Environmental Management
https://doi.org/10.1007/s00267-022-01714-8

Characterizing the Biological Community before and after Partial Removal of an Offshore Gas Platform in the Northwestern Gulf of Mexico

Michelle A. Johnston[1] · **Marissa F. Nuttall**[2] · **Emma L. Hickerson**[1] · **Kelly O'Connell**[2] · **Raven D. Blakeway**[2] · **John A. Embesi**[2] · **Jimmy MacMillan**[2] · **Douglas Peter**[3] · **George P. Schmahl**[1]

Received: 9 October 2021 / Accepted: 29 August 2022

Abstract
High Island A-389-A (HI-A-389-A) is a gas platform situated in 125 m water within Flower Garden Banks National Marine Sanctuary in the northwestern Gulf of Mexico, and provides habitat to a diverse array of benthic organisms and fish species. Platform production ceased in 2012, beginning the decommissioning process for structural removal. Rather than complete removal of the structure, the lower portion was left intact as an artificial reef and the upper 21 m was removed. The biological communities (benthic and fish) were characterized during diver and remotely operated vehicle surveys, both before and after removal of the upper structure. The platform's benthic community, primarily categorized as fouling organisms, was mainly composed of sponges, hydroids, macroalgae, bivalves, zoanthids, and stony corals. The dominant stony coral was orange cup coral (*Tubastraea sp.*), an exotic species, while native coral species were rare. Fish species were predominantly demersal planktivores. Analyses of the benthic and fish communities documented four distinct biological zones strongly associated with depth. Significant differences in the benthic community were observed after partial removal and varied with depth, including the loss of hydroids, increase in macroalgae cover, and sponge and coral community changes. Both demersal and pelagic fish communities exhibited significant differences by depth after removal but no significant changes were observed in federally managed species. Results reflect changes in benthic and fish communities after partial removal of the platform that is likely, in part, influenced by structure removal and temporal variations.

Keywords Artificial Reef · Biological Community · Decommissioning · Flower Garden Banks National Marine Sanctuary · Gas Platform

Introduction

Globally, the interest in offshore energy resources has resulted in the development of a prominent oil and gas industry with associated structures built for hydrocarbon production (Fowler et al. 2014). Approximately 1,621 oil and gas structures are currently located in the northern Gulf of Mexico (BSEE 2022), comprising the largest complex of artificial substrates in the world (Dauterive 2000; Ajemian et al. 2015). Oil and gas platforms are required to be decommissioned once they cease production (Kaiser and Pulsipher 2005); therefore, Rigs-to-Reefs programs were created to convert oil and gas platforms to artificial reefs (Sammarco et al. 2004; Kaiser and Pulsipher 2005; Doyle et al. 2008; Claisse et al. 2014; Ajemian et al. 2015; Paxton et al. 2020). Louisiana and Texas have the largest rigs-to-reefs programs, and as of 2021, 625 oil platforms installed

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s00267-022-01714-8.

✉ Michelle A. Johnston
Michelle.A.Johnston@noaa.gov

[1] National Oceanic and Atmospheric Administration—Flower Garden Banks National Marine Sanctuary, 4700 Avenue U, Bldg. 216, Galveston, TX, USA

[2] CPC, 4700 Avenue U, Bldg. 216, Galveston, TX, USA

[3] Bureau of Safety and Environmental Enforcement, 1201 Elmwood Park Blvd., New Orleans, LA, USA

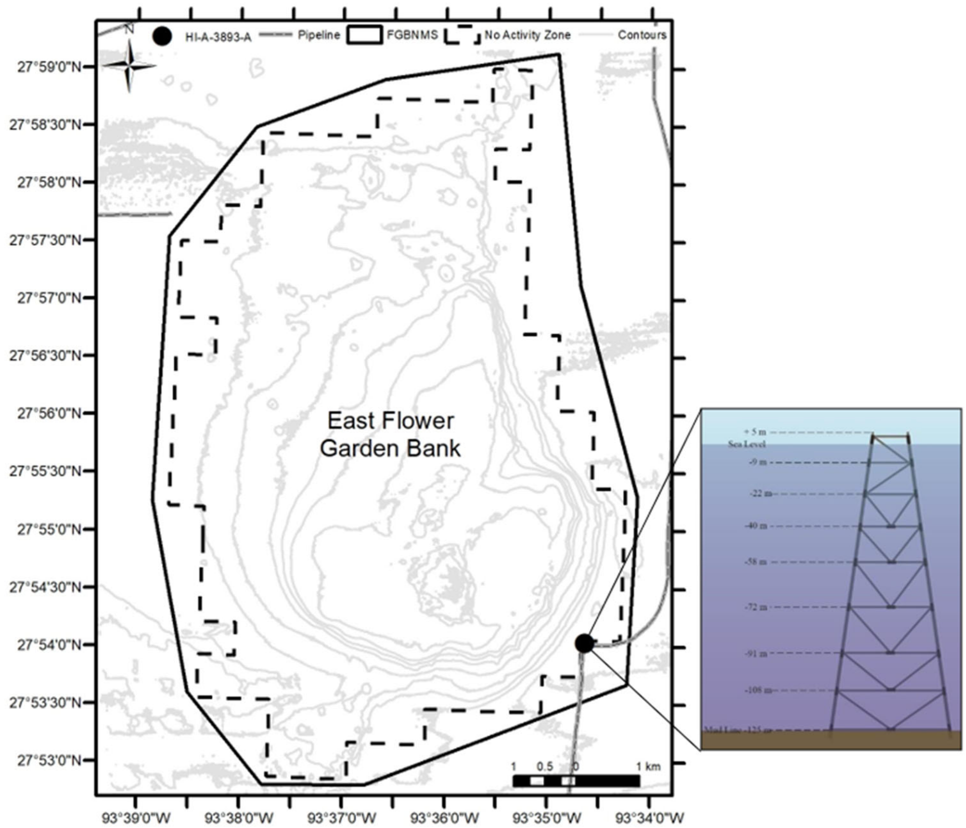

Fig. 1 HI-A-389-A and associated pipeline located inside FGBNMS boundaries, but outside of the No Activity Zone, with inset of underwater platform profile

on the U.S. Outer Continental Shelf have been reefed in the Gulf of Mexico (BSEE 2021).

Since the late 1940s, thousands of oil and gas platforms have been installed offshore in the Gulf of Mexico (Ajemian et al. 2015; Kolian et al. 2017; Dauterive 2000). One of these platforms, High Island A-389-A (termed HI-A-389-A based on the outer continental shelf area and numbered lease block naming convention), is a gas production platform with associated gas pipeline situated in 125 m water depth in the northwestern Gulf of Mexico (ONMS 2008) (Fig. 1). The platform, approximately 193 km southeast of Galveston, Texas, was installed in October 1981 within 1.6 km from the center of the coral reef cap at East Flower Garden Bank (EFGB). The platform was installed outside a “No Activity Zone” (NAZ) for oil and gas activity established by the Minerals Management Service (precursor agency to the Bureau of Ocean Energy Management) in an area that became part of Flower Garden Banks National Marine Sanctuary (FGBNMS) in 1992 (Fig. 1).

The National Oceanic and Atmospheric Administration (NOAA) marine sanctuary program serves as the trustee for a network of 17 marine protected areas authorized by the National Marine Sanctuaries Act in order to preserve the natural and cultural resources within these areas. FGBNMS was designated to protect the banks from increasing anthropogenic activities, including oil and gas extraction, anchoring, and the harvesting of fish, corals, and other invertebrates. Sanctuary regulations prohibit anchoring, most discharges, the take of any marine mammal, sea turtle, or ray, altering benthic habitat, the use of explosives, and spearfishing; however, conventional hook and line fishing is allowed. FGBNMS is best known for its coral reefs, consisting of over 50 percent living scleractinian coral cover, and associated high biomass reef fish community (Gittings 1998; Johnston et al. 2016; Gil-Agudelo et al. 2020). Upon designation in 1992, sanctuary boundaries were drawn using the outer edges of the NAZ, enclosing HI-A-389-A inside the southeast corner of the sanctuary boundary around EFGB (Fig. 1).

Since installation in 1981, a diverse array of encrusting and benthic organisms has colonized the underwater vertical and horizontal platform pilings. The platform is covered primarily with hydroids, sponges, macroalgae, bivalves, zoanthids, and a few stony coral species (Embesi et al. 2013; Kolian et al. 2017). The structure, along with its associated benthic community, attracts demersal reef fish and pelagic fish species common in the Gulf of Mexico and Caribbean region (Boland 2002). Damselfish, wrasse, grouper, jacks, and sharks regularly congregate on or near the structure (Rezak et al. 1990; Childs 2001; Boland 2002). Because of this, it has become of interest to fishers and diving communities.

