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Rapid assessment of fish communities on submerged oil and gas platform reefs using remotely operated vehicles

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ABSTRACT

Remotely operated vehicles (ROVs) provide a non-extractive approach to characterizing fish communities in complex habitats. Despite the demonstrated effectiveness of ROVs in studying reef fishes over natural hard-bottom and small artificial reefs, there has been little application of this technology to larger artificial structures (10s of m tall and wide). We explored the utility of ROVs in rapidly characterizing an assemblage of fishes associated with an artificial reef complex in the western Gulf of Mexico (26.9–28.2° N; 95.5–97.0° W) dominated by partially removed and toppled oil and gas platforms. This study reports on an efficient method to sample these structures, where we integrated depth-interval transect (DIT) and continuous roving transect (CRT) protocols to document fish distribution and community structure on 14 artificial reef sites. Consistent with previous hydroacoustic studies, south Texas artificial reefs exhibited a vertically heterogeneous distribution of fishes that varied with structure orientation. These reefs were dominated by economically important lutjanids and carangids, both of which presented sampling challenges due to their patchy distribution around these vast structures. The non-uniform distribution and mobility of these dominant taxa highlight the utility of adopting roving approaches to assess fish communities on these complex structures. We conclude our study with a discussion of important logistical challenges associated with micro-ROV surveys in deepwater habitats, and potential complementary approaches to assist documentation of demersal fishes inhabiting a persistently turbid bottom layer.

1. Introduction

Numerous studies have documented the dependence of fishes on complex nearshore and coastal habitats such as seagrass beds, oyster reefs, saltmarsh, mussel beds, and rocky shorelines (reviewed in Beck et al., 2001; Seitz et al., 2013). Unfortunately, fewer data exist for offshore benthic marine habitats where the study of fish communities is limited by a suite of logistical constraints. In general, these offshore habitats range widely in size (m^2–100s of km^2), and are often located at depths beyond most recreational and scientific diving limits (30 m). As a result, researchers often rely on other traditional fisheries sampling gears (e.g., hook-and-line, traps) over visual assessments to characterize these offshore communities, though such gear may be biased to certain trophic guilds and sizes (Bacheler et al., 2013; Gregalis et al., 2012; Patterson et al., 2012). In addition, the characteristic rugosity and sensitivity of high relief benthic environments pose new challenges to the use of these sampling methods in most areas.

Video-based approaches provide an opportunity to broadly sample a variety of species and size ranges of fish and increase visual survey times at depth. Accordingly, these approaches have been of prime utility to document diversity and abundance of fishes inhabiting offshore marine ecosystems. Video-based surveys have historically included drop cameras, carousels, manned diver cameras, and remotely operated vehicles (ROVs) (Bryan et al., 2013; Cappo et al., 2006; Murphy and Jenkins, 2010; Pacunski et al., 2008; Somerton and Gledhill, 2004). Due to reductions in their size and cost and the ability to maneuver around isolated structures, ROVs have become increasingly used by fisheries researchers over the past few decades. To date, the majority of ROV use in fisheries research has focused on abundance and diversity surveys of benthic species associated with natural habitat. There has been limited assessment of artificial structures, and especially reefs with large vertical relief (Table 1), where depth and sheer size of the structure

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Table 1
Summary table of previous ROV studies and the habitats and survey types used to assess fish assemblages.

Device	Habitat	Habitat type	Survey type	Reference
Hydrobot	Natural	Lake bottom	Horizontal transect	Davis et al. (1997)
MiniRover MK2/Phantom II	Natural	Natural substrate	Horizontal transect	Norcross and Mueter (1999)
Phantom 300/XTL	Natural	SE Alaska bays, coves, inlets	Horizontal transect	Johnson et al. (2003)
Seaeye Falcon	Natural	High relief rocky habitat	Horizontal transect	Martin et al. (2006)
Phantom S4	Natural	High relief pinacles and ridges	Horizontal transect	Koenig et al. (2005)
Commando II	Natural	Coral reefs	Horizontal transect	Lam et al. (2006)
Phatom HD2/DS4	Natural	Natural habitat	Horizontal transect	Butler et al. (2006)
Phantom S-2	Natural	Rocky reef habitat	Horizontal transect	Whitfield et al. (2007)
Phantom S-2	Natural	Rocky reef habitat	Horizontal transect	Whitfield et al. (2007)
VideoRay Pro II	Natural	Sand, shell-rubble, natural reef	Horizontal transect	Wells et al. (2008)
Phantom DS4	Natural	Shallow natural bank	Horizontal transect	Jones et al. (2012)
DOE HD 2	Natural	Deep water, hard bottom	Horizontal transect	Karpov et al. (2012)
Phantom S-2	Natural/artificial	Natural hardbottoms, shipwreck	Horizontal transect	Quattrini and Ross (2006)
Hyrdrobotics Orpheus/DOE HD2	Artificial	Oil/gas platform	Cylindrical/depth interval	Stanley and Wilson (1997)
Hyrdrobotics Orpheus/DOE HD2	Artificial	Oil/gas platform	Cylindrical/depth interval	Stanley and Wilson (2000)
Phantom HD2/VideoRay Pro II	Artificial	Oil/gas platform	Cylindrical/depth interval	Wilson et al. (2006)
VideoRay ROV	Artificial	Debris field	Horizontal transect	Gallaway et al. (2008)
XL-11 ROS camera	Artificial	Deep-water shipwreck	Horizontal transect	Kilgour and Shirley (2008)
VideoRay Pro III	Artificial	Concrete pyramids	Cylindrical point count	Patterson et al. (2009)
VideoRay Pro III	Artificial	Concrete pyramids	Cylindrical point count	Dance et al. (2011)
Hyball	Artificial	Oil/gas platform	Cylindrical/depth interval	Andaloro et al. (2013)

has the potential to greatly influence distribution and abundance of fish over a large area. Historically, these habitats have been conducive to survey methodologies that have generally involved straight-line horizontal transects and/or randomized drops of the ROV onto benthic habitats. As an index of survey effort, these protocols typically use a measure of transect distance, which can be computed from an ultra-short baseline (USBL) acoustic positioning system or extrapolated from survey time and a constant ROV speed. In these applications, the ROV is typically either "flown" away from a stationary vessel or suspended with a clump weight away from the ship and towed along a transect with limited maneuverability (Bryan et al., 2013; Pacunski et al., 2008). These types of ROV-based approaches generally involve sampling over large expanses of contiguous substrata often several square kilometers in size, and are unfortunately not always applicable to surveys of more isolated large habitats (e.g., pinnacle reefs, high relief artificial structures).

The majority of the benthos in the western Gulf of Mexico is characterized by clay, sand, or silt material (Parker et al., 1983). This general lack of complex bottom habitat relative to other areas has led to a great dependence on artificial reefs by fishermen and divers in this region, as these structures concentrate high densities of fish. The type and amount of artificial structure varies greatly throughout the Gulf of Mexico basin. For example, eastern programs (Florida and Alabama) have large numbers of small reef pyramids (2.5 m height × 3 m base), reef balls, and military tanks (7 m × 3.4 m × 3.2 m). Louisiana and Texas artificial reef programs consist largely of toppled or partially removed (cut-off) oil and gas platforms that are much larger in size (3800–8173 m^2). The state of Texas has one of the largest Rigs-to-Reefs programs in the United States and has reefed 140 oil and gas platforms since 1990. Despite several decades of reefing, there have been few assessments of fish populations using these submerged artificial structures, and previous authors have suggested that reefed platforms may not be as productive as standing structures or natural reef habitats (Stanley and Wilson, 1997, 2000a; Wilson et al., 2003). Because of the recent rapid removal of standing structures in the Gulf of Mexico, and the subsequent conversion of a portion of those to Rigs-to-Reefs programs, critical questions related to the construction and placement of artificial reefs remain to be addressed. For instance, it is unknown which Rigs-to-Reefs option (e.g., toppled versus partial removal) best supports fisheries production and diversity due to a lack of standardized fishery-independent surveys on these structures.

