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Hydroacoustics to examine fish association with shallow offshore habitats in the Arabian Gulf

Jack P. Egerton[1,5], Mohsin Al-Ansi[2], Mohamed Abdallah[3], Mark Walton[4], Jamie Hayes[1], John Turner[1], Brad Erisman[5], Ibrahim Al-Maslamani[2], Mohammed Mohannadi[3], Lewis Le Vay[1,4]

[1]School of Ocean Sciences, Bangor University, Menai Bridge, Wales, UK.

[2] Environmental Science Center, Qatar University,

[3] Department of Fisheries, Ministry of Municipality and Environment, State of Qatar

[4] Centre for Applied Marine Sciences, Bangor University, Menai Bridge, Wales, UK

[5] Marine Science Institute, University of Texas at Austin, Port Aransas, Texas, USA

Corresponding Author: j.egerton@bangor.ac.uk, j.egerton@utexas.edu

Abstract

In order to implement spatial fisheries management in the Arabian Gulf, a better understanding of the distribution of fish in relation to benthic habitats is required. To facilitate this, hydroacoustic fish surveys were conducted over oyster bed/reef (“shallow”) and surrounding soft sediment (“deep”) habitats in the offshore central Gulf, within Qatari waters. Transects at ‘shallow’ sites had significantly higher mean fish density and biomass. Mean target strength of individual fish was also significantly higher at ‘shallow’ sites. Fish positions in the water column were examined and overall there was a closer association with the seabed at the ‘shallow’ sites. Larger fish were found significantly closer to the seabed than smaller fish across all sites, but more so at ‘shallow’ sites than at ‘deep’ sites. Acoustic return from the seabed was extracted to provide information on the habitat type both using ‘Sonar5’ and ‘Visual Habitat’ software. The different site categories (‘shallow’ vs ‘deep’) were significantly different for all the measures of acoustic habitat. Fish density was significantly related to ‘Visual Habitat’ data, more so than depth alone. Our results show that fish distribution in the offshore Gulf is associated with complex, shallow oyster bed/reef habitats, and this is particularly the case for larger demersal fish that are commercially exploited. The ability to characterise benthic habitats from acoustic fish survey data shows promise, with important time saving implications for the monitoring of marine environments and developing a spatial approach to fisheries management. This may include the identification of habitats with a relatively high density of larger fish for inclusion in candidate marine protected areas.

Key Words: Hydroacoustics, fish, echo integration, habitat mapping, oyster reefs, Arabian/Persian Gulf.

Highlights

- Shallower more rugose habitats had significantly higher values of mean fish density, biomass and fish size than deeper softer sediment habitats.
- Larger fish found closer to the seabed than small fish at all sites, but more so at the shallower more rugose sites.
- There was a strong relationship between habitat type and depth, however acoustic data processed in Visual Habitat was a better predictor of fish density than depth itself.

1. Introduction

Fish are a vital source of protein throughout the world and the demand for fish resources continues to increase. This is also the case in the Arabian Gulf (hereafter referred to as ‘the Gulf’), where rapid coastal development has been accompanied by high human population growth (Feidi, 1998). This population growth will continue to increase pressures on fish stocks, especially on demersal high value species that are already reported as fully or overexploited in the area (De Young, 2006). This overfishing (Siddeek et al, 1999) has already resulted in a rapid decline in the health and sustainability of the Gulf ecosystem (Sheppard et al, 2010; Sale et al, 2011; Feary et al, 2011). Effective management of fish resources is therefore necessary in order to ensure that any overfishing is reduced and sustainability prevails (Pauly et al, 2002). A shift towards resource management that is ecosystem-based with long-term perspectives is urgently needed in the Gulf (Khan, 2007). From a fisheries science perspective, one step towards effective management is to develop an understanding of fish distribution and fish-habitat linkages as a component of ecosystem-based management (EBM) (Larkin, 1996). Relating marine fish with specific habitats is however a difficult task obscured by uncertainty due to the variety of habitats used over fish lifetimes, large variations in fish density and complex spatial heterogeneity in habitats (Rose, 2000; Minns and Moore, 2003; Anderson, 2008). Nevertheless, hydroacoustics have shown that seabed substratum is one of the most important components determining the spatial ecology of demersal fish (Ellis et al, 2000; McConnaughey and Syrjala, 2009; Moore et al, 2009; van der Kooij et al, 2011) and also with pelagic species (Maravelias et al, 2006).

Benthic habitat is primarily determined by substrate type (Kostylev et al, 2001) and throughout this manuscript we use the term ‘habitat’ to describe what others may term ‘substrate’ (Diaz et al, 2004). The most widespread habitats offshore in the Gulf are muddy and sandy substrata (Sheppard et al, 2010; Feary et al, 2011), however these are interspersed by shallower limestone outcrops (Riegl et al, 1999). These shallower outcrops (locally known as ‘hairãt’) provide a hard substrate that is typically colonised by benthic epifauna including oyster beds and corals (Riegl et al, 1999; Sheppard et al, 2010; Smyth et al, 2016). There are no true coral reefs in the Gulf (Sale et al, 2011), rather corals form more of a veneer over the hard substrates present (Riegl, 1999; Sheppard et al, 2010; Feary et al, 2011; Sale et al, 2011). When hard substrates do host coral communities, these areas provide habitat to a relatively abundant and diverse fish community in the Gulf (Feary et al, 2011).

Qatari fisheries are artisanal in terms of methods but are active on a large scale (Al-Abdulrazzak, 2013). Fishing in Qatari waters occurs almost entirely on the eastern side of the peninsula in offshore waters of the central Gulf, mostly less than 50m depth (Al-Ansi and Priede, 1996). Industrial trawling was banned in Qatari waters in 1992 and since then the demersal catch has increased through the use of gill nets, hook and line and fish traps (gargoor) (Al-Ansi and Priede, 1996, Siddeek et al, 1999). Landings of demersal species represented around 71% of the total catch in Qatar in 1992 and 1993 (Siddeek et al, 1999). The demersal fish most commonly targeted by the Qatar trap fishery are *Lethrinus* and *Epinephelus* spp, which together account for around 29% of the annual total catch in Qatar (Stamatopoulos and Abdallah, 2016). Demersal fishing effort tends to be focused on traditional offshore fishing grounds which include the shallow 'hairãt' habitats, which are considered highly productive and support high benthic biodiversity (Smyth et al, 2016). Such characteristics would justify the inclusion these habitats in protected areas for both biodiversity conservation and spatial management of fish stocks. However, to date there is limited evidence to confirm their role as essential fish habitat (EFH). Whilst there has been some effort in determining the distribution of fish in the region via scientific trawling (e.g. Sivasubramaniam and Ibrahim, 1982) this has largely been confined to the softer sediments, due to safety issues and potential damage to both fishing gear and to the reefs themselves. The hydroacoustic method however allows a comparable methodology over the different habitats. Additional advantages of the methodology include rapid acquisition and retention of raw data and any size selectivity of fishing gear is removed (Trenkel et al, 2011). Hydroacoustics can be the most efficient remote sensing tool for mapping and monitoring the subsurface oceans over large areas (Anderson et al, 2008). To further increase efficiencies, the same hydroacoustic fish data can also be processed to give information on habitat type with time and cost saving implications (Freeman et al, 2004; Mackinson et al, 2004). The coverage of the data is also likely to be greater than that of traditional point sampling techniques for habitat mapping (Freitas et al, 2008). There are a number of bespoke acoustic ground discrimination systems (AGDS) used for habitat mapping (e.g. RoxAnn, QTC-View, EchoPlus) (Brown et al, 2011) which categorise the acoustic responses from the seabed based on roughness and hardness (Foster-Smith and Sotheran, 2003). Recently, Biosonics Ltd have released Visual Habitat (VH) software that can be used in conjunction with their DTX echosounders, which we examine for discriminating between the different habitat types present within the survey area. Additionally we examine how acoustic reflection parameters from the seabed extracted from Sonar5 (Balk and Lindem, 2006) compare with the habitat data given by VH. Hydroacoustic data were also processed to investigate fish height in the water column over the different habitats present. Such data is often examined to help classify fish echoes into species groups (e.g. Parker-Stetter et al, 2009), and to examine diel vertical migration (DVM) (e.g. Hrabik et al, 2006; Jensen et al, 2011). There has however been little use of such data to examine fish utilisation of habitat. We investigate how this data can be used, in addition to fish size, to further highlight any effects of benthic habitat on the vertical distribution of fish between study sites.

In this study we use hydroacoustics to help understand fish distribution in Qatari waters of the central Gulf through examining fish-habitat linkages in order to test the potential role of shallow oyster beds/reefs as fish habitat. We test the hypotheses: (a) that these areas have a greater fish density and mean sizes and also therefore biomass, (b) that fish will have closer association with the shallower and more rugose sites, and (c) acoustic data processed to provide information on habitat will be able to better predict fish distribution than depth alone. Through this examination, we aim to provide evidence that can inform future planning and aid the development of appropriate Ecosystem Based Management (EBM) in the region.