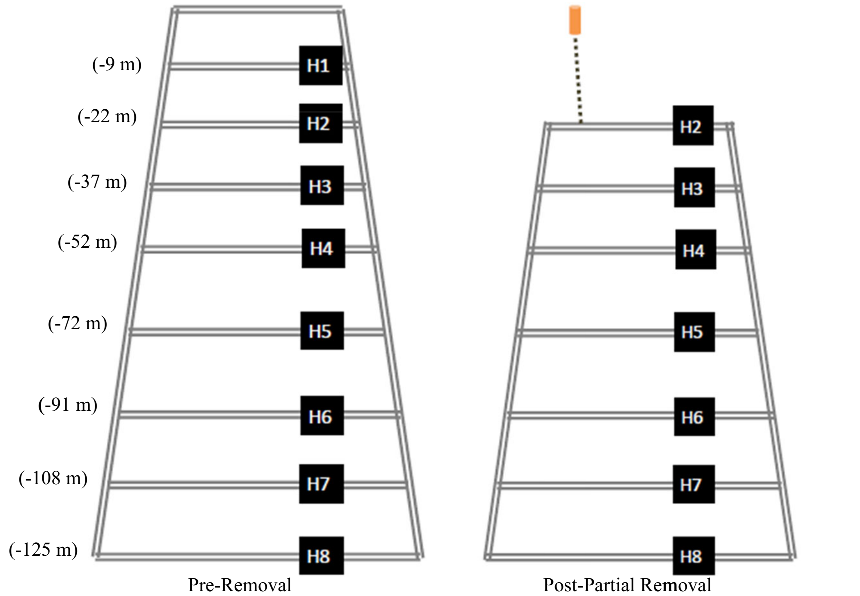

Fig. 2 HI-A-389-A platform horizontal (H) level depth delineations for pre- and post-removal surveys

HI-A-389-A produced or processed oil and natural gas from 1981 until production ceased in 2012, prompting the decommissioning process (BSEE 2020). Decommissioning regulations require complete structural removal; however, the conversion of a platform to an artificial reef can be considered and approved if certain criteria are met (30 CFR part 250, subpart Q (§250.1730)). Due to interests expressed from stakeholders in the oil and gas industry and local diving and fishing communities, NOAA and the Bureau of Safety and Environmental Enforcement (BSEE) approved a partial-removal decommissioning plan in 2018 that would allow the remaining structure to be incorporated into Texas Parks and Wildlife Department's artificial reef program. The decision was to leave the lower portion intact as an artificial reef, while the upper 21 m would be removed.

The benthic and fish communities on HI-A-389-A have been the subject of opportunistic studies due to its presence within the marine sanctuary and interest in documenting the ecological differences between the artificial and natural habitats within the EFGB boundaries (Rooker et al. 1997). Other studies in the region have addressed community change between standing platforms and those that have been toppled or reefed, and suggest that maintaining some structure is valuable for ecological function and biodiversity (Dokken et al. 2000; Sammarco et al. 2014a; Stunz and Coffey 2020). On the other hand, there is debate over the potential of artificial reefs in facilitating the movement and establishment of nonindigenous species and influence on fish communities on nearby natural habitats (Sammarco et al 2004; Broughton 2012; Sammarco et al. 2014b).

HI-A-389-A is the only gas platform situated within a U.S. national marine sanctuary in close proximity to a thriving coral reef (Johnston et al. 2016). Platform decommissioning in marine protected areas is complex and requires an understanding of environmental consequences that may ensue in response to removal of any or all of the structure (Burdon et al. 2018). This study used a before-after experimental design and included survey methods appropriate for collecting benthic and fish data from the surface to the seafloor (125 m). This study lacked a control; thus, causality cannot be deduced. However, the experimental study design presents an opportunity to explore observed quantitative changes in the biological communities that may represent ecological responses of structure removal. We hypothesized that benthic and fish communities would shift with the change in habitat structure in shallower depths, but would remain unchanged in deeper depths where habitat remained stable. To our knowledge, this is the first study within a marine protected area documenting observed differences in biological communities after removal of a production platform. Results of this study contributes to literature evaluating environmental consequences of platform decommissioning that may inform future decisions about converting structures in the region to artificial reefs.

Methods

Study Site Description

HI-A-389-A (27°54.02´N, 93°34.38´W; Fig. 1) consists of eight primary support legs with horizontal and diagonal support members (Fig. 2). The deck and upper 21 m of the platform were removed in July 2018 after almost 37 years. Mechanical severance techniques were utilized for removal.

Study Design

This study was conducted using a before-after experimental design by which fish and benthic community structure were analyzed for differences associated with partial removal of the production platform via scuba and remotely operated vehicle (ROV) surveys. Field operations were conducted off NOAA's *R/V Manta* through multiple expeditions in consecutive years separated by survey technique. Quantitative measures of benthic organisms (i.e., percent cover) and fish (e.g., abundance, diversity) were collected in July 2015 and July 2017 before the partial removal of the platform and after post-removal in June, October, and September of 2019. Logistical challenges associated with the remoteness of the study location (i.e., 120 miles offshore), limited space on the research vessel, equipment availability, and ambient weather conditions constrained the ability to conduct multiple survey techniques (i.e., scuba and ROV) on a single research expedition.

The platform was divided into horizontal (H) sections delineated by depth for analyses (Fig. 2). Prior to partial removal, HI-A-389-A consisted of eight horizontal sections (H1-H8) and following removal, seven sections remained (H2-H8) (Fig. 2).

Data Collection

Benthic transects

Photographic benthic transects were conducted by scuba divers down to 40 m water depth, while a ROV was used to complete transects from 9 m to 125 m depth. ROV (July 2015) transects were conducted on eight horizontal sections of the platform (H1-H8) and scuba (July 2017) transects were conducted on three horizontal sections of the platform (H1-H3) prior to partial removal. After partial-removal in July 2018, scuba (June and October 2019) transects were completed on H2 and H3 and ROV transects (September 2019) were completed within H2-H7 (Fig. 2). During post removal surveys, H8 was not surveyed due to strong currents and low visibility at depth.

Random photographic transects via scuba Non-overlapping photographs were taken along a 15 m transect on the top, bottom, and each side of horizontal beams (H1-H3) where the starting point was randomly generated using the RAND function in Microsoft Excel© (Table S1 and Fig. S1). Photographs were taken perpendicular to the structure at pre-marked 80 cm intervals along the measuring tape, producing 16 images covering 0.25 m^2 of the substrate, resulting in 4 m^2 transects. In total, 39 random transects were completed during pre-removal surveys from H1-H3 ($n = 624$ images) and 35 during post-removal surveys on H2 and H3 ($n = 560$ images). A Canon Power Shot® G11 digital camera in an Ikelite® housing with standard port, mounted on a 0.625-m T-frame and two Inon® Z240 strobes was used to capture photographs by scuba divers along random benthic transects (Fig. S2).

Repetitive transect via ROV Repetitive benthic transects were conducted along horizontal beams (H1-H8), where non-overlapping photographs were taken every 5 m. Transects using a forward-looking camera mounted onto the ROV occurred approximately 1.5 m from the structure on the external side of horizontal beams to avoid ROV entanglement and began and ended at each corner. The length of horizontal beams increased with depth, thus the number of photographs on the transect also increased. In total, 41 transects were completed pre-removal ($n = 598$ images) from H1-H8 and 24 transects were completed post-removal ($n = 561$ images) from H2-H7. A SubAtlantic 18 ROV Mohawk, maintained and operated by the University of North Carolina Wilmington—Underwater Vehicle Program, was equipped with an Insite Pacific Mini Zeus II high definition (HD) video camera with two Deep Sea Power & Light 3100 Light-emitting diode (LED) lights and two parallel Sidus SS501 50 mW green spot lasers set at 10 cm for scale. The ROV was equipped with a Kongsberg Maritime OE14-408 10 MP digital still camera with OE11-442 strobe and two parallel spot lasers set at 10 cm visible in the still camera frame for scale.

Percent cover

Photographs were reviewed, where poor quality images were removed from processing due to an inability to accurately identify organisms. Each image was analyzed using Coral Point Count with Microsoft® Excel® extensions (CPCe) version 4.1 with a customized CPCe code file specific to the benthic organisms (sessile and motile) on HI-A-389-A. ROV photographs were cropped to 50 × 50 cm in ImageJ® using the 10 cm green spot lasers for scale, to standardize the area of each image to 0.25 m^2, consistent with photographs taken via scuba. Using the random point generator function in CPCe, images were overlaid with 25 spatially random points for species identification (Aronson et al. 1994; Kohler and Gill 2006). Organisms positioned beneath each random point were identified to the lowest possible taxonomic level.