In the northern Gulf of Mexico, ROV methods to estimate fish density at smaller scale artificial reefs have been developed. For example, some researchers have modified stationary point count (SPC) methods of Bohnsack and Bannerot (1986) to estimate fish density within a cylinder comprising the physical footprint of a pyramid (Dance et al., 2011; Patterson et al., 2009). For larger scale artificial reefs composed of oil and gas platforms, previous studies have used SCUBA surveys, manned submersibles, or hydroacoustics to assess fish density or community structure (Andaloro et al., 2013; Dokken et al., 2000; Gallaway et al., 2008; Love and York, 2006; Rooker et al., 1997; Stanley and Wilson, 1997, 2000a; Wilson et al., 2003), and the use of ROVs has been secondary. Typically, those ROV surveys used cylindrical point counts and were confined to pre-determined depth and time intervals (Table 1). Because previous studies in the Gulf of Mexico have been focused on extrapolating density estimates of fish from a proportion of the total habitat (Gallaway et al., 2008; Stanley and Wilson, 1997, 2000a; Wilson et al., 2003), these assessments have not comprehensively evaluated the fish community on these structures.

In this study, we describe a rapid ROV-based assessment protocol for acquiring abundance and diversity indices for reef fishes on artificial reefs created by oil and gas platforms. Given the size, depth, and high relief of these offshore structures (10s of m, tall and wide), we integrated ROV sampling methodologies previously used for both large and small scale habitats, namely depth interval-based and roving (horizontal and vertical) transects. In our assessment, we discuss some of the challenges and logistical constraints associated with implementing ROV surveys in this region and compare and contrast the two techniques that should prove beneficial to researchers assessing the value of artificial reefs in enhancing fish populations.

2. Materials and methods

2.1. Artificial reef site description and location

Our study region comprised 14 artificial reef sites situated along the coastal-bend of south Texas in shelf waters of the Gulf of Mexico (Fig. 1). Multiple structures of varying materials were reefed within each artificial reef site. The predominant bottom type surrounding the reefs was a silt-clay mixture. A total of 20 ROV surveys were completed on various artificial structures in 2012 (Table 2). These

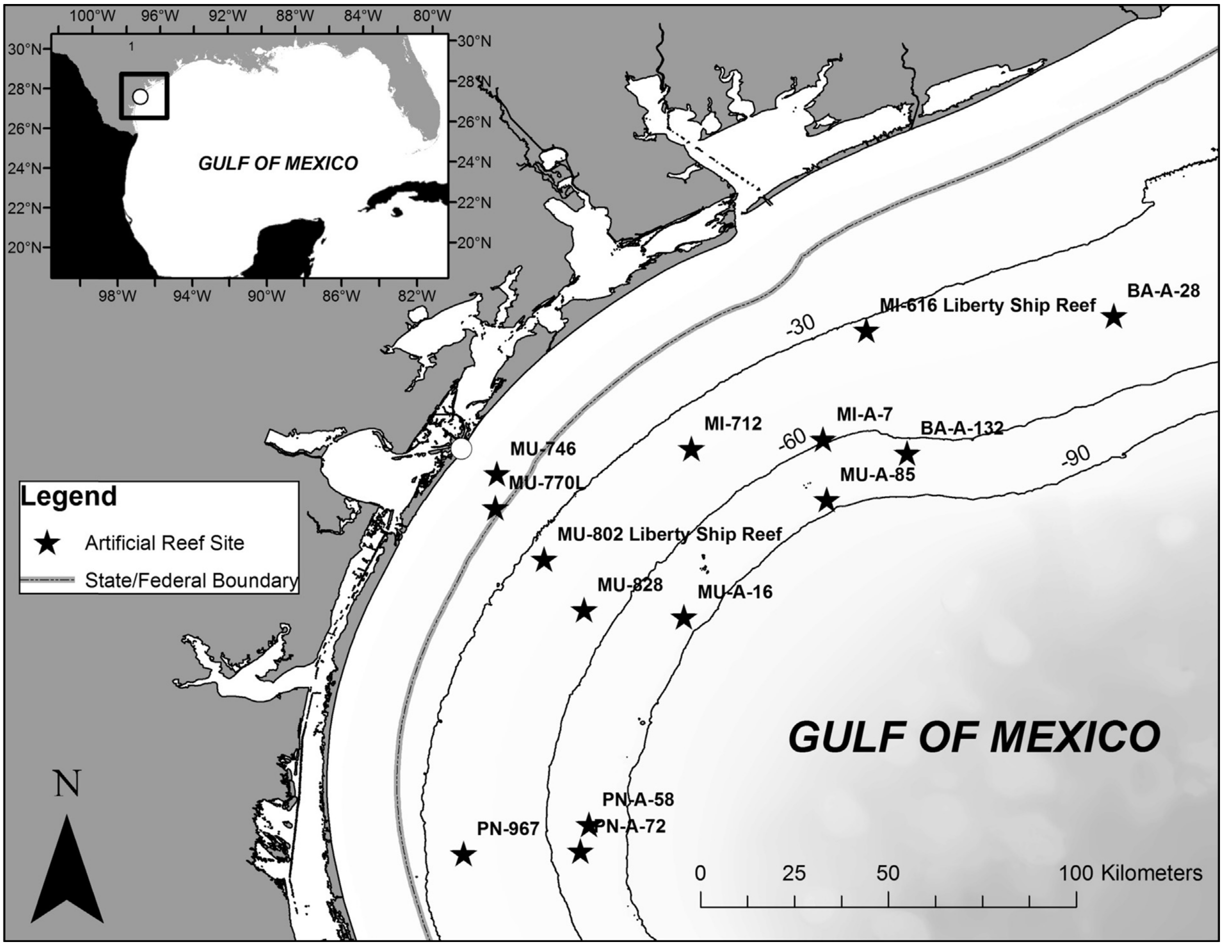

Fig. 1. Map of artificial reef site locations for the Texas coastal-bend. Stars represent locations of reefs, labeled by site name. White dot represents home port of Port Aransas, TX. 30-m isobaths are shown out to 90 m depth. Although shown on the map, nearshore sites (state waters) MU-746 and MU-770L were not surveyed due to visibility limitations.

Table 2
Description of sites surveyed by ROVs in 2012.

Survey date	Site name	Reefing date	Reef type	Ambient depth (m)	Relief (m)	Dive time (min)	ROV type
6/7/2012	MI-712	7/17/1991	Deck	40	13	39	VideoRay
6/7/2012	MU-828	8/29/2001	Topple	50	20	26	VideoRay
6/18/2012	MI-A-7	11/25/2002	Cutoff	60	33	39	VideoRay
9/21/2012	MU-A-16	8/22/2006	Topple	83	18	35	VideoRay
9/21/2012	MU-A-16	8/22/2006	Cutoff	83	56	19	VideoRay
9/21/2012	MU-A-85	10/3/2006	Cutoff	84	55	48	VideoRay
9/21/2012	MU-A-85	7/12/2011	Cutoff	84	23	36	VideoRay
10/9/2012	BA-A-28	7/11/1992	Topple	46	14	35	GlobalEx
10/9/2012	BA-A-28	11/24/1991	Cutoff	46	19	85	GlobalEx
10/12/2012	MU-802	6/1/1976	Ship	34	5	35	VideoRay
10/15/2012	PN-58	9/12/1995	Cutoff	51	23	57	GlobalEx
10/15/2012	PN-58	9/12/1995	Topple	75	15	56	GlobalEx
10/15/2012	PN-967	6/11/1997	Topple	36	10	27	GlobalEx
10/15/2012	PN-967	6/11/1997	Topple	36	6	93	GlobalEx
10/15/2012	PN-A-72	7/27/1998	Cutoff	72	40	64	GlobalEx
10/15/2012	PN-A-72	7/27/1998	Topple	71	39	56	GlobalEx
10/16/2012	BA-A-132	8/21/2005	Topple	61	20	51	GlobalEx
10/16/2012	BA-A-132	11/15/1992	Topple	61	29	66	GlobalEx
10/17/2012	MI-616	6/1/1976	Ship	36	7	54	VideoRay
10/17/2012	MI-616	6/1/1976	Ship	36	9	40	VideoRay

VideoRay = Video Ray Pro4 micro-ROV operated by authors; GlobalEx = Global Explorer ROV operated by Schmidt Ocean Institute.

surveys included partially removed (i.e., "cutoff"; $n = 7$) and toppled ($n = 9$) oil and gas platforms, as well as liberty ships ($n = 3$) and a single platform deck structure. Vertical relief (top of structure to benthos) was variable among structure types with partially removed platforms having the highest relief (19–56 m; $\bar{x} = 36$ m), followed by toppled platforms (6–39 m; $\bar{x} = 19$ m), the deck (13 m), and liberty ships (5–9 m; $\bar{x} = 7$ m). Ambient water depth also varied across these sites (Table 2).