2. Methods

2.1 Study sites

Acoustic surveys were performed in May 2015, from a speed boat working alongside the Qatar University research vessel RV Janan which was used for other aspects of the overall study (towed camera, diving, and fishing) and accommodation. Sites were chosen through examination of bathymetric charts and local knowledge. All sites are shown in Fig. 1 and locations, depths and groundtruthed habitat type are given in Table 1

'Shallow' sites: These sites aimed to target the raised limestone mounds that have a patchy distribution amongst the surrounding deeper waters with muddier sediments. These mounds are mainly located in water depths of 10-20m and are hereon referred to as 'shallow' sites. They have more consolidated coarse and rugose substrate, and are typically colonised by oyster bed or mixed reefs communities (Smyth et al 2016). Of the sites included in this study, there is most live coral at the site of Halul Island (site S6), where five species have been recorded in recent surveys (Sheppard et al, 2010).

'Deep' sites: Sites located in the deeper waters surrounding the raised mounds are referred to as 'deep' sites. These are in water depths of circa 25-40m comprising finer and more mobile sediments of sand and mud.

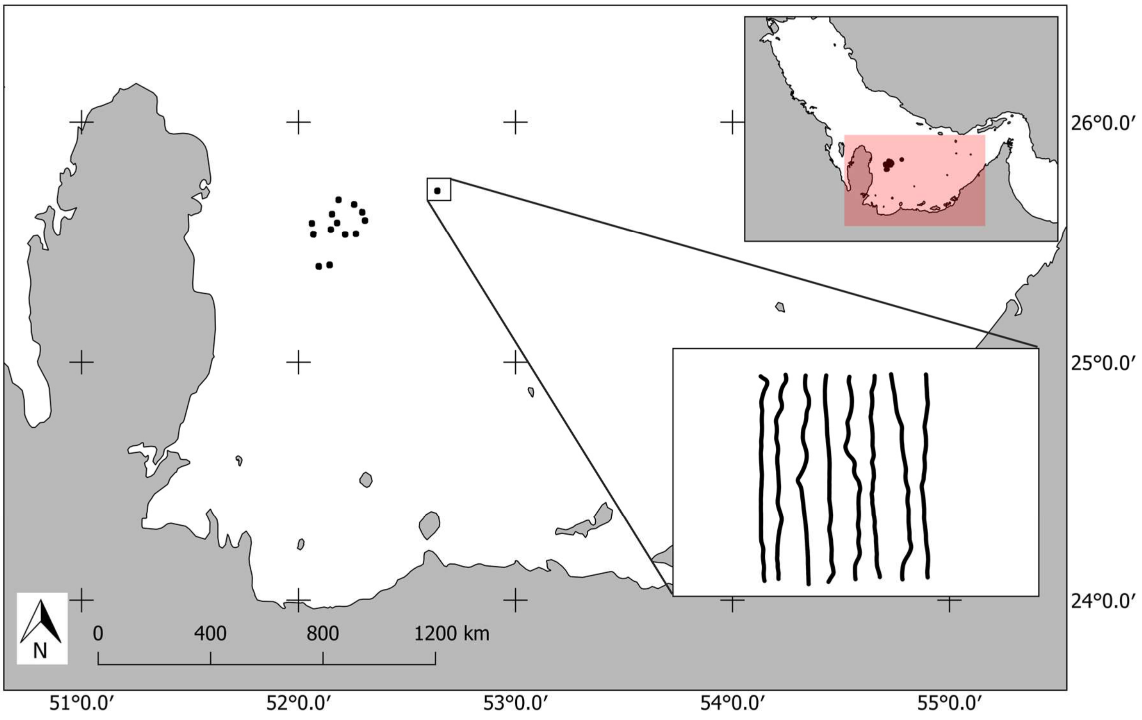

Figure 1. Location of the survey sites within Qatari waters. The black dots represent the survey sites and the zoomed in box show the transect lines that are present within each of these. The overview map shows the location of Qatar in the Gulf, with the extent of the main map highlighted in red.

Table 1. Site locations with groundtruthed habitat type and mean depth (±S.E.M).

Site	Latitude	Longitude	Groundtruthed Habitat	Mean Depth (m)	±S.E.M
S1	52.0673	25.5312	Oyster Reef	13.47	0.038
S2	52.15353	25.61665	Sand	21.42	0.023
S3	52.2561	25.65897	Oyster Reef	18.95	0.035
S4	52.21457	25.53402	Oyster Reef	17.90	0.024
S5	52.3058	25.5919	Oyster Reef and Sand	18.96	0.014
S6	52.63953	25.71557	Oyster Reef inc live Coral	21.89	0.072
S7	52.09082	25.3949	Oyster Reef	16.94	0.016
D1	52.18418	25.679	Mud	32.17	0.042
D2	52.29328	25.62682	Mud	32.46	0.016

D3	52.26392	25.53658	Mud	32.48	0.007
D4	52.14867	25.55352	Mud	27.58	0.003
D5	52.06132	25.57995	Mud	28.27	0.005
D6	52.14158	25.40567	Mud	31.70	0.007
D7	52.17705	25.58188	Mud/Sand	27.44	0.028

2.2 Equipment

A Biosonics® DTX Split beam echosounder with a 200 kHz transducer was used for the surveys. The transducer was mounted over the port side of the survey vessel as close to the centre of roll and pitch as possible, attached to a pole secured by bespoke brackets. Acoustic data were georeferenced with an integrated Garmin 17Xhvs GPS, and collected with Biosonics acquisition software (Visual Acquisition). The circular transducer has a beam opening angle of 6.8º. Pulse duration was 0.4 ms and the specified ping rate was 10 per second. Calibration of the echosounder occurred before the start of the surveys on 03/05/2015 using a 36mm Tungsten Carbide 200 kHz Calibration Sphere following the standard methods of Foote et al (1987).

2.3 Survey Coverage.

In acoustic fish surveys, there needs to be adequate coverage over the survey areas to gain a reliable picture of the fish distribution. Degree of coverage (Λ) is defined as: $\boldsymbol{\Lambda = D/\sqrt{A}}$ where: D is the cruise track length, and; A is the size of the survey area. Empirical data from Aglen (1989) showed that Λ needs to be 6 or over. This was achieved in all the different survey sites with 8 parallel transects covering a survey box of 1km by 1km leading to $\Lambda = 8$ at each site. Survey speed was restricted to between 5 and 6 knots and all surveys were conducted during daylight hours.

2.4 Data processing.

The data were collected with the Biosonics software Visual Acquisition (Biosonics, 2010) as DT4 files. These files were then converted and post processed with the software package Sonar5 (Balk and Linden, 2006). Analysis in Sonar5 followed the Software Guided Analysis (SGA) routine (based on the Standard Operating Procedure of Parker Stetter et al, 2009) to ensure a consistent approach. Acoustic fish density was calculated by Echo Integration (EI) which divides the sum of backscattered energy from fish over a segment (the volume backscattering coefficient, sv in m^2/m^3) by the mean *in situ* backscattering cross section (σ_{bs}) from individual fish within that segment (Rudstam et al, 2009; Winfield et al, 2012). The backscattering cross section (σ_{bs}) is related to the Target Strength (TS) in dB through the equation: **TS = 10*Log(σ_{bs}),** whilst sv is gained from Sv (dB) through the equation: **sv = 10^(Sv/10)**. Volumetric fish densities (ρ) are therefore calculated as: **ρ= sv/σ_{bs}.** Analyses were based upon Single Echoes Detected (SED). The criteria to accept SED were a minimum echo length of 0.8dB a maximum of 1.2dB and a maximum angle standard deviation of 0.8 degrees. Multipeak suppression was set to ‘medium’ in the software which demands a local dip of 1.5dB between peaks before rejecting the echo. In order to initially separate fish from other particulate targets such as plankton (Parker-Stetter et al, 2009) thresholds of -60dB for SED and -66dB for Sv were applied. Acoustic SED returns with a TS below -60dB were therefore excluded by this, and any other remaining noise was removed by eye. A Time Varied Gain (TVG) correction of 40log(R) for TS values and 20log(R) for Sv values are applied by the software as standard (Balk and Linden 2006). Each 1km transect was taken as an elementary distance sampling unit (EDSU), to minimise the numbers of cells with no backscattered echo energy (Emmrich et al., 2012). The seabed was automatically detected and manual editing occurred when necessary. In order to ensure that no echoes from the seabed were classified as fish, a bottom margin of 0.5m was applied and data from this layer were not analysed. Similarly, a layer of between 1 and 5m (depending on the sea state) was applied to remove any surface noise. The Nv index (Sawada et al, 1993), was calculated for all transects and all were acceptably low (Nv<0.1) indicating TS estimates were unbiased (Rudstam et al, 2009; Yule et al, 2013).

2.5 Fish distribution

In examining fish distribution between sites and habitats the arithmetic mean of transects per each site category of fish density (# individuals per 1000m^3) and also the volume backscattering coefficient (Sv) (dB) were investigated. Sv quantifies the sum of fish backscattering cross sections per volume, and is often used as a proxy for biomass (Simmonds and MacLennan, 2005; Boswell et al, 2010). In order to calculate means and for statistical analyses, the linear form 'sv' (m^2/m^3) was used. Statistical analyses were conducted to determine if differences were present in these fish parameters between shallow sites and deep sites, by the use of two-sample T tests. Data were checked that assumptions of normality and equal variance were satisfied and log transformed if necessary. If these assumptions were still not achieved then nonparametric Mann Whitney Wilcox tests were used.