Cover was categorized into: fire corals, hydroids, octocorals, black corals, stony corals, erect sponges, encrusting sponges, macroalgae (i.e., thick algal turfs covering underlying substrate and algae longer than approximately 3 mm), bivalves, barnacles, bare substrate, motile organisms (e.g. fish, urchins), sessile invertebrates (e.g. anemones, tunicates, zoanthids), and non-data points (e.g., tape measures, shadows, water column). Non-data points were excluded from further analyses. Mean percent cover was determined by averaging all transects per horizontal level. Results were presented as mean percent cover ± standard error (SE).

Roving fish surveys

Roving fish surveys were standardized to 10 min and conducted at each horizontal level including the horizontal, vertical, and diagonal supports (Fig. 1). The standard Roving Diver Technique (RDT) (Schmitt and Sullivan 1996), whereby a diver swims freely throughout the dive area recording every fish observed and approximate abundance (single [1], few [2–10], many [11–100], and abundant [>100]), was modified to address the unique area of the platform. Fish surveys were restricted to the same horizontal level with the ceiling limit one meter below the next upper level. Fish observed on support beams were counted in surveys of the respective horizontal level. Herein, this method will be referred to as a modified RDT survey.

Fish surveys were conducted via scuba divers from H1-H3, while the ROV was used to complete surveys from H1-H8. Surveys were non-repeating and designed to cover the whole area of each level. Poor visibility and strong currents did not allow for the completion of ROV fish surveys on H8 during post-removal data collection.

Thirty-three surveys were conducted pre-removal in 2017 and 18 were completed post-removal in 2019. Post-removal surveys were conducted in the water column at 9 m to provide a comparative dataset for the pre-removal H1 depth. Surveys were conducted randomly throughout the day, from dawn to dusk (0700–1800), to reduce diurnal effects of fish species observed.

Environmental data

Daily sea surface temperature (SST) and sea surface salinity (SSS) data were downloaded from the NOAA Environmental Research Division Data Access Program (ERDDAP) data server for the study period (2015–2019) from the HI-A-389-A location. Satellite-derived one-day mean SST data were available as a level-4 global 0.01-degree grid produced at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center under support by the NASA MEaSUREs program. Satellite derived SSS data were available as a level-3 gridded three-day mean dataset from the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) satellite observations over the global ocean.

Statistical analysis

Benthic transects

Bray-Curtis similarity resemblance matrices used square root transformed percent cover data from benthic groups identified in CPCe. Permutational multivariate analysis of variance (PERMANOVA) was used to test for benthic community differences and estimate components of variation between horizontal depth levels and removal status (i.e. pre- and post-removal) (Anderson et al. 2008). There were no significant differences by survey type (scuba and ROV), thus data were pooled for analyses. No comparative analyses were completed for H8, as no post-removal surveys were conducted on this level due to inclement environmental conditions. When significant differences were detected, similarity percentages (SIMPER) were used to assess the percent contribution of dissimilarity between groups (Clarke et al. 2014). Primary group means by depth were visualized using metric multi-dimensional scaling plots (mMDS), based on Bray-Curtis distance matrices (Anderson et al. 2008; Clarke et al. 2014). Cluster analyses for horizontal levels were performed on Bray-Curtis distance matrices with Similarity Profiles (SIMPROF) analysis to identify significant ($\alpha = 0.05$) clusters within the data (Clarke et al. 2014).

Roving fish surveys

Species were classified into four primary trophic guilds, herbivores (H), piscivores (P), invertivores (I), and planktivores (PL), based on information provided from FishBase (Froese and Pauly 2019), and as demersal or pelagic species (Robins and Ray 1986; Felder and Camp 2009; Humann and Deloach 2014; Froese and Pauly 2019). Semi-abundance metrics (density index [DI], on a scale from one to four, and percent sighting frequency [%SF]) were assigned to each species observed on surveys following methods described in REEF (2019). Shade plots were used to visually compare changes in fish community pre- and post-partial removal using untransformed DI*%SF data. These plots were limited to the 20 most important species using type III SIMPROF.

PERMANOVA was used to examine significant differences in fish community composition between survey type (two fixed levels: ROV and diver), level (eight fixed levels: H1-H8), and removal status (two fixed levels: pre- and post-partial removal). PERMANOVA was performed using a modified Gower (log10) resemblance matrix with Type III sum of squares and 9999 permutations under a reduced model. Where the main test found significant differences, pairwise tests were performed.

Federally managed Gulf of Mexico reef fish, as listed in NOAA's Fisheries Federally Managed Gulf of Mexico Reef Fish (NOAA 2022), were examined for changes in abundance as these species are of particular interest in fisheries management. However, as species observations varied in number, a modified percent coefficient of variation (CV%) was calculated to determine if there was sufficient power to statistically analyze the data (CV < 20%) and reduce type I

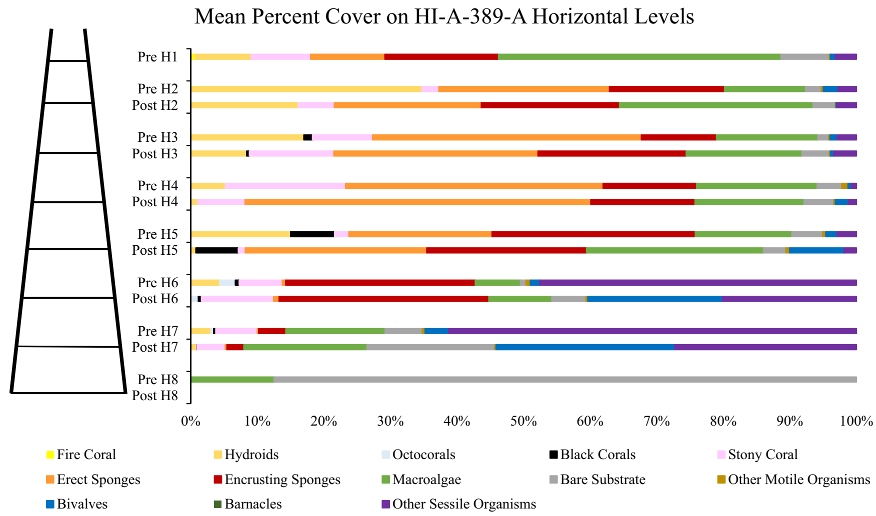

Fig. 3 Percent composition of cover groups per horizontal level (H1-H8) from pre- and post-removal surveys. The platform outline corresponds to the following depths: H1 (−9 m), H2 (−22 m), H3 (−37 m), H4 (−52 m), H5 (−72 m), H6 (−91 m), H7 (−108 m), and H8 (−125 m). No post-removal surveys were conducted on H8

errors. Modified CV% was calculated where SE = standard error and $\bar{\bar{X}}$ = mean of weighted abundance categories:

$$CV\% = SE/\overline{X}$$

If CV < 20%, PERMANOVA was used to examine differences in species abundance by level (eight fixed levels: H1-H8) and removal status (two fixed levels: pre- and post-partial removal). PERMANOVA was performed using a modified Gower (log10) resemblance matrix with Type III sum of squares and 9999 permutations under a reduced model. Where the main test found significant differences, pairwise tests were performed.

Abundance was summed across trophic guilds for each survey to examine changes in trophic structure. PERMANOVA was used to test for differences in trophic abundance by level (eight fixed levels: H1 - H8) and removal status (two fixed levels: pre- and post-partial removal). PERMANOVA was performed using a modified Gower (log10) resemblance matrix with Type III sum of squares and 9999 permutations under a reduced model. Where the main test found significant differences, pairwise tests were performed.

All nonparametric benthic and fish analyses for non-normal data were conducted in Primer® version 7.0 with PERMANOVA extensions (Anderson et al. 2008; Clarke et al. 2014).

Environmental data

Monotonic trends of SST and SSS were analyzed using the Seasonal-Kendall trend test for averaged monthly SST and SSS data in a Microsoft Windows® DOS executable program developed by USGS for water resource data, accounting for serial correlation in repeating seasonal patterns (Hipel and McLeod 1994; Helsel and Hirsch 2002; Helsel et al. 2006).