2.2. Equipment

We used a VideoRay Pro 4 micro-ROV equipped with a compass, depth sensor, temperature sensor, auto-depth holding capabilities, forward facing color camera (520 line, 0.1 lx), LED array for illumination and Lynn Photo enhancer software to enhance video in poor visibility. The ROV was piloted with an integrated control box connected via a tether. Surface real-time observations were conducted with live feed from the camera (160° tilt and a 105° viewing angle). Depth and heading were visible on the real-time image screen. Because the VideoRay Pro 4 system did not record high-definition footage, we additionally mounted a GoPro© camera (HD Hero2). The HD Hero2 filmed at 960p (30 fps) and had a 170° field of view. However, because GoPro cameras had restricted use and battery life, footage from these devices was used to solely supplement identification, with all counts conducted within the VideoRay field of view. The VideoRay system was used for a total of 10 dives. Our study also utilized a larger working-class ROV, the Global Explorer (Deep Sea Systems International, Inc.), to survey 10 artificial reefs during an oceanographic cruise aboard the R/V Falkor (8–20 October 2012). The Global Explorer is a large (25,000-lb) deep water (3000-m rating) ROV, equipped with Ocean ProHD Cameras (1080i resolution), a digital photo and laser scaler, digital scanning sonar (BlueView), 2 vertical thrusters, 4 horizontal thrusters, and LED lights. Despite significant differences in the VideoRay and Global Explorer ROV size and capabilities, we conducted surveys of artificial reefs using the same standardized methods.

2.3. Survey methodology

We surveyed artificial reefs by either anchoring the vessel next to or on the actual structure, or "live-boating" from a fixed distance away from the structure. We generally conducted VideoRay deployments from anchored vessels (36–42′) that could be held into the reef with a small anchor (Seasense, Mighty Mite). Global Explorer surveys were conducted from the R/V Falkor, which maintained its position a fixed distance away from the reef using the ship's dynamic positioning system. The Global Explorer ROV position relative to the ship was tracked using an ultra-short baseline (USBL) system.

Because we were interested in how fish communities changed in the presence/absence of structure, it was imperative to collect fish count data throughout the water column. Where possible, a depth-interval transect (DIT) was performed based on methods used in previous platform surveys (Stanley and Wilson, 2000a; Wilson et al., 2006). Upon entry, the pilot hovered the ROV above the structure then descended at 5 m intervals until reaching 30 m (or top of structure), where intervals were adjusted to every 10 m until reaching ambient bottom depth or a depth where visual assessments were no longer possible due to visibility (i.e., nepheloid layer). During these intervals the ROV was held stationary a few meters from the structure with the camera facing up-current (toward the structure) for a 1 min period. These short, precise intervals reduce time associated with video post-processing. Although previous authors have used variations of the Stationary Point Count method during ROV surveys, we found completion of a 360° spin to be challenging for the micro-ROV under most currents. In addition, estimating a visual cylindrical area was problematic without a known visual reference. In some instances, due to strong currents and logistical concerns (e.g., ship positioning), we were unable to perform a complete DIT survey (surface to depth).

Our site assessments also included roving transects across the structure at the top and bottom of the reef (where possible). These transects were designed to mimic roving diver surveys commonly used in SCUBA-based underwater visual censuses (REEF, 2013). Once the ROV reached the surface of the artificial reef and completed the associated depth interval, the ROV was flown along a continuous horizontal rove to document fishes around the structure top. When the surface rove was complete, the ROV resumed the depth interval sampling to the bottom of the reef. Upon reaching the maximum survey depth, the ROV was again flown continuously to span the outer surface area of the down-current side of the structure. We avoided entering the interior and up-current side of all oil and gas platform reefs to reduce the risk of entanglement and because fishes within the interior were generally visible from outside. For analysis, the entire survey from ROV water entry to exit was treated as the continuous roving transect (CRT). Once the survey was completed, the ROV was brought back to the surface and retrieved. Logistically, it was not possible to survey more than one structure per site per day, which prevented replicate surveys.

2.4. Video analyses

In the laboratory, videos from the ROV recording systems (ROV standard, GoPro HD, and OceanPro HD) were downloaded to a computer and analyzed by two readers with open-source video software (VLC™ media player). The entire video was reviewed and fish were identified to the lowest possible taxon, enumerated and recorded onto a spreadsheet each time they entered the field of view. Counts from both readers were compared and re-analyzed only if they varied by >5%. A mean of both counts was then computed. Time of day, depth of occurrence, temperature and heading of ROV were also recorded. For each survey, the time in and out of the water was recorded to calculate a dive time. Observations recorded within the entire dive time were treated as the CRT dataset. To separate the DIT data set, each 1-min depth interval start and end time was used to create an additional data set.

For both survey types, we generated a MinCount for each species, which is the greatest number of individuals captured on screen at any one time. This conservative count represented the total number, at minimum, of individuals for a particular species during the dive and is a commonly used index of abundance reported for video survey data (Ellis and DeMartini, 1995; Merritt et al., 2011; Watson et al., 2005; Willis et al., 2000). For large schools of fish that exceeded the field of view, numbers of individuals were estimated using paused frames. Consecutive frames were then summed to encompass the entire school if directionality was apparent. This modification of the MinCount was possible due to the roving nature of the ROV survey, as the mobility allowed readers to visualize an entire school and minimized double-counting. A MaxCount (sum of all counts), and MeanCount (mean of all counts) were also generated for each species. The MeanCount is a recently developed metric shown to be useful for indexing fish abundance for stationary cameras (Bacheler et al., 2013; Schobernd et al., 2014). We also created a minimum count for the total fish community (ComMinCount) by pooling species-specific MinCount values.

2.5. Data analyses

A variety of performance metrics were calculated to evaluate the capacity of ROVs to capture fish communities on artificial reefs. Overall sample size sufficiency (i.e., number of surveys) was assessed with a species accumulation curve. Curves were created in PRIMER v6 and estimated the cumulative number of fish species across samples (S_{obs}) based on richness data from all sites surveyed. To remove the effect of sampling chronology on curve smoothness, the order was randomized across 999 permutations. If the curve approached an asymptote, the number of dives was considered sufficient in explaining fish diversity across our sites. At individual structures (i.e., dives), we also used time-series depth tracks of our ROVs overlain with a species-accumulation plot to qualitatively examine the vertical portions of the reef that contributed to the species diversity. Relationships between survey time and species richness and log transformed total fish community MinCount (ComMinCount) were evaluated using linear regression ($\alpha = 0.05$).

We examined overall fish vertical distribution patterns throughout the water column to help guide future sampling efforts. To simplify this analysis, we only used count data from the DIT as effort was more broadly and consistently distributed across the water column, and only used those surveys where DIT surveys were successfully completed from surface to depth ($n = 7$); surveys at Liberty Ships and the platform deck were not included in this comparison. To allow for consistent comparisons among sites with varying levels of ambient bottom depth (34–84 m), we converted all depths at which fish were observed into proportional structure depths (D_{pS}), or the proportion of the water column above (positive) and below (negative) the top of the submerged structure (D_S).

$$\text{when} \quad D_O > D_S; \quad D_{pS} = \frac{D_S - D_O}{D_S},$$

$$\text{when} \quad D_O < D_S; \quad D_{pS} = \frac{D_O - D_S}{D_S - D_A}$$

Thus, the D_{pS} values ranged from −1 (seabed) to 0 (top of structure), to +1 (water surface). Proportional count data (count at depth/counts across all depths) were plotted with D_{pS} to qualitatively examine fish distribution.

Using pooled CRT observations from all sites ($n = 20$), we examined potential species-related count variability. We first generated a scatter plot to qualitatively determine the relationship between proportional occurrence (# observations for each species/sum of total observations for all species) and proportional count (MinCount for each species/ComMinCount) for individual species. These analyses were only conducted for species occurring on at least 3 different dives ($n = 21$). Coefficients of variation (CV) were determined for the abundance estimate of each individual species to further identify high ($CV > 1$) and low ($CV < 1$) variance taxa. We also converted counts to categories to qualitatively examine high and low variance species. For this qualitative analysis, individual species counts were further characterized into single (S; one individual), few (F; 2–10 individuals), many (M; 11–100 individuals), and abundant (A; >100) categories. We also compared species-specific ratios of the various metrics (MaxCount:MinCount) and (MinCount:MeanCount) to determine which species were most greatly affected by each abundance metric.