2.6 Fish size

In order to examine TS from individual fish, fish were tracked in Sonar5 using criteria of; a minimum of 4 pings, 2 pings gap and gaiting of 0.3m, to define a track. It is difficult to track individual fish when they occur in dense schools (on occasion the ratio of Sv in tracks to total Sv was <10%), and although in such cases it was possible to gain some fish from the school periphery, the resultant TS's should therefore be thought of as indicative rather than absolute. In order to provide estimates of fish length, TS was converted with a logarithmic equation similar to multi species equation of Love (1971) following Brandt (1991). Modified for a 200 kHz frequency transducer this takes the form: **TS=19.1 log10(L) -64.07**. We examined fish size between sites categories both as Mean TS in decibels (dB) (calculated in the linear domain and then converted back to dB) and also as length in cm via application of this formula. Differences in fish size class distributions between the two depth categories were tested by performing a Two-sample Kolmogorov-Smirnov test.

2.7 Fish association with habitat

Potential association of fish with the different habitat types was investigated by examining the heights of tracked fish in the water column over the different habitats and sites. A spatial join was performed in a GIS (QGIS, 2016) so that mean depth values were provided in a 5m radius buffer around the tracked fish positions. Fish height off seabed was then calculated as seabed depth minus fish depth. We then examined the relationship between fish size and height off seabed between the different site categories through Mann Whitney Wilcox tests and regression analysis. Due to the same issues of tracking fish in dense schools as mentioned above, this data should however be thought more of an indication of fish depths and sizes rather than absolute values for all fish surveyed.

2.8 Fish sampling

A variety of methods was used to sample the fish species present, unfortunately due to logistical constraints it was not possible to conduct the same strategy at each station. SCUBA surveys were conducted at all shallow sites and additionally D5 and D7. SCUBA surveys consisted of a timed search method to quantify the species present and imagery was recorded on GoPro cameras for subsequent analysis. A cut off of 11 minutes was taken as the limit of video analysis, as this was the length of the shortest bottom time, allowing comparable data across the shallow sites where it was collected. Gill nets were set at three locations (S1, S7 and D5) which consisted of and 8 nets of 90m with 2m overlap with a soak time 2.5hrs.and set at a depth of 14m. Handlines were utilised to sample fishes at sites S2, S4, S5, S6, S7, D5, and D7. Data from fish traps was also gathered opportunistically one station (D6).

Tables of the recorded fish species along with the sampling strategy are given in ESM 2a and b.

2.9 Habitat.

The data were also processed to provide habitat type by the use of the software Visual Habitat (VH) (Biosonics Inc). Substrate classification in VH uses Principal Components Analysis (PCA) on returning echoes from the seabed and clustering occurs based on similarities of the echo components, resulting in the delineation of areas with similar acoustic properties based on relative hardness and smoothness of the seafloor (Munday et al, 2013). The depth normalisation option was applied in the software using the mean depth across the surveys. Habitat type along 10 ping sections of each transect was placed in one of three categories following PCA analysis routine in VH. Three classes were chosen as the groundtruthing showed three main habitats (mud, sand, and reef). The process can be thought of as 'unsupervised' as acoustic data are segmented before being assigned a habitat type identified from groundtruth observations (Calvert et al, 2014). These habitat categories (1, 2 or 3) were then averaged for each transect and site to provide a mean value. During the surveys, the habitat type was confirmed by either the use of towed camera or via SCUBA divers. Data from different acoustic habitat types were plotted against depth and mean habitat values compared with that from the video groundtruthing in order to determine the efficacy of the acoustic method. We also examined how the Biosonics VH software compared to properties of the bottom echo extracted in Sonar 5. Specifically we extracted the 'attack' and 'decay' of the bottom echo parameters which correspond to the seabed hardness and roughness respectively (Balk and Lindem, 2006). We subsequently examine how the data from both software packages are capable of explaining the differences in the fish parameters through regression analysis.

3 Results

3.1 Fish distribution parameters between sites.

In order to test hypothesis (a), fish density, mean size and sv are tested between the two site categories. Numerical data on fish distribution between sites is given in ESM 1. With fish density (in numbers of fish per $1000m^3$), a significant difference was detected at the 95% level between transects at shallow category sites and deep category sites by the use of a two-sample t-test ($T_{108} = -10.63$, $P < 0.001$) with greater fish density at the shallow sites (Fig.2).

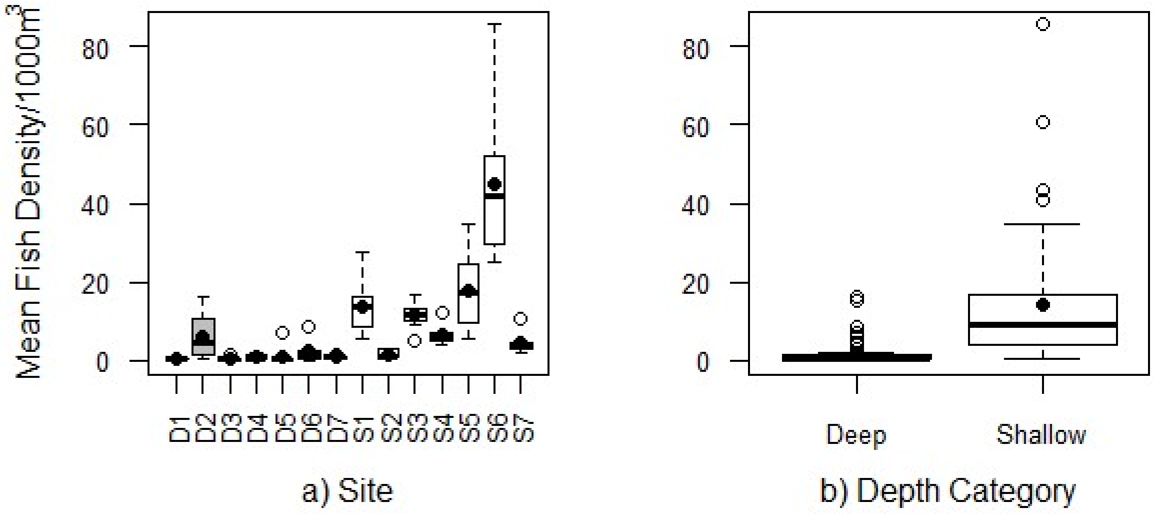

Figure 2. Mean fish density expressed as number of fish per $1000m^3$ at survey transects at each site. Box plots show mean values (black circle), median values (solid horizontal line), and the lower and upper ends of the box are the 25% and 75% quartiles respectively. The whiskers indicate 1.5 times the inter-quartile range and points beyond this range are shown by empty circles.

Tracked fish were used to examine fish sizes between the different site categories and mean values of TS (calculated in the linear domain) and corresponding fish length were significantly higher at transects over shallow category sites in comparison to transects at deep category sites (W = 61270, P <0.001) (Fig.3). Fish size class distribution data was also shown to differ significantly between the two depth categories using a Two-sample Kolmogorov-Smirnov test (KS test statistic =0.266, KS critical value = 0.097, P<0.05).

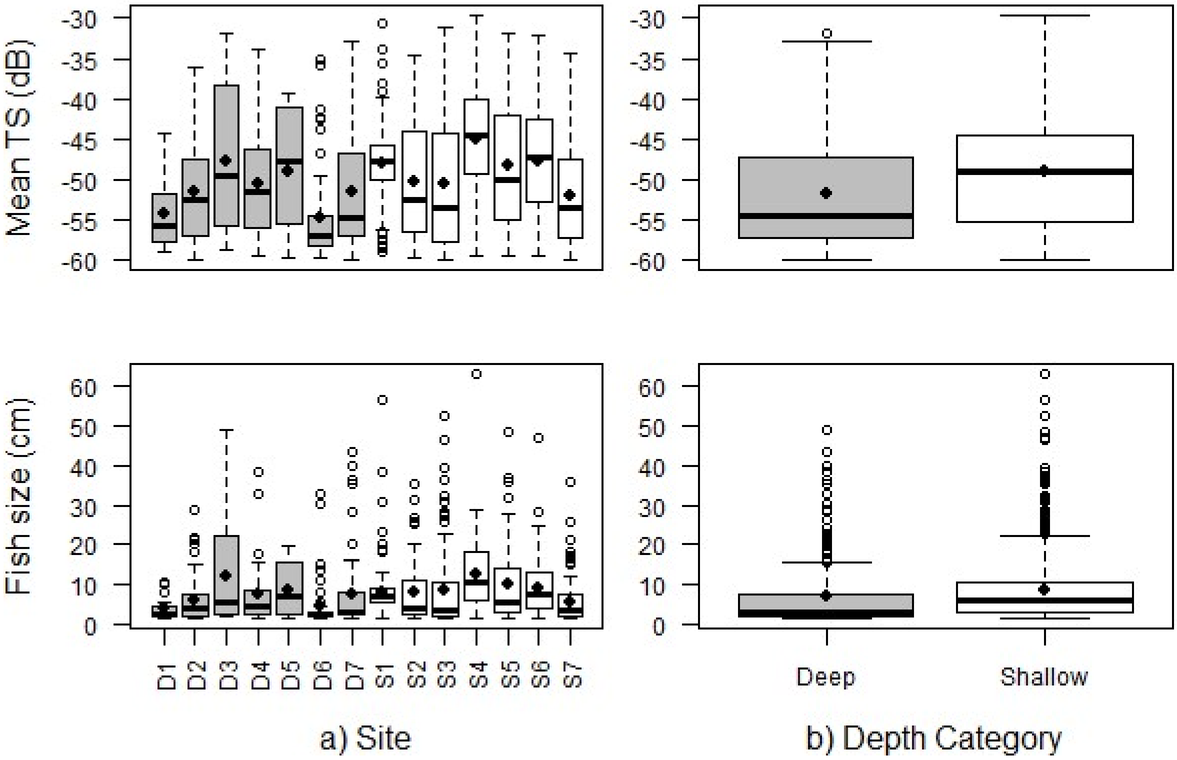

Figure 3. The Mean TS values in decibel (top panels) and the Mean fish size derived using the Love (1971) equation (lower panels) of fish at a) survey sites b) depth category. See Fig. 2 caption for further box plot explanation.