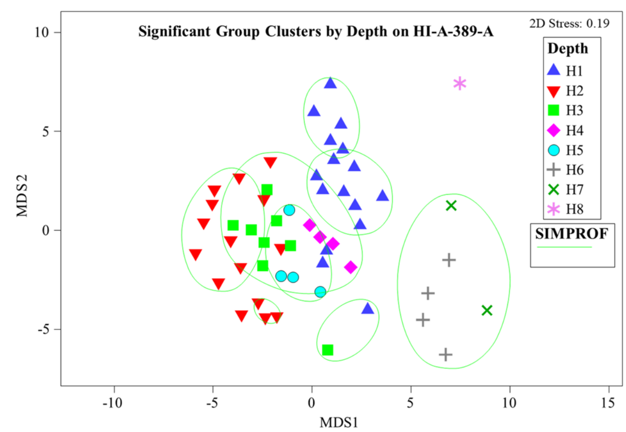

Fig. 4 MDS plot of significant group clusters by horizontal level depth on HI-A-389-A from pre-removal surveys. The ovals are SIMPROF groups representing significant clusters

Results

Benthic composition differed significantly with depth (PERMANOVA, df = 7, $p = 0.001$; Fig. 3; Table S2), reflecting distinct biological zonation (Fig. 4). Four zones were distinguished by significant clusters of horizontal levels including H1, H2-H5, H6-H7, and H8 (Fig. 5). SIMPER analysis identified that, on average, the primary contributor to clustering of H1 was macroalgae, H2-H5 erect and encrusting sponges, H6-H7 other sessile invertebrates (predominantly zoanthids), and H8 bare substrate (Fig. 5). Scleractinian corals were found on levels H1- to H7, but were most abundant on H4. Corals were identified to species to further examine differences in mean percent cover by level. *Tubastrea* sp. was the dominant stony coral on H1-H5, and was highest on H4 at 17.98% ± 3.77 (Fig. 3). Few native species, including *Madracis* sp. (0.24% ± 18, H1-H3) and *Pseudodiploria strigosa* (0.02% ± 02, H1 only), were detected on the structure.

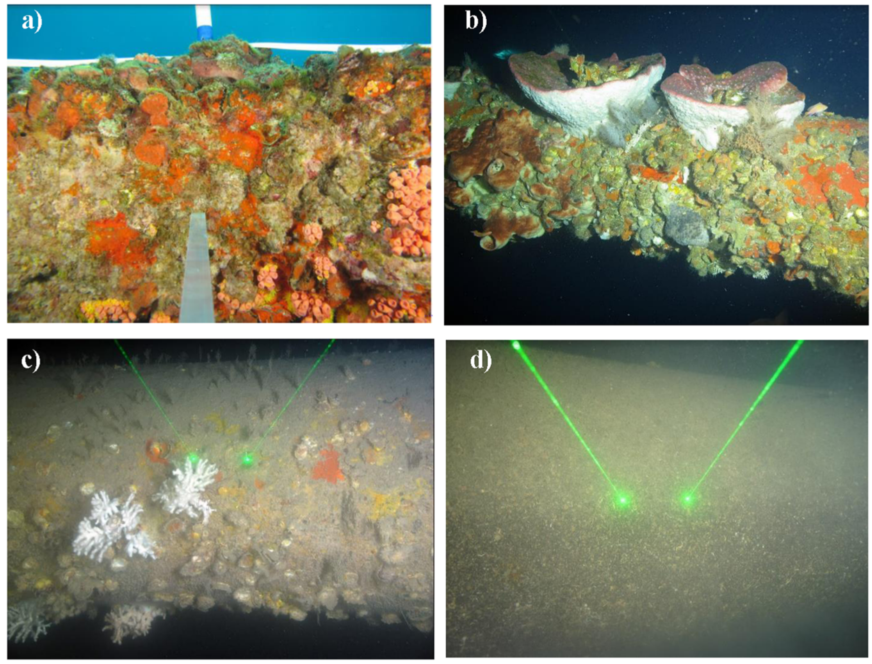

Fig. 5 Select images highlighting benthic communities from distinct community zones by horizontal level on HI-A-389-A including (**a**) high prevalence of turf algae and *Tubastrea* sp. colonies on H1 (−9 m), erect and encrusting sponges on H5 (−72 m), zoanthids on H7 (−108 m), and bare substrate on H8 (−125 m)

Native corals represented 27% of the stony coral cover observed on the platform, while 73% were *Tubastraea* sp. Other sessile invertebrates dominated the lower levels of the platform (H6-H7), chiefly through the increased presence of zoanthids on H6 (47.29% ± 10.69) and H7 (61.05% ± 38.01).

Significant changes in the benthic community were observed post-partial removal of the platform (PERMANOVA, df = 1, $p = 0.003$), with the loss of hydroids being the main contributor to these differences (SIMPER, 15%; Table S1). Hydroids were observed from H1-H7 pre-removal, ranging in mean percent cover 3–35%. In post-partial removal surveys, hydroid cover significantly decreased (PERMANOVA, df = 1, $p = 0.002$), with the greatest change occurring on H2 (19% loss; Fig. 3). Pairwise comparisons detected significant differences in the benthic community on H2-H5, but not H6 and H7 (Table 1), suggesting changes occurred in the benthic community from H5 upward.

Fish diversity was significantly higher in scuba surveys from H-H3 than ROV surveys for the same levels ($p < 0.001$, $F = 28.176$); therefore, survey methods for fish data were analyzed independently. Seventy fish species (or species complex, e.g., Goby spp.), spanning 23 families, were observed from H1-H3 in scuba surveys, including seven federally managed species. In ROV surveys, 101 fish species or species complex, spanning 33 families, were observed from H1-H7, twelve of which were managed species.

Differences were observed in demersal and pelagic fish communities in scuba surveys, with a significant interaction between removal status and platform level. Independent analysis by level showed significant differences in the demersal and pelagic communities pre- and post-partial removal at all levels, with the exception of pelagic species on H2 (Fig. 6; Table 2). After removal of H1, no demersal species were observed in the water column and pelagic species composition changed (Fig. 6); however, there was no apparent movement of species from H1 to the remaining levels. Federally managed species were observed in low abundances on H2 and H3 both pre- and post-partial removal, and because the CV > 20% for all species, no further statistical analyses were performed (Fig. 6).

Table 1 PERMANOVA pairwise test results for significant differences between pre- and post-removal surveys from H2 to H7 at HI-A-389-A

Groups	*t*	Unique perms	*P* (perm)
H2 - Pre, Post	3.1979	999	**0.001**
H3 - Pre, Post	1.7717	997	**0.022**
H4 - Pre, Post	1.7559	35	**0.032**
H5 - Pre, Post	1.9906	35	**0.033**
H6 - Pre, Post	1.6276	35	0.073
H7 - Pre, Post	1.4465	10	0.191

Bold text denotes significant value

Demersal and pelagic fish communities differed by removal status and level in ROV surveys, with a significant interaction between removal status and platform level. Independent analysis by level showed significant differences in the demersal community pre- and post-partial removal on all levels except H6. In contrast, pelagic communities were similar pre- and post-partial removal on most

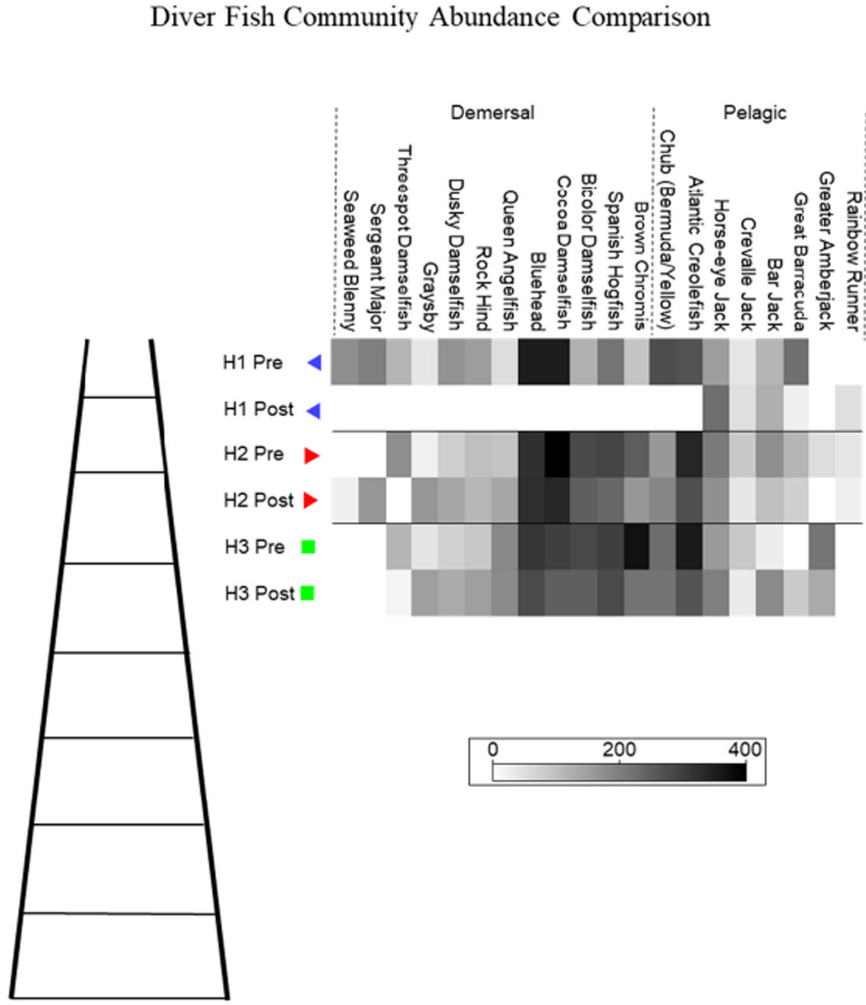

Fig. 6 Comparison of diver fish community DI*%SF shade plot, limited to 20 species. Shade represents DI*%SF value. Post-removal surveys for H1 were completed by divers mid-water at 9 m. The upper three horizontal beam platform outline corresponds to the following depths: H1 (−9 m), H2 (−22 m), H3 (−37 m)

