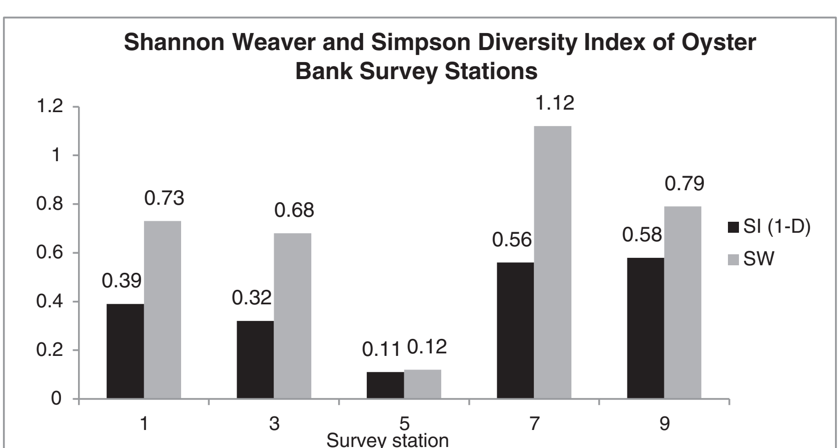

Fig. 3. Shannon-Weaver Index and Simpson Diversity Index for each oyster bank survey station.

re-populate a considerable area if hydrodynamic conditions are favourable. In Strangford Lough Northern Ireland in 1998 a spawning event from an aquaculture stock of 100,000 *Ostrea edulis* re-established a wild standing stock of 1.6 million over a period of three years (Kennedy and Roberts, 1999; Smyth et al., 2009; Smyth et al., 2016b). A similar stock enhancement was recorded in the Republic of Ireland where naturally occurring *O. edulis* beds in Kilkieran Bay located in close proximity to low density spawning cultured oysters displayed a significant increase in recruitment (Barry, 1981). It is therefore not inconceivable that the mature *P. radiata* oysters although in low densities were providing recruitment to St1.

The patchy nature of the soft rock and coral features at St.3 may be responsible for the continued presence of the mature fecund oysters as the biotope topography would provide a degree of protection to the spawning *P. radiata*. In Qatari waters the most practised fishing method is via a large wire trap known as a *Gargoor* which is normally fished in a line of 5–10 (De Young, 2006). The retrieval of long lines of connected traps or pots has been shown to have major impacts on benthic assemblage function and structure with the practice in many circumstances resulting in irreversible damage to the benthos (Tillin et al., 2006; Strain et al., 2012). Biogenic reefs or beds of byssal attached bivalves such as the Pterioidea, Pinnidae, Mytilidae and the Dressenidae are extremely vulnerable to the impacts of mobile fishing gear as their attachment to substrates is via byssal threads and not through the cementation of the shell (Gosling, 2003). Although oysters are no longer fished in Qatari waters the Pterioida oysters of the Gulf would be susceptible to damage and dislodgement from mobile fishing gear (Strain et al., 2012).

Non-fishing related anthropogenic stressors overexploitation and the environmentally damaging effects associated with the retrieval of long lines of traps may go some way to explaining the biotope classification of the three remaining oyster banks at stations 5, 7 and 9. Prior to this current research it was expected that these northerly oyster banks would be classified as oyster biotopes (Fig. 1A). As this northerly area was rich in highly productive oyster banks since the 10th century (Carter, 2005; Hightower, 2012) and indeed research carried out on the banks in 1992 by Al-Madfa et al. (1998) recorded oysters in densities of >85 m^{-2} (Table 2). However no live or dead oysters were recorded at any of the three sites during this survey. It may be the case that non-fishing related impact has influenced oyster densities and biotope classification at these sites. Al-Madfa et al. (1998) suggested that the low numbers of oysters recorded in this region was a result of pollution from the petrochemical industry. This argument may have some merit as there is a major petrochemical refinery located in close proximity to the sites at Halul Island. The surface circulation would bring any pollutants in the direction of the three sites and Al-Madfa et al. (1998) did show high concentrations of heavy metal pollutants in oysters surveyed from the region.