We compared differences in survey type (DIT vs. CRT) using both qualitative and quantitative techniques. Because the DIT represented a smaller fraction of survey effort and still spanned the vertical relief of the structure, we were interested in whether this survey type could still sufficiently capture the fish community and produce similar indices of abundance generated by the CRT. We explored the number of concurrent surveys each species was reported (i.e., positive surveys), and then expressed the MinCount generated using the DIT as a proportion of the CRT to examine potential deflation in abundance indices using the time-restricted and less mobile DIT.

3. Results

3.1. Survey effort and species diversity

Our 20 ROV surveys culminated in 960 min (16 h) of total underwater video footage (Table 2). A total of 48 species were identified from the footage, representing 20 families. The randomly permutated species accumulation plot displayed a curve approaching an asymptote (Michaelis–Menten $S_{max} = 52.18$), indicating the sample size captured an estimated 92% of the fish species that could be documented on artificial reefs with our sampling methods (Fig. 2). Within a survey, we noted that the ROV would need to span the entire vertical expanse of the structure to cover the range of species present. This was demonstrated in a time-series species-depth plot, which showed higher accumulation rates at the top and bottoms of these structures during roving parts of the survey (Fig. 3). Our example also showed that a single span of the vertical aspect of the reef can cover as much as 83% of the diversity within 30 min of survey time. Subsequent spans of the top and bottom generally yielded few additional species.

Species richness displayed a significantly positive linear relationship with survey time for Global Explorer surveys (Linear regression, $r^2 = 0.52$, $F_{1,9} = 8.66$, $P < 0.05$) but not for Video Ray surveys (Linear regression, $r^2 = 0.27$, $F_{1,9} = 2.96$, $P = 0.124$) (Fig. 4A). However, these differences may be related to disparate survey effort ranges between the Global Explorer (27–93 min) and Video Ray (19–54 min) systems. There were negligible differences in the slopes of the best fit lines (0.22–0.23), suggesting an artifact of survey effort range on the significance levels of these relationships. Survey time exhibited a significantly positive relationship with log-transformed total fish counts for the Global Explorer surveys (Linear regression, $r^2 = 0.78$, $F_{1,9} = 28.99$, $P < 0.001$) but not Video Ray surveys (Linear regression, $r^2 = 0.15$, $F_{1,9} = 8.66$, $P = 0.275$) (Fig. 4B), though the slopes of the best-fit lines for both regressions were similar (0.0144–0.0148).

3.2. Vertical distribution

Using DIT-based data, we observed divergent trends in fish vertical distribution between cutoff and toppled oil and gas platform reefs. On cutoff platforms ($n = 5$), maximum proportional counts were observed between +10% to −20% of the structure top (Fig. 5A). Although sample size was considerably lower on toppled platforms ($n = 2$), maximum counts were observed at the bottom half of the reef (Fig. 5B).

3.3. Species-specific observation rates and counts

Fish count categories varied greatly by species (Fig. 6). Four species were encountered at "abundant" levels (>100) at least once in our ROV surveys. These included schooling species such as Blue Runner (*Caranx crysos*), Horse-eye jack (*Caranx latus*), Lookdown (*Selene vomer*), Vermilion Snapper (*Rhomboplites aurorubens*) and the Ephippid spadefish (*Chaetodipterus faber*). These abundant species also had the highest maximum coefficients of variation (Table 3). Species occurring maximally under the "many" category (11–100) included two lutjanid species, Gray (*Lutjanus griseus*) and Red (*Lutjanus campechanus*) Snapper, carangids such as the Almaco (*Seriola riviolana*) and Crevalle Jacks (*Caranx hippos*), Spotfin Hogfish (*Bodianus pulchellus*), Bermuda Chub (*Kyphosus sectatrix*), and Atlantic Creolefish (*Paranthias furcifer*). Coefficients of variation for species occurring in these categories were generally between 1 and 3, or moderately variable. A diverse array of species did not occur more than 10 individuals at a time and included Greater Amberjack (*Seriola dumerili*), Bluehead Wrasse (*Thalassoma bifasciatum*), Spanish Hogfish (*Bodianus rufus*), French (*Pomacanthus paru*) and Blue angelfish (*Holacanthus bermudensis*), Great Barracuda (*Sphryaena barracuda*), Gray Triggerfish (*Balistes capriscus*), Rock Hind (*Epinephalus adscendionis*), Sheepshead (*Archosargus probatocephalus*), and Tomtate (*Haemulon aurolineatum*). The CVs for these species were <1, indicating they were "low-variance" species.

On average, no single species exceeded >25% of proportional counts or occurrence across sites (Fig. 7). However, our plots of species proportional occurrence vs. proportional counts revealed interesting patterns. For example, two species of jacks (Blue Runner

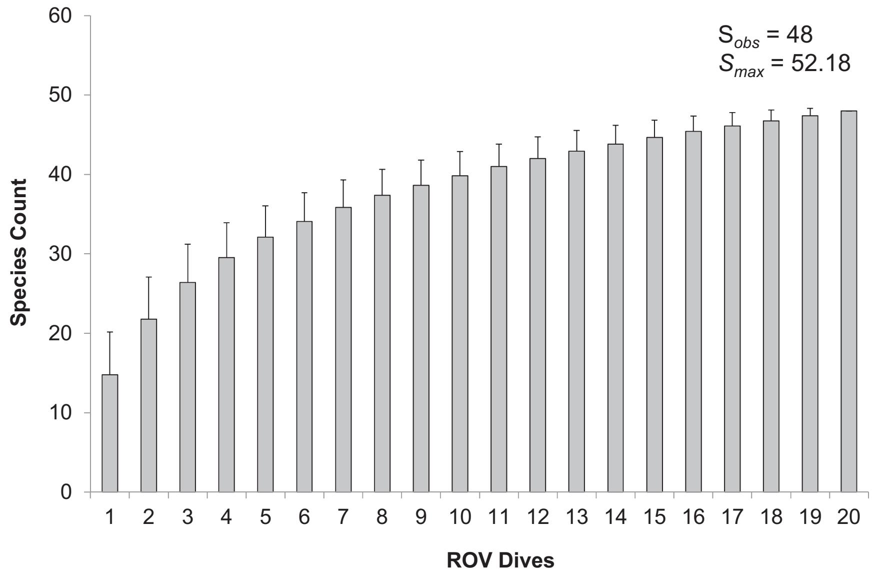

Fig. 2. Bar plot of means of species counts from randomized permutations of community data from 20 ROV dives of 2012. Error bars represent standard deviation.

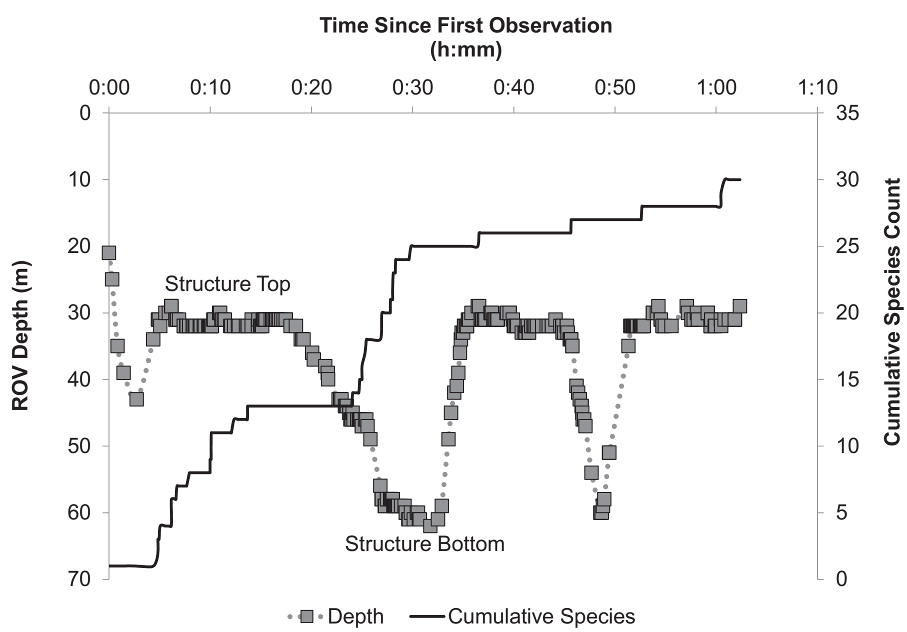

Fig. 3. Dual time-series plot of ROV position (depth; gray squares) and cumulative species counts (black line) for an ROV dive on site BA-A-132 on 10/16/2012.

and Horse-eye Jack) often dominated the overall counts; although, these species were observed relatively infrequently (i.e., low proportional occurrence). The proportional counts of snapper species (Red, Gray, and Vermillion) were also relatively high compared to others, though these levels remained relatively constant across species. Of the three major snapper species, Gray Snapper stood out as a species that dominated in terms of both occurrence and counts. Several more reef-oriented species (i.e., rarely found off the structure) such as wrasses (Spotfin and Spanish Hogfish), angelfishes, and Rock Hind maintained consistently low levels of both proportional counts and occurrence.