As it has been shown above that there was greater fish density and mean size at shallow category sites, it follows that there should also be higher values of the biomass proxy, sv. A Mann Whitney Wilcox test confirmed this revealing significantly higher values of linear sv (in units of m^2/m^3) at shallow category transects (W = 293, P <0.001) (Fig. 4).

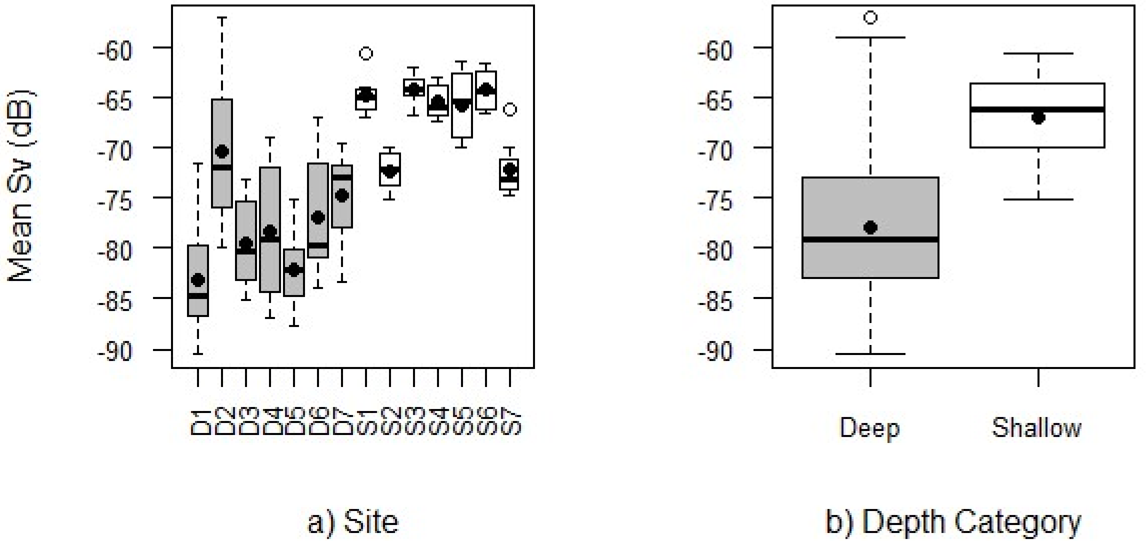

Figure 4. The mean scattering coefficient Sv (expressed in dB, for ease of view)) a) values per site b) values per depth category. See Fig. 2 caption for further box plot explanation.

Hypothesis (a) was therefore confirmed in that shallower sites had significantly greater fish density, biomass and mean fish lengths. In order to visualise this finding and to demonstrate how these parameters relate, the data are plotted in the bubble plot below (Fig. 5).

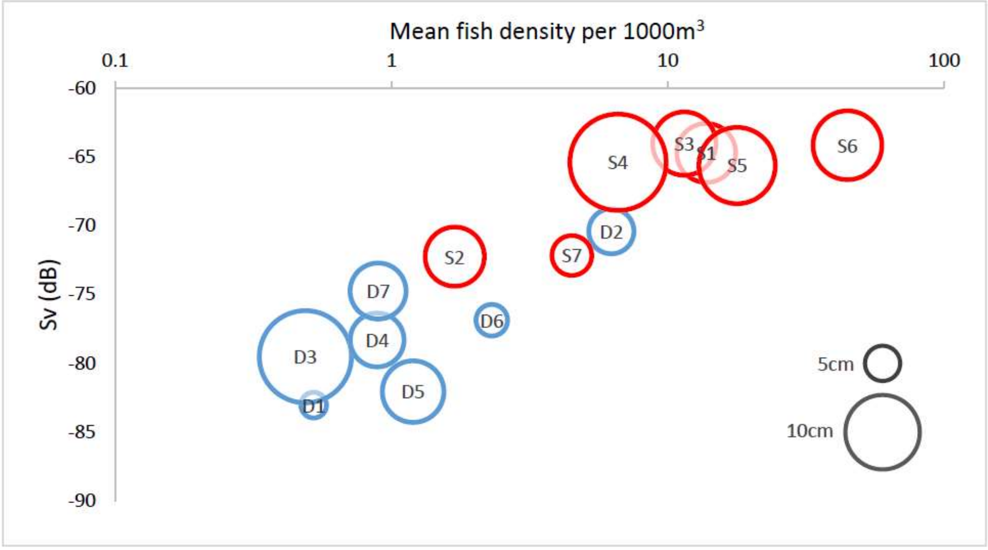

Figure 5. Graph summarising the main findings in this study. Width of the bubbles represent the mean length of fish from each site. Blue circles are from 'Deep' category sites whilst red are from 'Shallow' sites. N.B. Density data are plotted on Log$_{10}$ scale.

3.4 Fish height over seabed

A Mann Whitney Wilcox test revealed that the tracked fish were significantly closer to the seabed at shallow sites compared to deep sites (W = 437020, P<0.001), confirming hypothesis (b) (Fig. 6). This exploration was taken further by examining fish height above the seabed against fish length for tracked fish at all sites, deep sites and shallow sites (Fig. 7). Larger fish (log transformed) were seen to be significantly closer to the seabed across the depth categories; ($F_{1,1569}$= 1010, R^2=0.392, P<0.001) for all sites, ($F_{1,654}$= 139.6, R^2=0.176, P<0.001) for deep category sites and ($F_{1,913}$= 820.9, R^2=0.473, P<0.001) at shallow category sites.

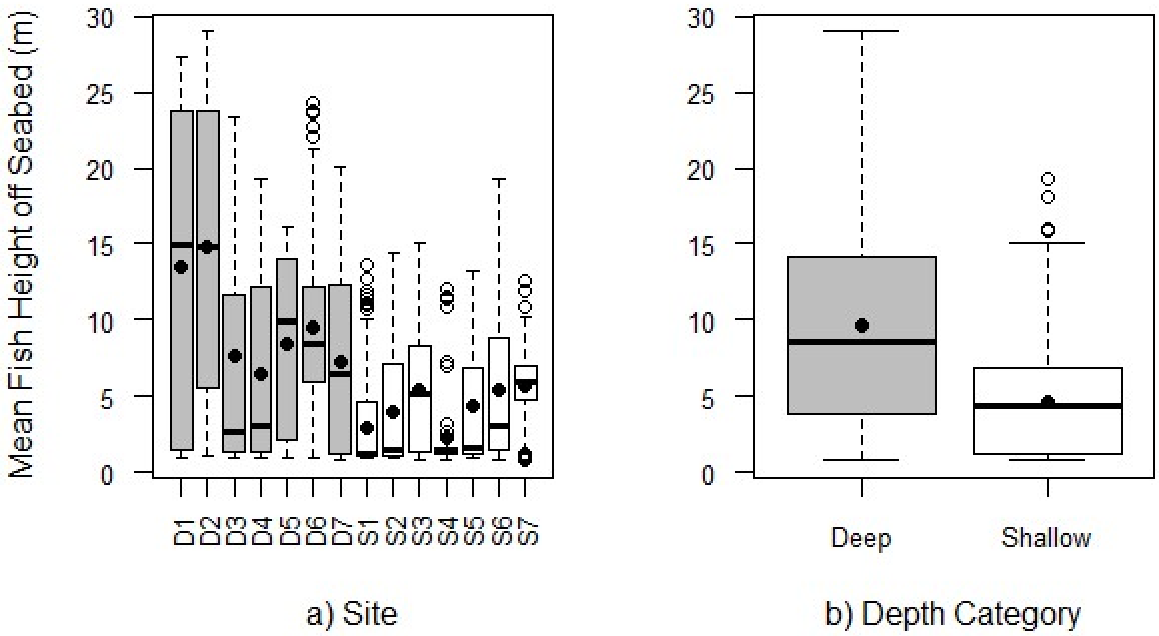

Figure 6. Mean values of fish height in the water column a) per site b) per depth category. See Fig. 2 caption for box plot explanation.