The site with the lowest diversity indices station 5 (Fig. 3), revealed a particularly barren featureless substrate of mixed sediment with no visually obvious species (Table 1 and Fig. 2). The expanse and featureless nature of the bank would suggest that it was extremely heavily impacted through intense fishing during the pearl epoch or that the bank never supported an oyster assemblage. However local authorities are adamant that the site was a productive pearling bank in years gone by and historical records tend to agree with these statements (Carter, 2005). Subtidal biotopes within heavily fished oyster fisheries in Europe, New Zealand and the USA have experienced similar changes in biotope classification as a result of overfishing and the accumulative effects of other anthropogenic stressors (Cranfield et al., 2003; Smyth et al., 2009; Bromley et al., 2016). Extensive largescale removals of live oysters and their shell debris was exactly the scenario experienced in the *O. edulis* beds in Europe and the *Crassostrea virginica* reefs in USA during the late 1800's (Gosling, 2003; Laing et al., 2006; Smyth et al., 2009). These removals resulted in the fragmentation of assemblages, the resuspension of sediments and the loss of future settlement areas for subsequent oyster generations (Laing et al., 2006). Kaiser (2001) highlights that largescale direct removal, damage, displacement or death of a proportion of animals and plants living in or on the seabed can be an ecosystem changing event.

Historical records would suggest that the oyster banks experienced a comparable series of events in the early 1900's (Table 2). In fact in 1905 the pearling boat captains and the Superintendent of the pearl fishery Mr. Hornell remarked upon the large quantities of oyster shell which were being kept for mother of pearl and that this was having a marked effect on landings (Burdett, 1995; Carter, 2005). It is quite possible that the removal of shell and the subsequent resuspension of sediment would affect the settlement of oyster larvae and smother adults. When combined with the effects of mobile fishing gear a previously diverse area could become featureless and barren. Marine benthic habitats in the Bay of Fundy Canada, the Wadden Sea along the Dutch and Danish coast and the Foveaux Straits New Zealand have all experienced dramatic changes in biodiversity and biotope classification through the effects of overfishing (Kenchington, 2002; Hill et al., 2010).

The hydroid dominant biotope at station 7 had no live or dead oysters recorded. Video analysis in conjunction with the quadrat imagery revealed a relatively high diversity of species in comparison to the other sites which was reflected in the highest Shannon-Weaver index (1.12) (Fig. 3). It has been documented in numerous studies that the colonisation of hydrozoans follows the settlement of bacteria and diatoms as the third stage of epibiotic succession on hard substrates (Smyth and Roberts, 2010; Kirschner and Brennan, 2012). It may be that station 7 is undergoing a successional stage of epibiotic settlement onto the remnants of a once productive oyster bank, however further investigation of the site would be required to confirm if this was indeed the case.

The most northerly of the oyster banks station 9 was situated within a historically productive pearl fishery area (Fig. 1A). The biotope was classified as an offshore biogenic reef dominated by coral (Fig. 2). It was part of the renowned eastern pearl banks referred to by the merchant Al-Masudi in 1750 as producing the finest pearls and being highly productive (Hightower, 2012). However in 1770 concerns were being voiced by the East India Trading Company with the suggestion that the eastern banks were exhausted (Table 2) (Burdett, 1995). No substrate data or biotope description of St. 9 area post-1770 exists. Shinn (1976) and Riegl (1999) recorded dense *Acropora* and *Porites* coral communities at Al-Ruwais to the north of St. 9. If the oyster assemblage at St. 9 had been exhausted as early as the 1800's and no broodstock was in a favourable location to provide larvae it is possible that the coral larvae under the influence of the south easterly surface current could have settled and occupied the vacant niche of hard substrate.