In general, MinCount was more reflective of MaxCount for largely schooling species such as jacks and snappers (Fig. 8A). Conversely, for more solitary species and those encountered in small groups (Blue Angelfish, Gray Triggerfish, and Barracuda), MaxCount was on average >5× greater than MinCount. These latter species likely represented individuals with the greatest potential to be counted more than once. The relationship between MinCount and MeanCount was not as divergent and average ratios ranged between 1 and 3. Gray Snapper were likely the most underestimated with MeanCount, as values averaged more than three times less than the MinCount. Generally, MinCount:MeanCount ratios were lower for more reef-associated species (Fig. 8B).

3.4. Comparisons between depth-interval and roving surveys

Pooled minimum counts for all species (i.e., ComMinCount) from CRT footage were on average 18x (range: 3–90×) greater than those obtained from DIT. Notable species present on at least 3 CRTs yet absent in all DITs included Blue Angelfish, Horse-eye Jack, and Rainbow Runner. Other less common species missed on the list included Spadefish, Spotfin Butterflyfish, Tomtate, Bicolor Damselfish, Blue tang, Creole Wrasse, Lionfish, and Yellowmouth Grouper (Fig. 9A). Indices of abundance (i.e., MinCount) for other

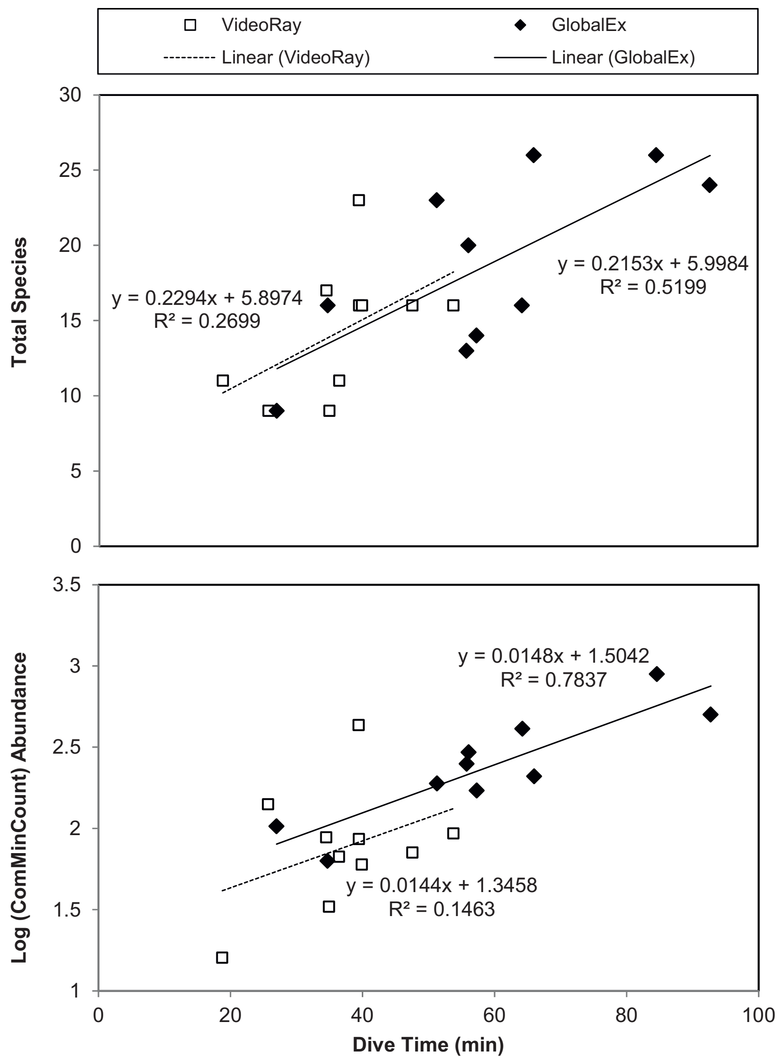

Fig. 4. Scatter plots displaying relationships between survey time and total species richness (A) and log-transformed abundance. Data are shown for surveys conducted with Video Ray micro-ROV (white square) and Global Explorer ROV (black diamonds). Linear best fit-lines, regression equations and R^2 values are shown for each ROV and metric.

species observed regularly on DITs were consistently 30–80% of the MinCount derived from the CRT (Fig. 9B).

4. Discussion

The function and fishery enhancement potential of artificial reefs remains a contentious issue in fisheries research (Bohnsack, 1989; Carr and Hixon, 1997; Cowan et al., 2011; Gallaway et al., 2009; Grossman et al., 1997; Macreadie et al., 2011; Powers et al., 2003; Shipp and Bortone, 2009) and requires a comprehensive and efficient assessment to best determine the role of these structures in marine ecosystems. Our ROV surveys show that coupled roving and interval-based approaches can quickly and effectively characterize fish assemblages on extensive and highly structured artificial reefs. Certainly, there are logistical constraints and challenges of such sampling approaches in these environments including intensive video analysis, sea state, water clarity needs (see below), and accounting for patchily distributed fishes. Nonetheless, this approach offers a valuable tool to determine indices of abundance for reef fish populations using large artificial reefs and can be conducted from small vessels without the expense and logistics of a large ship or working-class ROV. Although we took advantage of the R/V Falkor and Global Explorer for comparative purposes, much smaller and less cost-prohibitive research platforms can routinely conduct these fish community assessments with micro-ROVs with much success.

Our study confirms clear patterns in the vertical distribution of fishes associated with reef orientation (e.g., cutoff vs. topple). Similar to our ROV-based findings, a previous hydroacoustic study of reefed oil and gas platforms found comparable fish peak density patterns at the top of partially removed structures and near the bottom of toppled platforms (Stanley and Wilson, 2000). These convergent findings suggest that fish assemblages in the Gulf of Mexico shelf may respond consistently to these structures depending on the amount of vertical relief. However, additional studies are needed on oil and gas platform reefs over a continuum of sizes and bottom depths. Should future studies concentrate on partially removed and toppled oil and gas platforms, we recommend that researchers maximize survey effort in depths immediately surrounding the reef as fish appear to largely avoid the water column above, and sampling these areas can take considerable time from the study objectives.