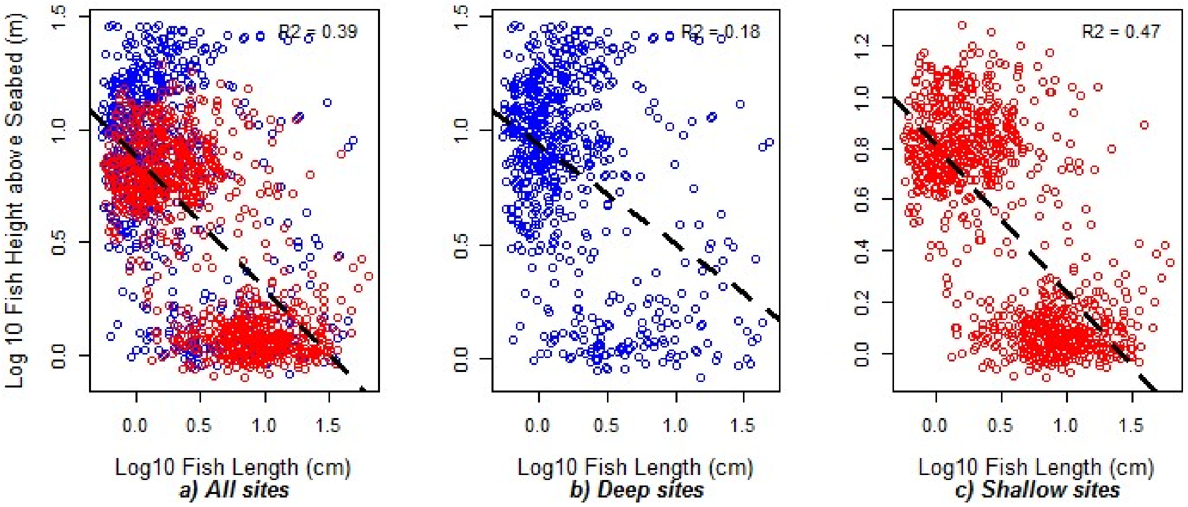

Figure 7. Log$_{10}$ Fish height above seabed (m) plotted against Log$_{10}$ Fish length (from application of the Love 1971) equation on tracked fish. Blue circles are fish from 'Deep' category sites whilst red are from 'Shallow' sites.

3.5 Groundtruthing of fish species

A total of 306 fish were caught during the fishing-based groundtruthing, 230 of these caught at shallow category sites. Across sites the most commonly caught fish species was *Lethrinus borbonicus* which represented 37% of the total catch and of these 95% were caught at shallow sites (35% of total catch). Amongst the deep sites the most commonly caught species was *Carangoides chrysophysis* (6% of total catch, 24% of catch from deep sites), followed by *Diagramma pictum* (5% of total catch, 20% of catch from deep sites).

During the SCUBA surveys 821 individual fishes were recorded. Of this the most commonly recorded fish species was *Lethrinus lentjan* (25% of total individuals recorded) however these were only recorded in high density at one site (S7). The most widely recorded species across sites was *Acanthopagrus bifasciatus* (18% of total individuals recorded). Site S7 had the highest number of individuals recorded (34%) followed by S6 (23%). Full details on the fish species recorded during groundtruthing are given in ESM 2a and b.

3.6 Habitat

In comparison to groundtruth data (Table 1), the examination of the VH data revealed that higher mean values were associated with harder and more rugose habitats. All ‘deep’ category transects were then compared with all ‘shallow’ category transects and a two-sample t test was performed which confirmed statistical significant differences between the VH mean habitat values (T_{105}=10.48, P <0.001). Similarly with mean values of Attack (T_{95}= 5.64, P <0.001), and Decay (T_{97}=6.68, P <0.001). Acoustic habitat data was plotted against depth to examine possible correlation (Fig.8). There were significant relationships between depth and VH mean habitat (R^2 =0.3421, $F_{1,12}$=6.239, P<0.05), and Decay (R^2 = 0.5916, $F_{1,12}$= 17.38, P<0.05), but not with Attack (R^2 = 0.1521, $F_{1,12}$= 2.153, P= 0.168). It should be noted that with both VH Attack and the opposite trend with depth is displayed when only the shallow sites are examined. Further, Attack (in its linear form) was significantly correlated with VH data (R^2=0.89, $F_{1,12}$ =93.67, P <0.05).

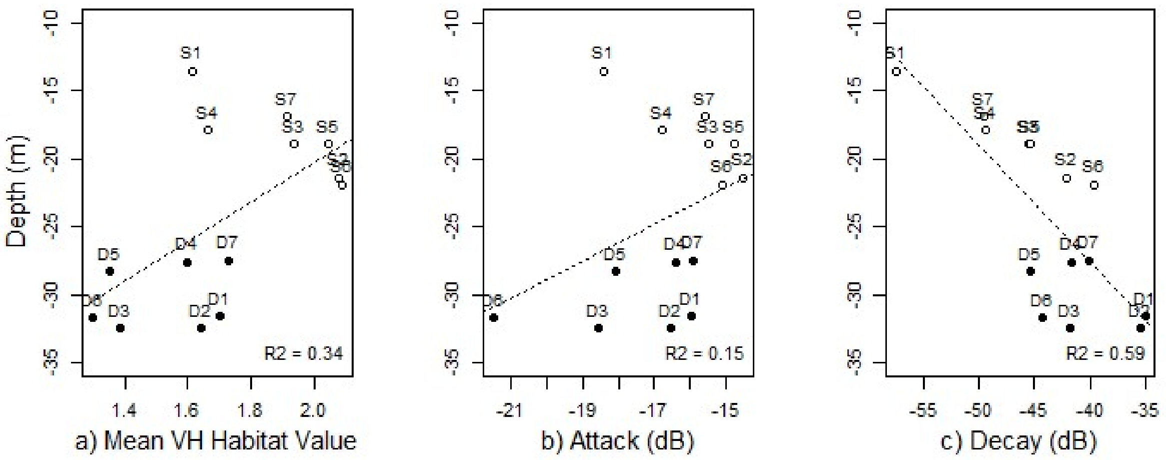

Figure 8. Mean values of acoustic data on habitat at the different sites plotted against depth a) Mean Habitat Value from VH, b) mean values of Attack (dB), c) mean values of Decay (dB)

3.7 Acoustic habitat data for predicting fish distribution

As correlation was seen to occur between the habitat parameters individual regressions were performed rather than multiple regression due to issues of multicollinearity. Mean habitat values (VH, and ‘Attack’ and ‘Decay’ from Sonar5) per site were plotted against mean site values of fish density and sv, and regression analyses performed (see Table 2 for details). This showed that there was a significant relationship with VH class as a predictor of fish density (R^2= 0.3022, $F_{1,12}$= 5.196, P< 0.05), but not of biomass (sv) (R^2= 0.1969, $F_{1,12}$= 2.943, P= 0.119). The same routine was performed against mean depth values in order to investigate if the acoustic VH habitat results show additional influence over depth alone. There was no significant relationship between depth as a predictor for either fish density or sv, thereby confirming hypothesis (c) with regard to the VH data.

Table 2. Results of regression analysis on acoustic habitat and depth in predicting mean Fish density (number per 1000m^3) and sv (m^2/m^3) (biomass proxy) per site. Regressions that are significant at the 95% level are highlighted in bold.

Acoustic Variable	Fish/1000m3	sv (m^2/m^3)
VH Habitat	**R^2=0.302, F=5.196, P<0.05**	R^2=0.1969, F=2.943, P=0.1119
Attack	R^2=0.0981, F=1.305, P=0.2755	R^2=0.073, F=0.9449, P=0.3502
Decay	R^2=0.004, F=0.04527, P=0.8351	R^2=0.03912, F=0.4885, P=0.498
Depth	R^2=0.1647, F=2.367, P=0.1499	R^2=0.2329, F=3.643, P=0.08051

4 Discussion

4.1 Fish distribution between sites.

Values of the fish parameters tested (density, sv, TS and corresponding fish length) were all significantly higher at the ‘shallow’ category oyster bed/reef sites in comparison to the ‘deep’ category muddier sites. This is in keeping with the behaviour of local fishers who target these areas, mainly by use of fish traps (“gargoor”) (Smyth et al, 2016). In other regions, oyster reefs have been also been noted as having higher densities of benthic fishes than sandy habitat (Harding et al, 1999; Harding and Mann 2001; Lenihan et al, 2001). Habitat complexity plays an important role in structuring ecological communities (Friedlander and Parrish, 1998) and this is likely to have been the case here. The greater structural complexity of the reef habitats at the ‘shallow’ category sites results in more areas of shelter for fish that are absent from the ‘deep’ category muddier habitats (Coles and Tarr, 1990), resulting in the higher densities. Generally, the more complex substratum provides habitat for many invertebrates which in turn serve as food resources for many reef fishes (Parrish et al, 1985). This effect of increased habitat rugosity showing greater fish density has been noted by many other authors (Risk, 1972; Luckhurst and Luckhurst, 1978; Öhman and Rajasuriya 1998; Brokovich et al, 2006; Graham and Nash, 2013). Cryptic species, with a close association with the reef matrix will not have been detected by our acoustic methods due to the presence of the ‘acoustic dead zone’ (Ona and Mitson, 1996) and it is therefore likely that our density estimates are conservative.