The deeper water sites (stations 10, 6, 4 and 2) historically documented as being non-productive areas (Carter, 2005) were included in the survey to ascertain if there had been any expansion in oyster assemblages. However they all presented a barren community feature as a biotope habitat complex. The nature of the topography of these sites, whereby they are low lying at the base of a raised mound of hard substratum means they will act as natural sinks for suspended sediments (Pilskaln et al., 1998; Ciutat et al., 2007). The removal of oysters from the high mounds would have increased the sediment load within the water column as the sediment stabilisation and benthic coupling services provided by the oysters would have been absent from the system. Similar scenarios have been documented on numerous oyster grounds where large scale exploitation has taken place (Pilskaln et al., 1998; Coleman and Williams, 2002). Although species richness and abundance was low at these sites in regards to visual abundance comparable biotopes have been shown to be rich in meiofauna or meiobenthic species (Schratzberger et al., 2002; Moreno et al., 2008). It is intended to sample these barren sand mud biotopes in future research to establish a more comprehensive biodiversity index and to allocate a more accurate biotope code that will be representative and specific to each site.

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This study represents the first classification and coding of the offshore biotopes of Qatar and has resulted in the identification of changes within ecosystem structures which would have otherwise remained undocumented. Coleman and Williams (2002) concluded their research into the overexploitation of marine ecosystem engineers with a statement that typifies the importance of the pearl oyster to the Gulf; "no matter what ecoregion they occupy, they warrant increased scientific and conservation emphasis, because of the fundamental role that they play in shaping habitats and providing services for their associated dependent communities from microbes to predators".

Unfortunately it is too late to protect many of the offshore oyster banks of Qatar. However the restoration of oyster beds is a rapidly increasing field of research (White et al., 2009; Baggett et al., 2015; Janis et al., 2016) and it is not beyond possibilities that some of the eastern banks could be restored to a favourable state of conservation. Although restoration in the region would be extremely challenging as there is a substantial suite of anthropogenic influences in the Arabian Gulf which would need to be considered before any restoration project or site was selected (Table 3).

5. Conclusion

The pearl oyster banks of Qatar where once an extremely productive economic resource within the Arabian Gulf, however more importantly they also provided ecosystem services which maintained the functional health and integrity of the marine environment of the region. The historical time line of the oyster fishery (Table 2) highlights the vulnerability of these ecosystem engineering bivalves and shows that if overexploited they can cease to exist within <100 years. This research has revealed the devastating effect that a variety of anthropogenic impacts can have on a relatively robust marine habitat like an oyster bed and these findings should act as a driver to investigate and map other more vulnerable habitats within the Arabian Gulf before they too become compromised. It is hoped that this work will promote further research and debate into how best to manage and protect the remaining marine environments within the region.

Table 3
Anthropogenic stressors on marine ecosystems within the Gulf (from Price (1993)) added to which are the natural extremes in environmental conditions.

Coastal and marine use	Actual or potential environmental pressures
Shipping traffic and ports	Oil spills, anchor damage, coastal reclamation, dredging, sedimentation and ballast water release.
Residential and commercial	Coastal reclamation, habitat loss, dredging, sedimentation, sewage, fertilisers and other effluents, eutrophication and solid waste disposal.
Industrial development oil and petrochemical industry	Oil, refinery and other effluents containing heavy metals, drilling muds and tailings.
Desalination and seawater treatment plants	Effluents with elevated temperatures, salinities, occasional heavy metals and other chemicals.
Power plants	Various effluents, air pollution increasing greenhouse gases and acid deposition.
Fishing and marine harvesting	Decline of target and non-target species, changes in ecosystem function, habitat damage, resuspension of sediments and decrease in biodiversity.
Recreation	Reef degradation from anchor damage and collecting.
Agriculture	Fertiliser induced eutrophication, pesticide; DDT, aldrin, dieldrin and lindane.

Authors contributions

Conceived the study DS, BG, MC and I Al-M. Conducted analyses and collation of historical records DS, BG, MC and I Al-M. Conducted video and CPCe analysis DS, BG and MC. All authors contributed to the writing and approved the final review.

Competing interests

The authors have declared no competing interests exists.

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