As with all field studies in fisheries, survey methodology is constrained by research objectives and the availability of sampling resources. Our analyses suggest that depth-interval transects (DIT) may be a useful ROV-based approach if the goal is to capture overall fish community composition and sampling time is a limiting factor. Moreover, post-processing time is significantly reduced by

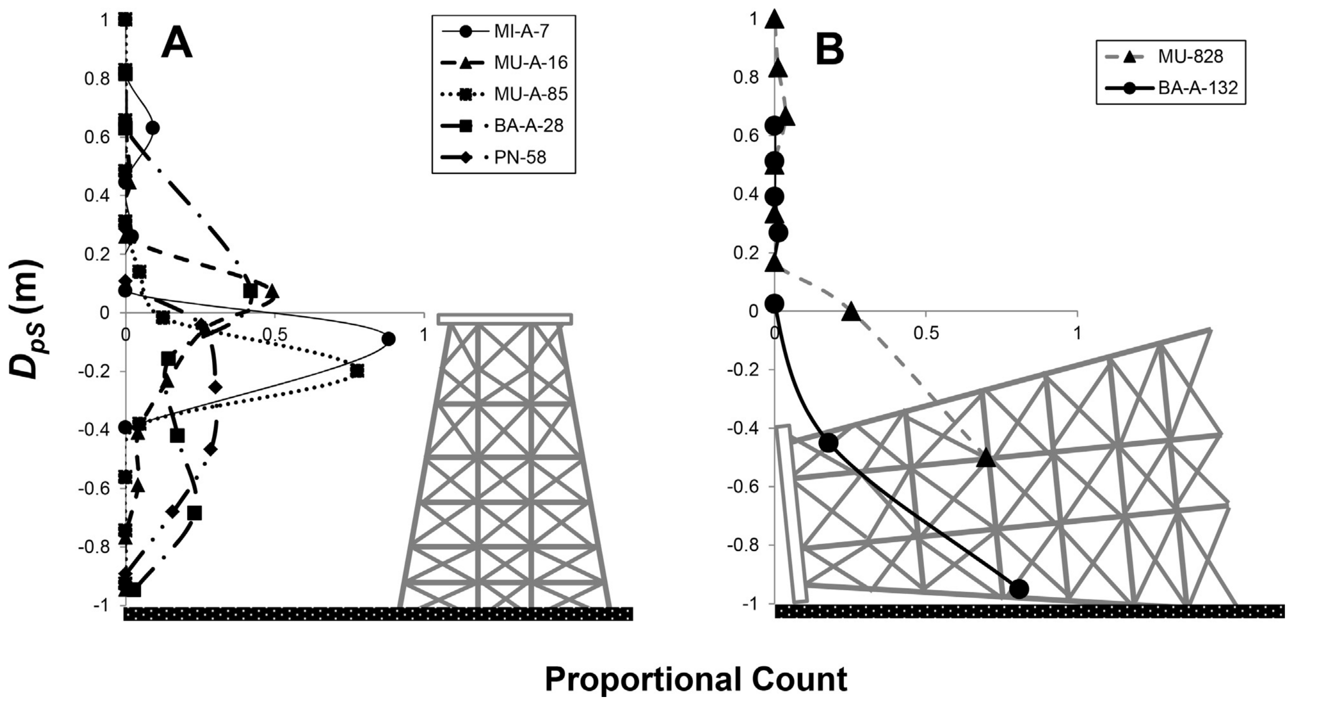

Fig. 5. Smoothed line-scatter plots displaying relationships between proportional abundance and proportional structure depth (D_{pS}). Symbols and lines indicate DIT sampling locations for a particular dive, and are overlain onto a schematic of the water column for cutoff (A) and toppled platforms (B).

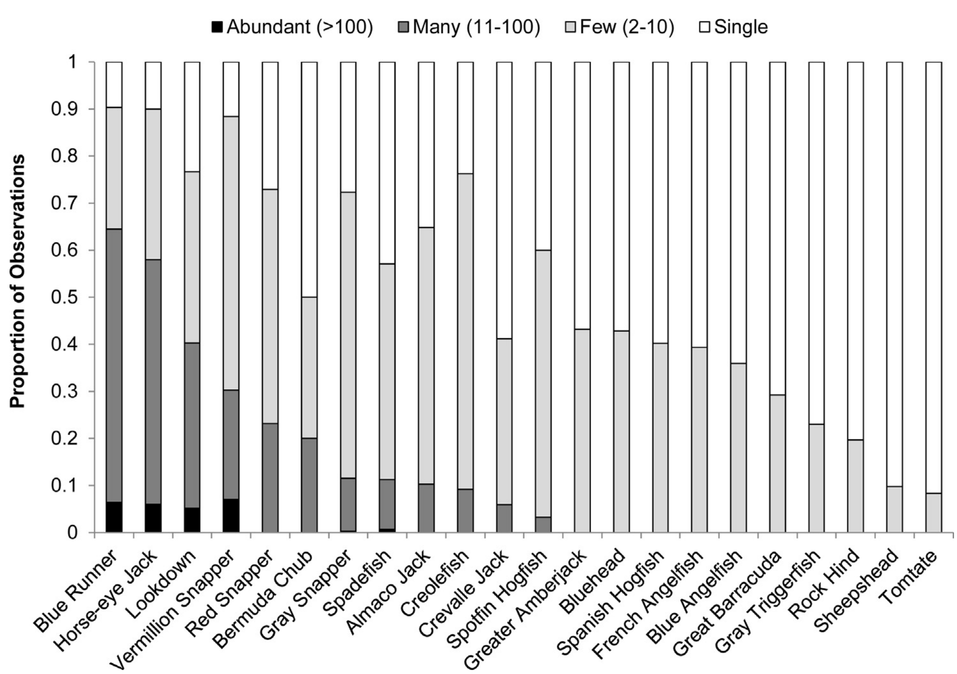

Fig. 6. Stacked bar chart of abundance categories for species observed on at least 3 separate dives.

limiting video review to timed interval segments. Operationally, the systematic depth intervals kept the ROV stable and can more accurately assess fish depth distribution. For example, during the continuous roving transect (CRT) the ROV may be momentarily oriented downward or upward (i.e., during descent or ascent), making the exact depth of the observed fish more difficult to estimate. Thus, DITs can also be used to estimate fish densities at distinct depth strata given a known sampling volume. However, used alone, the DIT does not appear adequate in approximating the MinCount of several important species occupying submerged oil and gas platform reefs. For example, despite being observed on more than half our sites with the CRT, minimum counts of both Gray and Red Snapper as well as Greater Amberjack were greatly underestimated (70–90% missed) using the DIT. These differences may be attributed to the overall patchiness of these species in relation to the size of the structure, or the limited time that is typically available for each sampling interval across the water column. As such, should resources allow, the CRT is recommended to potentially minimize inter-sample variability as well as provide indices closer to the true abundance of fishes inhabiting artificial reefs. The CRT additionally provides more robust estimates of richness at these sites, and was shown to capture several rare, but potentially important species

Table 3
Table of MinCount coefficients of variation (*CV*) for all species observed on ≥3 ROV dives.

Common name	Latin name	Family	Mean CV	Min CV	Max CV	Dives observed
Horse-eye Jack	*Caranx latus*	Carangidae	4.6	0.0	7.0	5
Blue Runner	*Caranx crysos*	Carangidae	4.3	1.3	9.2	5
Vermilion Snapper	*Rhomboplites aurorubens*	Lutjanidae	3.2	0.4	9.6	7
Lookdown	*Selene vomer*	Carangidae	3.1	0.0	7.5	8
Spadefish	*Chaetodipterus faber*	Ephippidae	2.9	0.3	11.1	9
Gray Snapper	*Lutjanus griseus*	Lutjanidae	2.0	0.0	9.0	17
Bermuda Chub	*Kyphosus sectatrix*	Kyphosidae	1.7	0.5	3.6	3
Red Snapper	*Lutjanus campechanus*	Lutjanidae	1.7	0.4	5.5	14
Creolefish	*Paranthias furcifer*	Serranidae	1.6	0.0	3.8	10
Almaco Jack	*Seriola rivoliana*	Carangidae	1.5	0.7	2.7	7
Bluehead	*Thalassoma bifasciatum*	Labridae	1.4	0.6	2.2	3
Yellow Jack	*Caranx bartholomaei*	Carangidae	1.3	0.4	2.8	4
Spotfin Hogfish	*Bodianus pulchellus*	Labridae	1.0	0.0	2.1	15
Blue Angelfish	*Holacanthus bermudensis*	Pomacanthidae	0.6	0.0	1.0	13
Spanish Hogfish	*Bodianus rufus*	Labridae	0.6	0.0	1.5	15
Greater Amberjack	*Seriola dumerili*	Carangidae	0.5	0.0	1.0	7
Great Barracuda	*Sphyraena barracuda*	Sphyraenidae	0.5	0.0	1.4	15
Reef Butterflyfish	*Chaetodon sedentarius*	Chaetodontidae	0.4	0.4	0.4	3
Gray Triggerfish	*Balistes carpiscus*	Balistidae	0.4	0.0	0.7	8
Spotfin Butterflyfish	*Chaetodon ocellatus*	Chaetodontidae	0.3	0.0	0.5	4
Rock Hind	*Epinephelus adscensionis*	Serranidae	0.3	0.0	0.7	9
Tomtate	*Haemulon aurolineatum*	Haemulidae	0.2	0.0	0.9	7
French Angelfish	*Pomacanthus paru*	Pomacanthidae	0.2	0.0	0.4	5
Sheepshead	*Archosargus probatocephalus*	Sparidae	0.1	0.0	0.4	7

Species are listed in order of highest to lowest mean *CV*.