Site S6 had the largest mean value of fish density and second highest mean value of sv. This site is also known to have the most complex habitat of the sites with greatest amounts of live coral in Qatari territorial waters (Rezai et al, 2004; Sheppard et al, 2010) dominated by the genus *Acropora* (Riegl, 1999) and confirmed by diver video. The amount of live coral has also long been known to have a positive relationship on the number of fish species and individuals (Carpenter et al, 1981; Bell and Galzin 1984; Bouchon-Navaro and Bouchon 1989; Graham and Nash, 2013). This area is known to be a highly productive fishing ground

(Al-Ansi & Al-Khayat, 1999), which is supported by our results. Of the shallow sites S2 had lowest fish density and here it should be noted that this site was groundtruthed as sand rather than reef, unlike the other shallow and more rugose sites.

In most studies of ecology of reef fishes, depth seems to be an important habitat variable affecting density and distribution (Friedlander and Parrish, 1998) and linear declines in taxonomic diversity have been seen with increased depths (Jankowski et al, 2015). In our study it is most likely that the differing habitat at depth is the main driver in the fish distribution rather than the depth *per se* as demonstrated by higher R^2 values (Table 2).

The one site in the ‘deep’ category that stands out as having higher fish density and sv values than the others in this category is site D2. Here, much plankton and schools of (presumably planktivorous) fish were seen on the acoustic record. The patchy nature of the fish schools at this site lead to large variability in the data especially with the sv (biomass proxy) values between transects. The reasons why such a distribution was only observed at this site are unclear and unfortunately were not possible to establish within the scope of the survey. These fish schools were however generally higher in the water column and therefore likely to be pelagic species, therefore less effect of depth and habitat type would be expected upon these.

From the fishing based groundtruthing the most common fish species caught was *Lethrinus borbonicus*. These are known to be found in sandy areas in proximity to reefs during daytime, and they mainly feed at night over reefs and slopes (Carpenter and Allen, 1989). Other lethrinid species were also regularly seen during the groundtruthing regime and *Lethrinus lentjan* was the most commonly recorded species during the SCUBA diving video surveys. This species is known to inhabit sandy substrates in coastal areas, deep lagoons and near coral reefs (Somer et al, 1996). It is acknowledged that the differing methods of fish groundtruthing are not quantifiably comparable and it is likely that hand lines and gill nets sample a more pelagic community in comparison to the mainly demersal species seen on the diver video. Underwater visibility also differed between sites and this may have had caused differences in fish avoidance of the divers (Zenone et al, 2016). Due to the lack of species specific TS–Length formulae for most of the species encountered, the multi-species TS–Length formula from Love (1971) was applied, which is likely to have resulted in inaccuracies in fish sizes (Simmonds and MacLennan, 2005). However it does provide a consistent and intuitive relative index from which comparison can be made (Yule, 2000; Boswell et al, 2007). We acknowledge however, that if acoustic returns could have been discerned to a species level (and TS-Length formula were available) then more accurate, length, weight and subsequently biomass estimates (in units such as t/ha) would have been possible.

In examining fish height in the water column, a stronger association with the seabed was shown at the more rugose shallow sites. Further, when examined in combination with fish size a clear trend was revealed with the near absence of larger fish higher in the water column, being more closely associated with the seabed over both site categories (but with stronger association at shallow category sites). Smaller fish were more ubiquitous throughout the water column. Rugosity has been seen to have an influence on fish size with increased complexity increasing fish size (Friedlander and Parrish, 1998). This is likely due to the larger sized fish mirroring the larger hole sizes in more rugose substrata (Hixon and Beets, 1993). Alternatively this may be due to a greater density of prey for larger fishes, both invertebrates and other fish, over more rugose areas. We acknowledge that diel cycles have a large effect on fish distribution in the water column, with fish tending to be more dispersed during night (e.g. Bohl, 1980). As surveys were all carried out during daylight hours, the data should however be comparable, but night-time surveys may have yielded different results.

We are unaware of any other studies examining fish-habitat linkages in this manner and therefore further targeted research would be invaluable.

Variation in fish distribution is also likely to have been introduced by environmental factors that unfortunately were beyond the scope of this study. Other studies have seen effects on fish distribution due to variables such as temperature, salinity and dissolved oxygen (Marshall and Elliott, 1998) and zooplankton (Maravelias et al, 2006) and future studies in the area incorporating these would be valuable. Other sources of unexplained variation could result from ecological or behavioural characteristics of the fish present (Moore et al, 2009). The distribution of fish we encountered could also be related to survey bias in the form of fish avoidance of the survey vessel (De Robertis and Handegard, 2013), which may have had a greater effect at shallower sites (Vabø et al, 2002). This effect may also have manifested itself differently with different fish sizes, with larger fish exhibiting greater avoidance than smaller fish, although as small fish have previously shown stronger avoidance behaviour (Soria et al, 1996; Draštík and Kubečka, 2005), this is considered unlikely. In freshwater systems using similar size survey vessels to ours, minimal ship avoidance has been reported (Draštík and Kubečka, 2005; Wheeland and Rose, 2015), we therefore expect any ship avoidance effects to be small.

EFH has been defined as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity” (Rosenburg et al, 2000). This definition however offers no opportunities to distinguish gradations in fish habitat quality (Harding and Mann, 2001). Some authors have previously defined oyster beds as EFH for some species (Breitburg, 1999), whilst others suggest that fish are drawn to oyster beds due to the greater amounts of food present (Harding and Mann, 2001), rather than being ‘essential’ *per se*. More detailed species specific habitat use and life history information is required to categorise the shallow sites as EFH. However we have confirmed the hypothesis that these shallow oyster bed/reef habitats, harbour significantly higher fish density, larger fish and biomass than surrounding areas and are highly important for fish in this region of the Gulf.

4.2 Acoustic Determination of Habitat

Developing acoustic monitoring programmes that can integrate habitat attributes and link them to population productivity and biodiversity have been identified as a priority area of research (Anderson et al, 2008). Through processing the acoustic data to additionally give information on habitat, this study has gone some way towards this with time and cost saving implications (Freeman et al, 2004; Mackinson et al, 2004; Koslow, 2009). The acoustic habitat data resultant from VH software was seen to be capable of distinguishing between habitat types with shallow reef sites being significantly distinct from the deeper muddy sites. This was also the case with Attack and Decay from Sonar5. Video data confirmed the ‘deep’ sites to be comprised of muddy sediments, whereas the ‘shallow’ sites were generally characterised by hard substrate/reef. Of the ‘shallow’ category sites S2 was groundtruthed as being more sand rather than reef, but the VH acoustic habitat data didn’t show separate this site significantly from the other ‘shallow’ sites, potentially indicating that water depth over the seabed may have had an overriding impact on the habitat clustering (Greenstreet et al, 1997). This may have also been the case with similar VH values between deep and shallow sites when differences in depth were not great. Further, the shallowest site S1 had acoustically dissimilar habitat from other shallow sites, but the groundtruthing showed this was not the case. It is difficult to determine the relative importance of depth and habitat as across the study area these two parameters are correlated and a thorough study examining similar habitats at different depths and/or different habitats at the same depth would yield valuable information. VH data was processed with depth normalisation applied and a TVG (20logR) was applied in Sonar5, so acoustic response in theory should not vary with depth. However, other studies have still found a depth-dependency in acoustic habitat data (e.g.

Greenstreet et al, 1997; Bax et al, 1999; Foster-Smith et al, 2004; Hutin et al, 2005) and the issue of an increasing acoustic footprint with depth has still not been fully resolved (Hutin et al, 2005). The pattern shown by both VH and Attack from Sonar 5 in the shallow sites with the inverse trend with depth compared to the full dataset is also worthy of future research. Further, the highly significant relationship between VH and Attack may indicate that Sonar 5 may also be of use for habitat mapping. As depth and habitat type were seen to be correlated, means it may be possible to create a habitat map of the area by the use of bathymetry alone with depth as a proxy for habitat (Walton et al, 2007). Of the acoustic habitat data, it is worthy to highlight that VH data had a significant relationship with fish density across all sites, which was not the case when using solely depth as a predictor.

4.3 Conclusions

Through hydroacoustic surveys we have seen the importance of the ‘oyster beds’/‘hairãt’ and the coral dominated reef site, for fish and fisheries within the Qatari Gulf, and how the use of inexpensive habitat mapping software for fisheries echosounders may assist with classifying these. In these contexts, hydroacoustics can provide a valuable role in Ecosystem Based Management (EBM) and the approach described in this study could be used to identify candidate MPAs with high densities of large fish in a fast, quantitative and non-destructive manner.

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References

Aglen, A. 1989. Empirical results on precision-effort relationships for acoustic surveys. ICES CM: 1989/B:30, 28 p.

Al-Abdulrazzak D. 2013. Total fishery extractions for Qatar: 1950-2010. pp. 31-37. In: Al-Abdulrazzak D and Pauly D (eds.) From dhows to trawlers: a recent history of fisheries in the Gulf countries, 1950 to 2010. Fisheries Centre Research Reports 21(2). Fisheries Centre, University of British Columbia [ISSN 1198-6727].