levels, apart from H2 and H5 (Table 2). The ROV shade plots consisted of 75% demersal and 25% pelagic species (Fig. 7). There was no significant shift of species from H1 to lower levels post-partial removal; however, Atlantic creolefish (*Paranthias furcifer*), were slightly more abundant on levels H2 and H3. Several demersal species that were present in pre-removal surveys were absent post-partial removal on H2 and H3, including Brown Chromis (*Chromis multilineata*) and Sharpnose Puffer (Canthigaster rostrata) (Fig. 7). The fish community was largely different between pre- and post-partial removal surveys on H7. No comparative ROV surveys were conducted on H1. Federally managed Greater Amberjack (*Seriola dumerili*) and Scamp (*Mycteroperca phenax*) abundance varied between levels ($p = 0.002$, $F = 4.040$ and $p < 0.001$, $F = 6.116$, respectively), with the greatest abundance of both species on H4 and H5 (Fig. 8). Red snapper (*Lutjanus campechanus*) abundance increased with depth but was not statistically tested as CV > 20% (Fig. 8).

In ROV surveys, planktivores were most prevalent, accounting for 29–68% of the DI on all levels both pre- and post-partial removal (Fig. 9). However, trophic structure was significantly different between level and removal status, with a significant interaction (pseudo-$F = 14.01$ and $p > 0.001$, pseudo-$F = 3.72$ and $p = 0.014$, and pseudo-$F = 2.71$ and $p > 0.001$, respectively). Independent analysis by level showed differences in trophic structure pre- and post-partial removal, with a few exceptions. Following partial removal of the platform, herbivore DI declined on H4 but increased on H5, piscivore DI declined on H4, and invertivores declined on H5.

SST displayed clear seasonality, with warmer temperatures in the summer and fall months (mean 28.82 °C, June-November) and cooler temperatures in the winter and spring months (mean 23.23 °C, December-May) during the study period. SSS was lower in summer and fall months (34.47 psu) and higher in winter and spring months (35.24 psu). For time-series mean SST and SSS data, the Seasonal-Kendall trend test did not reveal any significant monotonic trends from 2015 to 2019 in the water surrounding HI-A-389-A after adjusting for correlation among seasons.

Table 2 PERMANOVA results for significant differences in community composition between horizontal level and removal status from SCUBA and ROV surveys

Variable	Test	SCUBA							ROV						
Demersal	Two-way	Source	df	SS	MS	Pseudo-F	P(per m)	perms	Source	df	SS	MS	Pseudo-F	P(per m)	perms
		Level	**2**	**3**	**2**	**6.36**	**>0.001**	**9912**	**Level**	**7**	**12**	**2**	**5.91**	**>0.001**	**9837**
		Removal Status	**1**	**3**	**3**	**10.75**	**>0.001**	**9921**	**Removal Status**	**1**	**2**	**2**	**5.28**	**>0.001**	**9890**
		Level x Removal Status	**2**	**3**	**1**	**5.25**	**>0.001**	**9909**	**Level x Removal Status**	**5**	**4**	**1**	**2.60**	**1**	**0**
		Res	45	12	0				Res	**59**	**18**	**0**			
		Total	50	20					Total	72	37				
	One-way (removal Status)	Horizontal	df	SS	MS	Pseudo-F	P(per m)	perms	Horizontal	df	SS	MS	Pseudo-F	P(per m)	perms
		Level 1	**1**	**4**	**4**	**19.08**	**0.001**	**1083**							
		Level 2	**1**	**1**	**1**	**3.87**	**>0.001**	**9676**	**Level 2**	**1**	**1**	**1**	**5.14**	**0.006**	**165**
		Level 3	**1**	**0**	**0**	**1.66**	**0.019**	**1706**	**Level 3**	**1**	**1**	**1**	**2.31**	**0.006**	**165**
									Level 4	**1**	**1**	**1**	**2.76**	**0.024**	**120**
									Level 5	**1**	**1**	**1**	**5.33**	**0.012**	**84**
									Level 6	1	1	1	2.1	0.076	120
									Level 7	**1**	**1**	**1**	**1.79**	**0.039**	**56**
Pelagic	Two-way	Source	df	SS	MS	Pseudo-F	P(per m)	perms	Source	df	SS	MS	Pseudo-F	P(per m)	perms
		Level	**2**	**1.71**	**0.85**	**3.29**	**>0.001**	**9912**	**Level**	**7**	**11.62**	**1.66**	**6.71**	**>0.001**	**9899**
		Removal Status	**1**	**1.31**	**1.31**	**5.08**	**>0.001**	**9929**	**Removal Status**	**1**	**0.98**	**0.98**	**3.96**	**0.001**	**9927**
		Level x Removal Status	**2**	**1.60**	**0.80**	**3.09**	**0.001**	**9921**	**Level x Removal Status**	**5**	**2.96**	**0.59**	**2.39**	**>0.001**	**9892**
		Res	45	11.65	0.26				Res	59	14.59	0.225			
		Total	50	16.25					Total	72	30.90				
	One-way (removal Status)	Horizontal	df	SS	MS	Pseudo-F	P(per m)	perms	Horizontal	df	SS	MS	Pseudo-F	P(per m)	perms
		Level 1	**1**	**2**	**2**	**8.12**	**0.001**	**2345**							
		Level 2	1	1	1	1.82	0.086	9711	**Level 2**	**1**	**1**	**1**	**4.20**	**0.013**	**165**
		Level 3	**1**	**1**	**1**	**1.84**	**0.045**	**1711**	Level 3	1	0	0	1.56	0.163	165
									Level 4	1	1	1	2.32	0.10	120
									Level 5	**1**	**1**	**1**	**6.24**	**0.012**	**84**
									Level 6	1	0	0	1.4	0.182	120
									Level 7	1	0	0	1.70	0.178	26