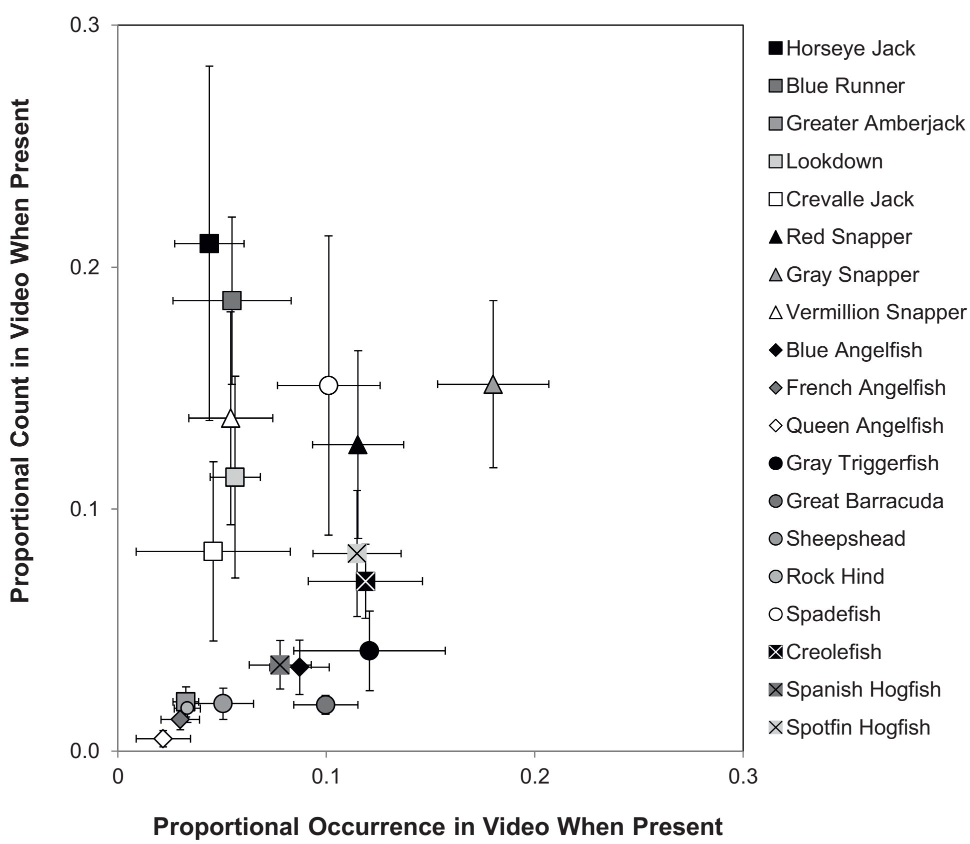

Fig. 7. Scatter bi-plot of species-specific proportional occurrence and abundance patterns. Species listed are those occurring on at least 3 surveys. Symbol shape corresponds to family for Carangids (open squares) and Lutjanids (triangles) and error bars represent standard error.

such as the invasive Lionfish (*Pterois volitans*). Our findings are consistent with recent publications indicating that roving approaches detect more species per site (Holt et al., 2013; Schmitt et al., 2002), and we thus recommend these methods where possible.

Due to the dynamic nature of the CRT (high mobility separated by periods of stationary counts) and the patchiness of fish schools on our artificial reefs, our data suggest the MinCount metric is the most appropriate index of abundance for species encountered on these surveys. Our approach of roving both the horizontal and vertical extent of the structures enabled us to encounter larger schools of dominant carangids and lutjanids, which generally exhibited heterogeneous distribution patterns. Other studies have shown the

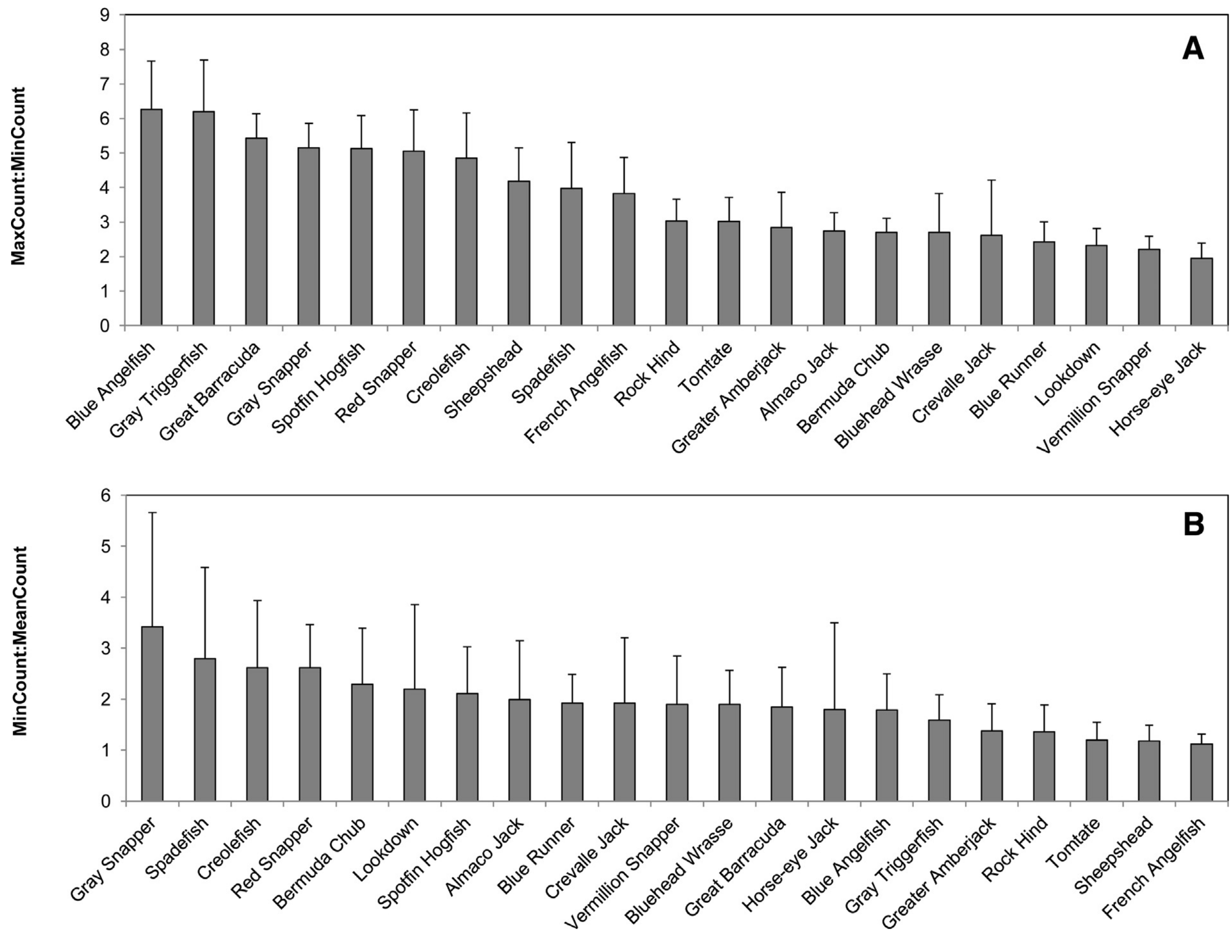

Fig. 8. Vertical bar charts showing the mean ratios of MaxCount:MinCount (A) and MinCount:MeanCount (B) for various fish species observed on ROV surveys. Species are listed from highest to lowest mean ratios from left to right, with error bars representing standard errors.

benefits of other indices like MeanCount (Bacheler et al., 2013; Schobernd et al., 2014); however, these studies used stationary cameras that were temporarily fixed to the bottom and thus documented communities from a significantly smaller area than roving ROVs. While this index of abundance may be effective and comparable across certain habitats in drop-camera surveys, we found it to vary in its relationship with MinCount depending on species. For species occurring in large schools (including managed Gray and Red Snappers), the MeanCount was two to three times less than MinCount. Such a discrepancy can lead to underestimates of abundance for these species, and has the potential to affect management of these exploitable resources. We advise future researchers to conduct approaches that limit re-encounters, such as timed surveys where the ROV flies along a straight path over a known distance (e.g., cross-beam of a submerged platform) and fish indices of abundances are thus more standardized. Such approaches would also enable extrapolations of fish density to the spatial extent of the reef (Pita et al., 2014), which is essential to quantifying the value of these structures. However, such approaches may again inadequately quantify the abundance of patchily distributed species.