Al-Ansi, M., Al-Khayat, J. A. 1999. Preliminary study on coral reef and its associated biota in Qatari waters, Arabian Gulf. Qatar Univ. Sci. J., 19 (1999), pp. 294–311

Al-Ansi, M., Priede, I.G. 1996. Expansion of fisheries in Qatar (1980–1992): growth of an artisanal fleet and closure of a trawling company. Fish Res 26, 101-111

Al-Khayat, J. A., Al-Ansi, M. A. 2008. Ecological features of Oyster Beds distribution in Qatari waters, Arabian Gulf. Asian Journal of Scientific Research, Volume: 1, 544-561.

Anderson, J. T., Holliday, D. V., Kloser, R., Reid, D. G., and Simard, Y. 2008. Acoustic seabed classification: current practice and future directions. ICES J Mar Sci, 65: 1004–1011.

Balk, H., Lindem, T. 2006. Sonar 4, Sonar 5, Sonar 6 e Post-processing Systems. Operator Manual. Lindem Data Acquisition, Oslo.

Bax, N., Kloser, R., Williams, A., Gowlett-Holmes, K., Ryan, T. 1999. Seafloor habitat definition for spatial management in fisheries: a case study on the continental shelf of southeast Australia. Oceanol Acta. 22:705-719.

Bell, J, D., Galzin, R. 1984. Influence of live coral cover on coral reef fish communities. Mar Ecol Prog Ser 15: 265−274

Bohl, E. 1980. Diel pattern of pelagic distribution and feeding in planktivorous fish. Oecologia 44: 368-375

Boswell, K. M., Wilson, M.P., Wilson. C, A. 2007. Hydroacoustics as a tool for assessing fish biomass and size distribution associated with discrete shallow-water estuarine habitats in Louisiana. Estuar Coast 30:607–617.

Boswell, K., Wells, R, J, D., Cowan, J, H., Wilson, C. A. 2010. Biomass, density, and size distributions of fishes associated with a large-scale artificial reef complex in the Gulf of Mexico. Bull Mar Sci, 86: 879–889.

Bouchon-Navaro, Y., Bouchon, C. 1989. Correlations between chaetodontid fishes and coral communities of the Gulf of Aqaba (Red Sea). Environ Biol Fish, Volume: 25 (1), pp. 47-60.

Brandt, S.B., Mason, D.M., Patrick, E.V., Argyle, R.L., Wells, L., Unger, P.A., and Stewart, D.J. 1991. Acoustic measures of the abundance and size of pelagic planktivores in Lake Michigan. Can. J. Fish. Aquat. Sci. 48: 894-908.

Breitburg, D. L. 1999. Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community? In Luckenbach, M. W., R. Mann, and J. A. Wesson, editors. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press. Gloucester Point, Virginia. pp. 239–250

Brokovich, E., Baranes, A., Goren, M. 2006. Habitat structure determines coral reef fish assemblages at the northern tip of the Red Sea. Ecol Indic 6:494– 507

Brown, C.J., Smith, S.J., Lawton, P., Anderson, J.T., 2011. Benthic habitat mapping: a review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. Estuar Coast Shelf Sci: 92, 502–520.

Carpenter, K.E. and G.R. Allen. 1989. FAO Species Catalogue. Vol. 9. Emperor fishes and large-eye breams of the world (family Lethrinidae). An annotated and illustrated catalogue of lethrinid species known to date. FAO Fish. Synop. 125(9):118 p. Rome: FAO.

Carpenter, K.E., Miclat, R.I., Albaladejo, V.D., and Corpuz, V.T. 1981. The influence of substrate structure on the local abundance and diversity of Philippine reef fishes. In: Proceedings of the 4th International Coral Reef Symposium (Vol. 2, pp. 497-502). Penang, Malaysia.

Calvert, J., Strong, J. A., Service, M., McGonigle, C., Quinn, R. 2014. An evaluation of the supervised and unsupervised classification techniques for benthic marine habitat mapping using multibeam echosounder data. ICES J Mar Sci. doi:10.1093/icesjms/fsu223

Coles, S.L., Tarr, A.B. 1990. Reef fish assemblages in the Western Arabian Gulf: A geographically isolated population in an extreme environment. Bulletin of Marine Science, Volume 47(3), pp.696-720.

Coll, C., Tito de Morais, L., Laë, R., Lebourges-Dhaussy, A., Simier, M., Guillard, J., Josse, E., Ecoutin, J, M., Albaret, J, J., Raffray, J., Kantoussan, J. 2007. Use and limits of three methods for assessing fish size spectra and fish abundance in two tropical man-made lakes. Fish. Res. 83: 306-318

De Robertis, A., Handegard, N. O. 2013. Fish avoidance of research vessels and the efficacy of noise-reduced vessels: a review. ICES J Mar Sci, 70:34-45.

De Young, C. (ed.) 2006. Review of the state of world marine capture fisheries management: Indian Ocean. FAO Fisheries Technical Paper. No. 488. Rome, FAO. 2006. 458p.

Diaz, R,J., Solan, M., Valente, R,M. 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. J Environ Manage: 73, pp. 165–181

Draštík, V., Kubečka, J. 2005. Fish avoidance of acoustic survey boat in shallow waters. Fish Res: 72 (2), 219-228

Ellis, J. R., Rogers, S. I., and Freeman, S. M. 2000. Demersal assemblages in the Irish Sea, St George's Channel and Bristol Channel. Estuar Coast Shelf Sci: 51: 299–315.

Emmrich, M., Winfield, I.J., Guillard, J., Rustadbakken, A., Verges, C., Volta, P., Jeppesen, E., Lauridsen, T.L., Brucet, S., Holmgren, K. and Argillier, C. 2012. Strong correspondence between gillnet catch per unit effort and hydroacoustically derived fish biomass in stratified lakes. Freshwater Biol, 57(12), 2436-2448.

FAO. 2003. Information on fisheries management in the State of Qatar. [Online]. Available at: http://www.fao.og/fi/oldsite/FCP/en/gat/body.htm [Accessed: 15/9/15].

Feary, D., Burt, J., Bartholomew, A. 2011. Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. Ocean Coast Manage. 54 (10) (2011), pp. 742–749

Feidi, I.H. 1998. Fisheries development in the Arab World. Transformations of Middle Eastern natural environments: legacies and lessons (ed. by J. Albert, M. Bernhardsson and R. Kenna) pp. 388–406. Yale School of Forestry & Environmental Studies: Bulletin Number 103. Yale University, New Haven, CT.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., Simmonds, E. J. Calibration of acoustic instruments for fish-density estimation: a practical guide. 1987. ICES Cooperative Research Report, 44.

Foster-Smith, R.L and Sotheran I, S. 2003 Mapping marine benthic biotopes using acoustic ground-discrimination systems. Int J Remote Sens. 24:2761-2784

Foster-Smith, R.L., Brown, C.J., Meadows, W.J., White, W.H., Limpenny, D.S. 2004. Mapping seabed biotopes at two spatial scales in the eastern English Channel. Part 2. Comparison of two acoustic ground-discrimination systems. Journal of the Marine Biological Association of the United Kingdom; 84:489-500.

Freeman, S, Mackinson, S., Flatt, R. 2004. Diel patterns in the habitat utilisation of sandeels revealed using integrated acoustic surveys. J Exp Mar Biol Ecol: 305: 141–154.

Friedlander, A.M., Parrish J.D. 1998. Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. J Exp Mar Biol Ecol: 224 (1998), pp. 1–30

Graham, N.A.J., Nash, K.I. 2013. The importance of structural complexity in coral reef ecosystems. Coral Reefs 32: 315−326

Greenstreet, S.P., Tuck, I.D., Grewar., G.N., Armstrong, E., Reid, D.G., Wright, P.J. 1997. An assessment of the acoustic survey technique, RoxAnn, as a means of mapping seabed habitat ICES J Mar Sci: Journal du Conseil, Volume: 54(5), 939-959.

Harding, J. M., R. Mann. 2001. Oyster reefs as fish habitat: opportunistic use of restored reefs by transient fishes. J. Shellfish Res. 20:951–959

Harding, J. M., Mann, R. 1999. Fish species richness in relation to restored oyster reefs, Piankatank River, Virginia. Bull Mar Sci. 65: 289–299

Hixon, M.A., Beets, J.P. 1993. Predation, prey refuges, and the structure of coral- reef fish assemblages. Ecol. Monog. 63 (1993), pp. 77–101

Hutin, E., Simard, Y., Archambault, P. 2005. Acoustic detection of a scallop bed from a single-beam echosounder in the St Lawrence. ICES J Mar Sci. 62: 966–983.

Hrabik, T.R., Jensen, O.P., Martell, S.J.D., Walters, C.J., Kitchell, J.F. 2006. Diel vertical migration in the Lake Superior pelagic community. I. Changes in vertical migration of coregonids in response to varying predation risk. Can J of Fish Aquat Sci, 63, pp. 2286–2295

Jankowski, M.W., Graham, N.A.J., and Jones, G.P. 2015. Depth gradients in diversity, distribution and habitat specialisation in coral reef fishes: implications for the depth-refuge hypothesis Mar Ecol Prog Ser, 540. pp. 203-215

Jensen, O.P., Hansson, S., Didrikas, T., Stockwell, J.D., Hrabik, T.R., Axenrot, T., Kitchell. J.F. 2011. Foraging, bioenergetic and predation constraints on diel vertical migration: field observations and modelling of reverse migration by young-of-the-year herring Clupea harengus. J Fish Biol, 78 (2011), pp. 449–465

Khan, N.Y. 2007. Multiple stressors and ecosystem-based management in the Gulf', Aquatic Ecosystem Health & Management, 10: 3, 259-267.