Bold denotes significant values

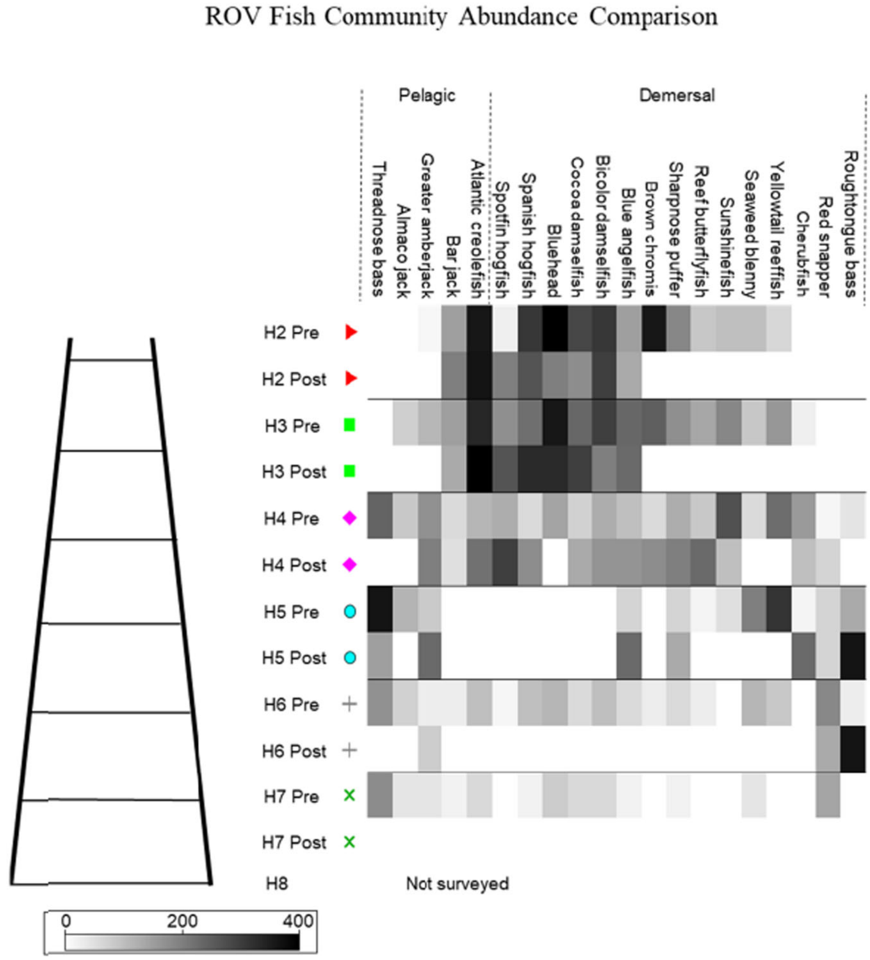

Fig. 7 Comparison of ROV fish community DI*%SF shade plot, limited to 20 species. Shade represents DI*%SF value. The platform outline corresponds to the following depths: H2 (−22 m), H3 (−37 m), H4 (−52 m), H5 (−72 m), H6 (−91 m), H7 (−108 m), and H8 (−125 m). No pre- or post-removal surveys were conducted on H8

Discussion

The present study documented changes in biological communities on a gas platform, located within the boundaries of FGBNMS, before and after the removal of the upper portion of the structure. The submerged infrastructure of the platform provided substrate upon which organisms could settle, grow, and congregate for over 37 years, while the working deck, top sections, and well conductors acted as a shade structure prior to their removal. The benthic community associated with the shallowest segment of the platform (H1) was distinct and partial removal eliminated those species, as the sessile organisms were unable to abandon the platform during removal. While significant changes in the demersal fish community were observed, the data did not indicate a large-scale movement to lower depth tiers (>H2).

A combination of factors likely contributed to the community changes observed following the partial removal of the platform. Although partial removal cannot be justified as a single causality for observed changes, it is arguably a major contributor to the differences detected in the benthic and fish communities. In effect, an entire habitat was removed from the upper 21 m of the water column, where a shift in the fish community (particularly the loss of demersal species) and a complete loss in the benthic community was expected. It is unknown whether fish species simply migrated deeper on the structure or emigrated to a new location/habitat; however, data collected indicates that there was little or no downward movement of fish species after partial removal. In combination with the partial removal of the structure, several factors likely contributed to fish and benthic community changes, such as seasonality, inter-annual variability, and food availability, though not all these factors were measured in this study as drivers of observed change (Stanley and Wilson 1997; Daigle et al. 2013).

Much scientific debate has also centered on comparisons of benthic and fish communities on artificial and natural reefs (Rooker et al. 1997; Thanner et al. 2006; Burt et al. 2011; Sammarco et al. 2012; Ajemnian et al. 2015). Despite seasonal variations and changing climate in the north-western Gulf of Mexico, the benthic community of the natural reef of the nearby EFGB changed little over time (i.e., 30 years) (Johnston et al. 2016, 2021). Mean coral cover at EFGB is approximately 50% and dominated by

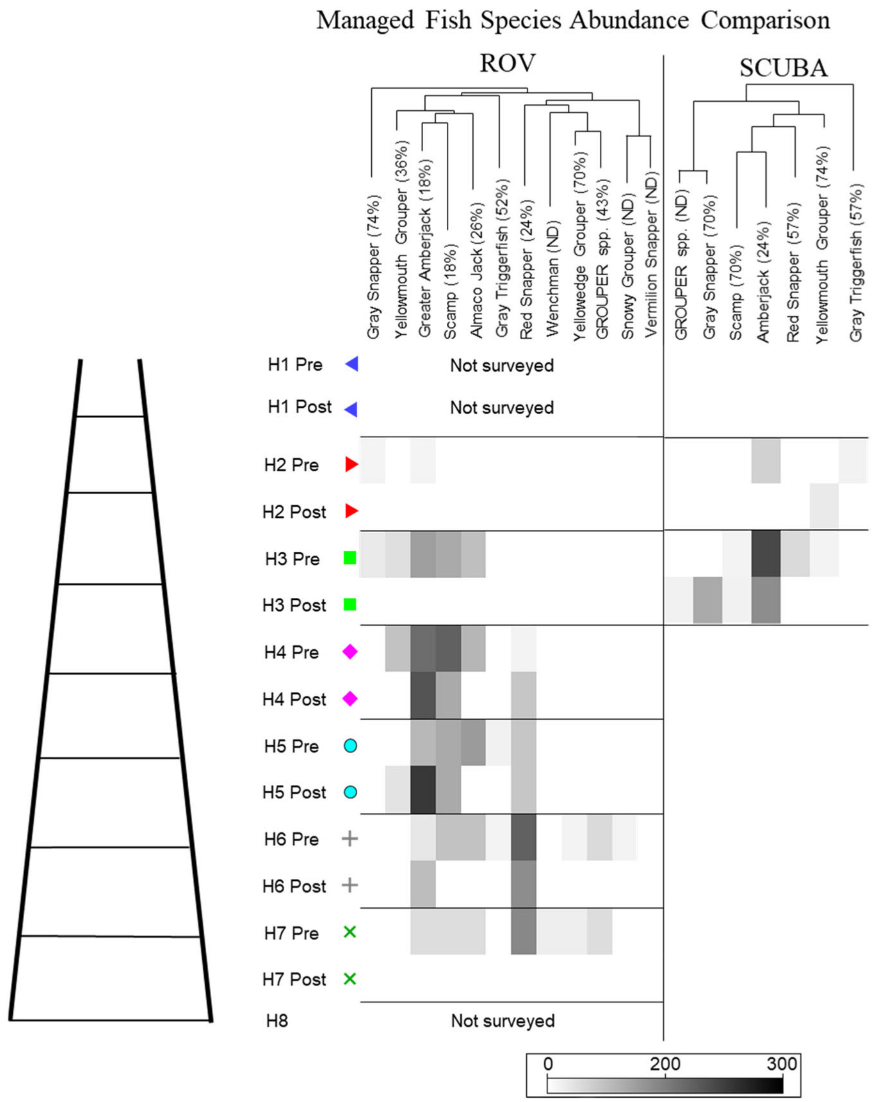

Fig. 8 Comparison of DI*%SF of federally managed Gulf of Mexico reef fishes from ROV and scuba surveys. Shade represents DI*%SF value. Values in parenthesis represent CV%. The platform outline corresponds to the following depths: H1 (−9 m), H2 (−22 m), H3 (−37 m), H4 (−52 m), H5 (−72 m), H6 (−91 m), H7 (−108 m), and H8 (−125 m). 125 m). No post-removal surveys were conducted on H8

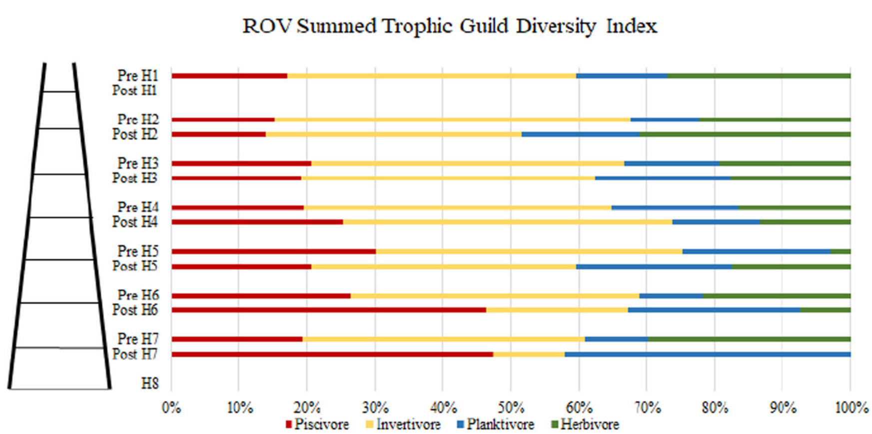

Fig. 9 Pre- and post-removal ROV summed trophic guild density index (DI) on horizontal levels H1-H8. The platform outline correspond to the following depths: H1 (−9 m), H2 (−22 m), H3 (−37 m), H4 (−52 m), H5 (−72 m), H6 (−91 m), H7 (−108 m), and H8 (−125 m). No pre- or post-removal surveys were conducted on H8

Orbicella franksi, *P. strigosa*, *Porites astreoides*, and *Montastraea cavernosa* (Johnston et al. 2021). The dominant coral on the platform, *Tubastraea* sp., is rare but present on the natural reef (ONMS 2008). *Tubastraea coccinea* is an ahermatypic cup coral native to the Indo-Pacific but is known to be exotic in the Gulf of Mexico (Fenner and Banks 2004; Precht et al. 2014). Two additional *Tubastrea* species have more recently been reported in the Gulf of

Mexico (Sammarco et al. 2014b; Figueroa et al. 2019), but species identification is difficult from pictures alone. *Tubastraea* sp. is the most abundant stony coral on artificial substrates within the Gulf of Mexico and hundreds to thousands of colonies can be found on a single platform (Fenner 2001; Sammarco et al. 2012), but it is not well-known what impact removing a portion of the structure can have on these communities. Sammarco et al. (2014b) found significantly higher densities of *Tubastraea* sp. on a toppled platform, compared to a standing production platform. Results from the present study cannot be directly compared, as coral densities were not measured; however, both studies reported abundant *Tubastraea* sp. above 50 m (Sammarco et al. 2014b), as *Tubastraea* sp. grow well on artificial substrates and in disturbed habitats (Byers 2002; Sheehy and Vik 2010).