4.1. Equipment limitations and logistical challenges

One of the major challenges to surveying structures with such extensive horizontal and vertical expanse is developing protocols that are comparable to other habitats and reefing materials. It is important to conduct surveys relative to the spatial footprint of the structure so that counts can be standardized by surface area and/or volume of the reefed materials. Such standardization requires knowledge of area sampled, which is a major challenge for micro-ROVs without USBL positioning systems (these can add substantial cost and sampling constraints). If available, we encourage researchers to use geo-referenced maps of reef sites (e.g., side-scan imagery) to provide visual estimates and better estimate the quantity of structure covered during surveys. Such aids can standardize counts to an area or volume (e.g., perimeter of liberty ship) and provide much-needed and comparable density estimates. Our data also show, as one might expect, longer ROV surveys are characterized by significantly higher richness and cumulative fish counts. Thus, as shown elsewhere, the length of sampling timeframe may also affect interpretation in future comparisons if not limited (Bortone et al., 1986, 1989).

Micro-ROV field surveys can be periodically challenged by the local environmental conditions. For example, we noted significant impacts of surface and subsurface currents on the micro-ROV and tether, which generally restricted surveys to the down-current side of the artificial reef to prevent entanglement. Thus, this design may underestimate fishes occupying the up-current side of the reef such as larger lutjanids (Ralston et al., 1986). The benthic nepheloid layer was another major impediment to carrying out ROV surveys. This layer of resuspended benthic sediment is a highly dynamic feature along the south Texas continental shelf (Shideler, 1981). On the artificial reefs we surveyed, the benthic nepheloid layer generally prevented video analysis from the bottom layer due to near zero visibility. We regularly observed large numbers of Red Snapper moving in and out of this feature, consistent with this species' benthic lifestyle (reviewed in Gallaway et al., 2009). Given the economic importance of Red Snapper and the challenges

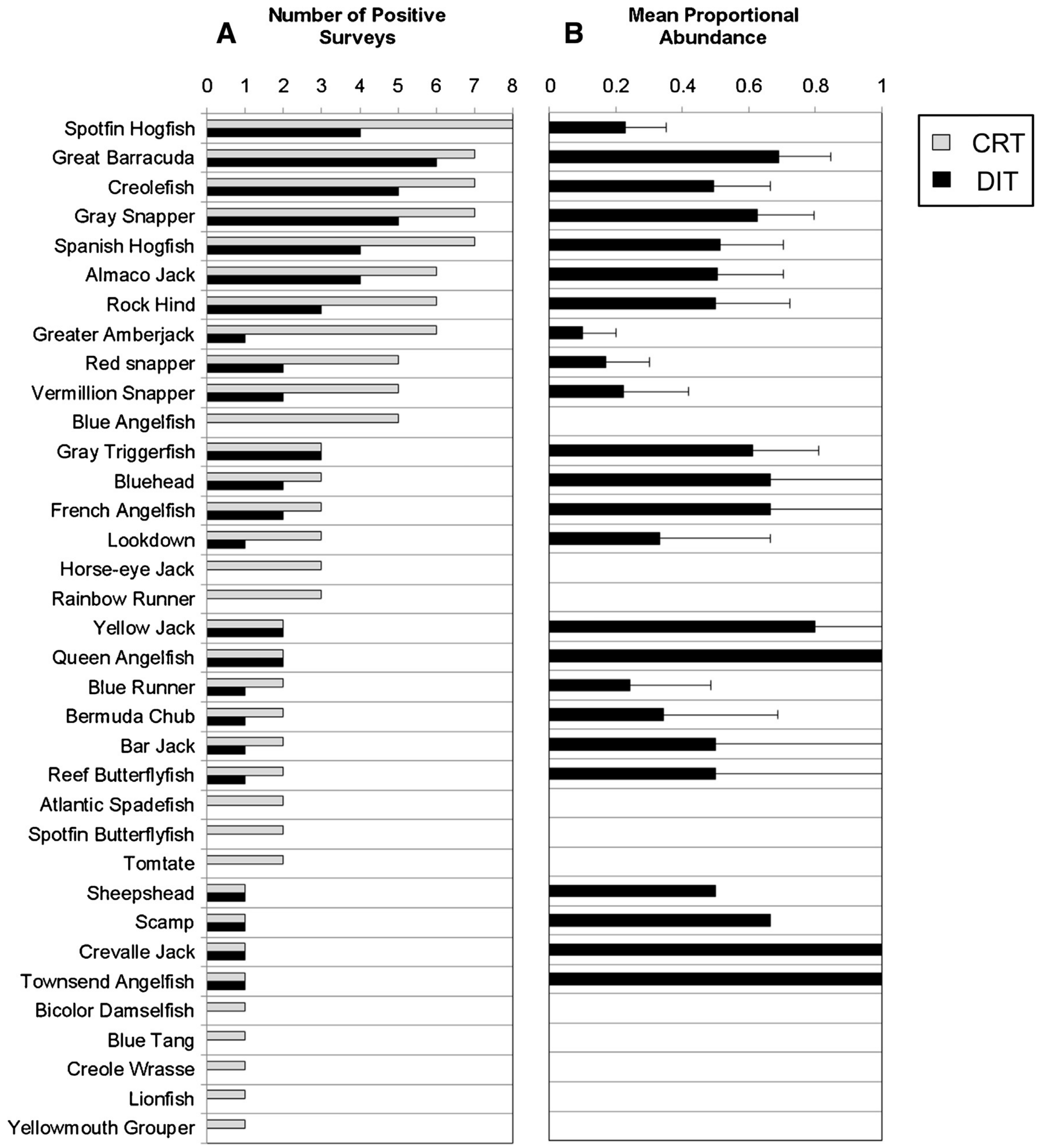

Fig. 9. Horizontal bar plots of individual species occurrence between the two survey types; continuous roving transects (CRT; gray) and depth-interval transects (DIT; black bars). Species are listed in order of occurrence on the CRT (A). (B) The average proportion of individuals seen (# seen in DIT/# seen in CRT) is shown again as black bars. Error bars represent standard errors, and are shown for the dominant species.

of obtaining video footage from the benthos of these artificial reefs, we recommend coupling ROV-surveys with additional approaches to generate indices of abundance for this species. For example, a recent study demonstrated the capacity of vertical longline gear to develop indices of abundance for Red Snapper along artificial reef complexes of the north-central Gulf of Mexico (Gregalis et al., 2012). While such approaches would certainly complement ROV surveys on western Gulf artificial reefs, they indeed target larger individuals and would not replace the utility of documenting a variety of size classes with video-based methods.

Our goal of documenting relatively conspicuous fisheries species also biased our fish community characterization on these artificial reefs. It is well known that submerged oil and gas platform reefs house several additional families of more cryptic fishes, including the Blennidae, Gobiidae, and Pomacentridae, among others (Beaver, 2002; Rooker et al., 1997; Topolski and Szedlmayer, 2004); and, we routinely observed these species on SCUBA. For a variety of logistical purposes we maintained a distance of 1–2 m away from the reef during our surveys, which consequently restricted our ability to document these more inconspicuous fishes. Future surveys that aim to quantify the composition of this more cryptic assemblage should consider designing independent ROV surveys for sampling these fishes and the use of macro-lenses. However, such surveys increase the chance of equipment damage or entanglement, and may be better performed by trained SCUBA divers.

4.2. Conclusions

Our methodology provides a non-extractive and repeatable approach to characterizing fish communities on large artificial reefs, in particular cutoff and toppled oil and gas platforms.

Although survey design and implementation will vary based on research needs and site characteristics, our work represents some of the initial attempts to quantify occurrence and distribution of fishes in these previously unassessed habitats of the south Texas continental shelf. We observed a unique set of fish species inhabiting these structures that would have been impossible to document on SCUBA or with baited longlines. Further, indices of abundance for a variety of reef fish are lacking from these artificial structures across the Gulf of Mexico, yet our methodology proved capable of providing these indices for a variety of managed species. Thus, continued monitoring of fish communities inhabiting these structures should be essential to the stock assessment process.

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