Koslow, J. A. 2009. The role of acoustics in ecosystem-based fishery management. ICES J Mar Sci, 66: 966–973.

Kostylev, V.E., Todd, B.J., Fader, G.B.J., Courtney, R.C., Cameron, G.D.M., Pickrill, R.A. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Mar Ecol Prog Ser, 219, pp. 121–137

Larkin, P.A. 1996. Concepts and issues in marine ecosystem management. Rev Fish Biol Fisher. 6, 139–164.

Lenihan, H.S., Peterson, C.H,. Byers, J.E., Grabowski, J. H., Thayer, G. W., Colby. D. R. 2001. Cascading of habitat degradation: oyster reefs invaded by refugee fishes escaping stress. Ecol Appl. 11:764–782

Love, R. H. 1971. Measurements of fish target strength: a review. Fish Bull: US. 69:703-715.

Luckhurst, B.E., Luckhurst K. 1978. Analysis of substrate variables on Coral Reef fish communities. Mar Biol. Volume 49(4), pp. 317-323.

Mackinson, S., Freeman, S., Flatt, R., Meadows, B. 2004. Improved acoustic surveys that save time and money: Integrating fisheries and ground discrimination acoustic technologies. J Exp Mar Biol Ecol: 305,129—140.

Maravelias, C.D., Reid, D., Swartzman, G. 2000. Seabed substrate, water depth and zooplankton as determinants of the prespawning spatial aggregation of North Atlantic herring. Mar Ecol Prog Ser, 195: 249–259

Marshall, S., Elliott, M. 1998. Environmental influences on the fish assemblage of the Humber Estuary, U.K. Estuar Coast Shelf Sci. 46, pp. 175–184

Minns, C.K., Moore J.E. 2003. Assessment of net change of productive capacity of fish habitats: the role of uncertainty and complexity in decision making. Can J of Fish Aquat Sci, 60:100-116

McConnaughey, R.A., Syrjala, S.E. 2009. Statistical relationships between the distributions of groundfish and crabs in the eastern Bering Sea and processed returns from a single-beam echosounder. ICES J Mar Sci, 66: 1425 –1432.

Munday, E., Moore, B., Burczynski, J. 2013. "Hydroacoustic Mapping System for Quantitative Identification of Aquatic Macrophytes, Substrate Composition, and Shallow Water Bathymetric Surveying." Paper presented at the OCEANS IEEE Conference, San Diego, CA

Öhman, M.C and Rajasuriya, A. 1998. Relationships between habitat structure and fish communities on coral. Environ Biol Fish. Volume: 53 (1), pp. 19-31.

Ona, E and Mitson, R.B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES J Mar Sci; 53, pp. 677–690

Parker-Stetter, S.L., Rudstam, L.G., Sullivan, P.J. and Warner, D.M. 2009. Standard operating procedures for fisheries acoustic surveys in the Great Lakes. Great Lakes Fish. Comm. Spec. Pub. 09-01

Parrish, J.D., Callahan, M.W., Norris, J.E. 1985 Fish trophic relationships that structure reef communities Proc. 5th Inter. Coral Reef Congr., 4, pp. 73–78

Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., Watson, R., Zeller, D. 2002. Toward sustainability in world fisheries. Nature 418:689–695.

QGIS Development Team, 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://www.qgis.org/

Rezai, H., Wilson. S., Claereboudt, M., Riegl, B. 2004. Coral Reef Status in the Ropme Sea Area: Arabian/Persian Gulf, Gulf Of Oman and Arabian Sea. p: 155-170 in C. Wilkinson (ed.). Status of coral reefs of the world: 2004. Volume 1. Australian Institute of Marine Science, Townsville, Queensland, Australia. 301 p

Riede, K. 2004. Global register of migratory species - from global to regional scales. Final Report of the R&D-Project 808 05 081. Federal Agency for Nature Conservation, Bonn, Germany. 329 p.

Riegl, B. 1999. Corals in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): fauna and community structure in response to recurring mass mortality. Coral Reefs, Volume: 18(1), 63-73.

Risk, M.J. 1972. Fish diversity on a Coral Reef in the Virgin Islands. Atoll Research Bulletin, Volume 193, pp. 1-6.

Rose, K. A. 2000. Why are quantitative relationships between environmental quality and fish populations so elusive? Ecol Appl. 10:367-385.

Rosenburg, A., Bigford, T.E., Leathery, S., Hill, R.L., Bickers, K. 2000. Ecosystem approaches to fishery management through essential fish habitat. Bull Mar Sci: 66, 535–542

Sale, P.F., Feary, D., Burt J.A., Bauman, A., Cavalcante, G., Drouillard, K., Kjerfve, B., Marquis, E., Trick, C., Usseglio, P., van Lavieren, H. 2011. The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio, 40 (2011), pp. 4–17

Sawada, K., Furusawa, M., Williamson, N.J., 1993. Conditions for the precise measurement of fish target strength in situ. J. Mar. Acoust. Soc. Japan 20, 15–21.

Siddeek, M.S.M., Fouda, M.M., Hermosa Jr, G.V. 1999. Demersal fisheries of the Arabian sea, the Gulf of Oman and the Arabian Gulf. Estuar. Coast. Shelf Sci., 49, pp. 87–89

Simmonds, J and Maclennan, D. 2005. Fisheries Acoustics: Theory and Practice. Second edition, Blackwell Science. Fish and Aquatic Resources Series 10.

Sivasubramaniam, K., Ibrahim A.M. 1982. Demersal Fish Resources Around Qatar. Qatar Univ. Sci. Bull. 2: 305-352.

Smyth, D.M., Al-Maslamani, I., Chatting, M., Giraldes, B.W. 2016. Benthic surveys of the historic pearl oyster beds of Qatar reveal a dramatic ecological change. Mar Poll Bull, http://dx.doi.org/10.1016/j.marpolbul.2016.08.085

Somer, 2003. State of the marine environment report. ROPME/GC-11/003. Regional Organization for the Protection of the Marine Environment, Kuwait.

Soria, M., Freon, P., Gerlotto, F. 1996. Analysis of vessel influence on spatial behaviour of fish schools using a multi-beam sonar and consequences for biomass estimates by echo-sounder. ICES J Mar Sci; 53:453-458

Stamatopoulos, C., Abdallah, M. 2016. Standardization of Fishing Effort in Qatar Fisheries: Methodology and Case Studies. J Marine Sci Res Dev 5: 170. doi:10.4172/2155 9910.1000170

Trenkel, V.M., Ressler, P.H., Jech, M., Giannoulaki, M., Taylor, C. 2011. Underwater acoustics for ecosystem-based management state of the science and proposals for ecosystem indicators. Mar Ecol Prog Ser 442: 285-301

Yule, D. 2000. Comparison of horizontal acoustic and purse-seine estimates of salmonid densities and sizes in eleven Wyoming waters. N Am J Fish Man. 20:759– 775

Yule, D.L., Adams, J.V., Hrabik, T.R,. Vinson, M.R., Woiak, Z., Ahrenstorff, T.D. 2013. Use of classification trees to apportion single echo detections to species: application to the pelagic fish community of Lake Superior. Fish Res. 140:123-132

Van Der Kooij, J., Fässler, S.M.M., Stephens, D., Readdy, L., Scott, B.E., Roel, B.A. 2016. 'Opportunistically recorded acoustic data support Northeast Atlantic mackerel expansion theory'. ICES J Mar Sci, vol 73, no. 4, pp. 1115-1126. DOI: 10.1093/icesjms/fsv243

Vabø, R., Olsen, K., Huse, I. 2002. The effect of vessel avoidance of wintering Norwegian spring spawning herring. Fish Res. 58:59-77

Walton, M.E., Hayes, J., Al-Ansi, M., Abdallah, M., Al Maslamani, I., Al-Mohannadi, M., Al-Shaikh, I., D'Urban Jackson, T., Szostek, C., Egerton, J. and Kaiser, M.J., 2017. Towards spatial management of fisheries in the Gulf: benthic diversity, habitat and fish distributions from Qatari waters. *ICES Journal of Marine Science*.

Wheeland, L.J., Rose, G.A. 2015. Quantifying fish avoidance of small acoustic survey vessels in boreal lakes and reservoirs. Ecology of Freshwater Fish. 24(1), 67-76. doi: 10.1111/eff.12126

Winfield, I.J., Emmrich, M., Guillard, J., Mehner, T., Rustadbakken, A. 2012 Guidelines for standardisation of hydroacoustic methods. WISER deliverable 3.4-3. 186-188. Available from http://www.wiser.eu/download/D3.4-3.pdf

Zenone, A.M., Burkepile, D.E. and Boswell, K.M., 2017. A comparison of diver vs. acoustic methodologies for surveying fishes in a shallow water coral reef ecosystem. Fisheries Research, 189, pp.62-66.