Sponge and algal abundance have been found to be negatively correlated; as algal cover increases, a corresponding decrease in sponge cover is observed (Cárdenas et al. 2012). This relationship proved true for macroalgae and sponge (erect and encrusting) percent cover on the upper three levels of HI-A-389-A following removal (H2-H4); however, it did not occur on the deeper levels of the structure. Percent cover of macroalgae increased on all levels except H4 after the top portion of the platform was removed and sponge (erect and encrusting) cover decreased on H2-H3, but not H4. Concurrently, hydroid cover decreased on all horizontal levels. The percent cover of macroalgae and hydroids was inversely related; where hydroid cover decreased, macroalgae cover increased. The loss in the hydroid community may be attributed to factors related to light exposure. While observations of light availability were not directly measured, the removal of the working deck (which served as shade structure) greatly impacted light availability and increased light exposure throughout the platform. Many species of hydroids are sensitive to ultraviolet light, and exposure can prevent colony growth or degeneration (Gili and Hughes 1996). Additionally, light can reduce settlement of negatively phototactic hydroid larvae. In general, hydroids are less abundant in well-lit environments where competition with algae for the substratum is greatest. It is not known whether this is an effect of direct competition or an evolved avoidance trait in hydroids (Gili and Hughes 1996); however, the generalized assumption is that as hydroid cover declines, it likely opens space that becomes colonized by macroalgae, which is supported by this analysis.

Percent cover of other sessile invertebrates (anemones, bryozoans, tubeworms, tunicates, and zoanthids) was highest below 91 m, with the greatest percent cover on H6 and H7. Zoanthids accounted for the greatest decrease in percent cover post-removal, with nearly a 30% decrease in cover on H6 and H7. The other four groups in this category had low percent cover pre- and post-removal, which suggests they are not significant components of the biotic composition of HI-A-389-A. For example, bryozoans are common on offshore platforms in the northern Gulf of Mexico, but often exhibit a patchy distribution and are subject to considerable dieback in warmer months (Gallaway and Lewbel 1982), which may have occurred in our study, as data were collected during July 2017 and June and September 2019.

Similar to earlier studies of this platform (Rooker et al. 1997) and other artificial reef structures in the Gulf of Mexico (Ajemian et al. 2015), the fish community varied with depth. While the partial removal of the platform impacted both the demersal and pelagic fish community on H1 due to the sudden loss of habitat and structural complexity, overall variations in the fish community on deeper levels pre- and post- removal were likely a result of interannual, seasonal, or diurnal changes (Luecke and Wurtsbaugh 1993; Barker and Cowan 2018). Neither Ajemian et al. (2015) or Claisse et al. (2015) observed significant differences in the fish communities or biomass of standing (intact) versus cut-off (partial removal) platforms and significant temporal variation has been previously documented on this platform (Rooker et al. 1997) and in fish communities on nearby natural banks within the sanctuary (Wetmore et al. 2020; Johnston et al. 2018, 2021). While the trophic structure of the fish community changed after the partial removal of the platform, planktivores were the predominant species in all surveys. At the nearby natural reefs within the sanctuary, piscivores predominate trophic abundance (Johnston et al. 2021) and the abundance of planktivores at the platform highlights this community's connection to the pelagic environment. It should be noted that fish surveys were taken throughout the day, but night surveys were not conducted due to diver safety and ROV entanglement precautions. Therefore, day versus night fish behavior and movement among the platform levels were not captured in this study.

While SST and SSS were not notably different over time, clear seasonality was observed within surface waters surrounding HI-A-389-A, typical to what has been observed at EFGB during annual monitoring (Johnston et al. 2021). Despite seasonal variation, sea surface temperature and salinity data were within the accepted limits for coral reefs located in the Western Atlantic Ocean (Johnston et al. 2021; Coles and Jokiel 1992), and therefore not considered significant drivers of change associated with the benthic and fish communities on the upper levels of the structure. It should be noted that salinity and temperature data were not available at depth.

Two different survey methods (scuba divers and ROV) were employed in this study to characterize the fish community of HI-A-389-A. While the associated sounds and visuals of both these survey methods, resulting in gear attraction or avoidance, have been known to alter fish behavior (Dickens et al. 2011; Sward et al. 2019; Wetz et al. 2020), these were the methods available and most appropriate for data collection for this study. Scuba diver-based surveys allowed for detailed observation of the platform, with divers able to swim within the structure and make closer observations of the fish community, but were restricted to the upper 40 m of the platform. ROV surveys were conducted from outside of the structure at a standardized speed with limited close up observations, but were able to collect data from the surface to the seafloor at 125 m. Results from both methods provided valuable insight into the fish community associated with the platform.

The data presented in this study reflect a snapshot in time following the removal of a large portion of HI-A-389-A. The observations between pre- and post-removal surveys allowed, in some capacity, for a comparison of the benthic and fish communities, in which significant differences were observed. Though it cannot solely be attributed to removal of the structure, it is evident that the benthic community was severely impacted by the extraction of habitat. Additionally, demersal fishes seemed inherently more impacted by removal of this structure than pelagic species; however, seasonal and interannual changes are likely occurring as well. This study offers valuable information that affords some understanding of impacts that can occur to biological communities with the removal of platform structures. Beyond the loss of considerable shallow habitat, other factors warranting further study include changes in light availability, water movement, and the biological interactions between the motile and sessile assemblages. Continued monitoring will help document further temporal shifts in the benthic and fish communities and better correlate causality of the observed changes. Monitoring of partially removed platforms is critical in fully understanding temporal changes which can better inform future platform decommissioning decisions in the region.

Data availability

Data are available from NOAA upon request.

Acknowledgements We thank the Bureau of Ocean Energy Management, Bureau of Safety and Environmental Enforcement, and the Flower Garden Banks National Marine Sanctuary Advisory Council for their contributions. We also acknowledge the volunteer divers, Moody Gardens Aquarium, NOAA Diving Center, National Marine Sanctuary Foundation, W&T Offshore, Army Corps of Engineers, and Texas Parks and Wildlife for their assistance. Work was conducted under U.S. Army Corps of Engineers permit SWG-2015-00068 and NOAA permits FGBNMS-2017-010 and FGBNMS-2017-011.

Author contributions All authors contributed to the study conception and design. Data collection was performed by JAE, JM, MFN, KOC, ELH, RDB, and GPS. Data analysis, tables, and graphics were prepared by MAJ, MFN, KOC, and RDB. The manuscript was written by MAJ, MFN, and RDB and all authors provided input on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was funded through an interagency agreement between the Bureau of Safety and Environmental Enforcement and the National Oceanic and Atmospheric Administration's National Ocean Service, Office of National Marine Sanctuaries, through Flower Garden Banks National Marine Sanctuary under BSEE IA number E14PG00057 and ONMS contract number M14PG00020. Fieldwork from 2015 to 2019 was carried out under permits: FGBNMS-2014-001 and FGBNMS-2019-001.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Ajemian MJ, Wetz JJ, Shipley-Lozano B, Shively JD, Stunz GW (2015) An analysis of artificial reef fish community structure along the northwestern Gulf of Mexico shelf: potential impacts of "Rigs-to-Reefs" programs. PLoS ONE 10(5):e0126354. https://doi.org/10.1371/journal.pone.0126354

Anderson MJ, Gorley RN, Clarke KR (2008) PERMANOVA+ for PRIMER: guide to software and statistical methods. PRIMER-E Ltd, Plymouth, United Kingdom

Aronson RB, Edmunds PJ, Precht WF, Swanson DW, Levitan DR (1994) Large-scale, long-term monitoring of Caribbean coral reefs: simple, quick, inexpensive methods. Atoll Res Bull 421:1–19

Barker VA, Cowan JH (2018) The effect of artificial light on the community structure of reef-associated fishes at oil and gas platforms in the northern Gulf of Mexico. Environ Biol Fishes 101:153–166. https://doi.org/10.1007/s10641-017-0688-9

Boland GS (2002) Fish and epifaunal community observations at an artificial reef near a natural coral reef: nineteen years at High Island platform A-389-A, from bare steel to coral habitat. In: Proceedings of Gulf of Mexico Fish and Fisheries: Bringing together new and recent research. New Orleans, LA, MMS 2002-004, p. 372-392

Broughton K (2012) Office of National Marine Sanctuaries Science Review of Artificial Reefs. Marine Sanctuaries Conservation Series ONMS-12-05. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD, p 42

BSEE (Bureau of Safety and Environmental Enforcement) (2020) BSEE Data Center. Accessed 8/10/2020. https://www.data.bsee.gov/Production/ProductionData/Default.aspx

BSEE (Bureau of Safety and Environmental Enforcement) (2021) BSEE Rigs-Reefs. Accessed 06/16/2022. https://www.bsee.gov/what-we-do/environmental-compliance/environmental-programs/rigs-to-reefs

BSEE (Bureau of Safety and Environmental Enforcement) (2022) BSEE Offshore Instructure Dashboard. Accessed 06/12/2022. https://bobson.maps.arcgis.com/apps/dashboards/400bba386d3d4ec58396dbaa559c422c

Burdon D, Barnard S, Boyes SJ, Elliott M (2018) Oil and gas infrastructure decommissioning in marine protected areas: System complexity, analysis and challenges. Mar Poll Bull 135:739–758

Burt J, Bartholomew A, Sale PF (2011) Benthic development on large-scale engineered reefs: A comparison of communities among breakwaters of different age and natural reefs. Ecol Eng 37(2):191–198

Byers JE (2002) Impact of non-indigenous species on natives enhanced by anthropogenic alteration of selection regimes. Oikos 97:449–458

Cárdenas CA, Davy SK, Bell JJ (2012) Correlations between algal abundance, environmental variables and sponge distribution patterns on southern hemisphere temperate rocky reefs. Aquat Biol 16:229–239

Childs JN (2001) The occurrence, habitat use, and behavior of sharks and rays associating with topographic highs in the Northwestern Gulf of Mexico. Texas A&M University. https://oaktrust.library.tamu.edu/handle/1969.1/ETD-TAMU-2001-THESI S-C45.

Claisse JT, Pondella DJ, Love M, Zahn LA, Williams CM, Williams JP, Bull AS (2014) Oil platforms off California are among the most productive marine fish habitats globally. PNAS 111(43):15462–15467

Claisse JT, Pondella DJ, Love M, Zahn LA, Williams CM, Williams JP, Bull AS (2015) Impacts from Partial Removal of Decommissioned Oil and Gas Platforms on Fish Biomass and Production on the Remaining Platform Structure and Surrounding Shell Mounds. PLOS ONE 10(9):e0135812. https://doi.org/10.1371/journal.pone.0135812

Clarke KR, Gorley RN, Sommerfield PJ, Warwick RM (2014) Change in marine communities: an approach to statistical analysis and interpretation, 3rd edition. PRIMER-E, Plymouth, Devon, UK, p 260

Coles SL, Jokiel PL (1992) Effects of salinity on coral reefs. In: Connell DW, Hawker DW eds. Pollution in tropical aquatic systems. CRC Press, Boca Raton, FL, p 147–166

Daigle ST, Fleeger JW, Cowan Jr JH, Pascal PY (2013) What is the relative importance of phytoplankton and attached macroalgae and epiphytes to food webs on offshore oil platforms? Mar Coast Fish 5:53–64

Dauterive L (2000) Rigs to reefs policy, progress, and perspective. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region. OCS Report MMS 2000–073, New Orleans, LA

Dickens LC, Goatley CHR, Tanner JK, Bellwood DR (2011) Quantifying Relative Diver Effects in Underwater Visual Censuses. PLoS ONE 6(4):e18965. https://doi.org/10.1371/journal.pone.0018965

Dokken QR, Withers K, Childs S, Riggs T (2000) Characterization and comparison of platform reef communities off the Texas coast. Prepared by the Center for Coastal Studies. Texas A&M University-Corpus Christi, Corpus Christi, TX: Texas Parks and Wildlife Department. TAMU-CC-0007-CCS, Austin, TX

Doyle MW, Stanley EH, Havlick DG, Kaiser MJ, Steinbach G, Graf WL, Galloway GE, Riggsbee JA (2008) Aging infrastructure and ecosystem restoration. Science 319(5861):286–287

Embesi JA, Eckert RJ, Hickerson EL, Johnston MA, Nuttall MF, Schmahl GP (2013) Benthic community composition associated with a gas platform, High Island A-389-A, located within the Flower Garden Banks National Marine Sanctuary. Proceedings of the 66th Annual Gulf and Caribbean Fisheries Institute. Corpus Christy, TX. Volume 66: 538 p.

Felder DL, Camp DK (2009) Gulf of Mexico Origin, Waters, and Biota: Volume 1, Biodiversity. Texas A&M University Press, College Station, TX, p 1314

Fenner D (2001) Biogeography of three Caribbean corals (Scleractinia) and the invasion of *Tubastraea coccniea* into the Gulf of Mexico. Bull Mar Sci 69(3):1175–1189

Fenner D, Banks K (2004) Orange cup coral *Tubastraea coccinea* invades Florida and the Flower Garden Banks, Northwestern Gulf of Mexico. Coral Reefs 23:505–507. https://doi.org/10.1007/x00338-004-0422-x

Figueroa D, McClure A, Figueroa N, Hicks D (2019). Hiding in plain sight: invasive coral *Tubastraea tagusensis* (Scleractinia:Hexacorallia) in the Gulf of Mexico. Coral Reefs. 38. https://doi.org/10.1007/s00338-019-01807-7.

Fowler AM, Macreadie PI, Jones DOB, Booth DJ (2014) A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. Ocean Coast Manag 87:20–9. https://doi.org/10.1016/j.ocecoaman.2013.10.019

Froese R, Pauly D. Editors (2019). FishBase. World Wide Web electronic publication. Accessed 12/10/2019. www.fishbase.org

Gallaway BJ, Lewbel GS (1982) Ecology of petroleum platforms in the northwestern Gulf of Mexico: a community profile. U.S. Fish and Wildlife Service, Office of Biological Sciences, FWS/OBS-82/27. Bureau of Land Management, Gulf of Mexico OCS Regional Office, Washington, D.C, p 92

Gil-Agudelo DL, Cintra-Buenrostro CE, Brenner J, González-Díaz P, Kiene W, Lustic C, Pérez-España H (2020) Coral reefs in the Gulf of Mexico large marine ecosystem: conservation status, challenges, and opportunities. Front Mar Sci 6:807. https://doi.org/10.3389/fmars.2019.00807

Gili JM, Hughes RG (1996) The ecology of marine benthic hydroids. Oceanogr Lit Rev 43(12):1250

Gittings SR (1998) Reef community stability on the Flower Garden Banks, northwest Gulf of Mexico. Gulf Mex Sci 1998:161–169

Helsel DR, Hirsch RM (2002) Statistical methods in water resources. Techniques of water-resources investigations of the United States Geological Survey. Book 4, Hydrologic analysis and interpretation. U.S. Geological Survey, Washington, DC, p 522

Helsel DR, Mueller DK, Slack JR (2006) Computer program for the Kendall family of trend tests: U.S. Geological Survey Scientific Investigations Report 2005–5275. 4 pp.

Hipel KW, McLeod AI (1994) Time series modelling of water resources and environmental systems. http://www.stats.uwo.ca/faculty/aim/RPackages.htm

Humann P, Deloach N (2014) Reef Fish Identification: Florida, Caribbean, Bahamas, Fourth edition. New World Publications, Inc, Jacksonville, FL, p 537

Johnston MA, Nuttall MF, Eckert RJ, Embesi JA, Sterne TK, Hickerson EL, Schmahl GP (2016) Persistence of Coral Assemblages in Flower Garden Banks National Marine Sanctuary, Gulf of Mexico. Coral Reefs 35:821–826

Johnston MA, Sterne TK, Blakeway RD, MacMillan J, Nuttall MF, Hu X, Embesi JA, Hickerson EL, Schmahl GP (2018) Long-term monitoring at East and West Flower Garden Banks, 2017 Annual Report. Marine Sanctuaries Conservation Series ONMS-18-02. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX, p 124

Johnston MA, O'Connell K, Blakeway RD, MacMillan J, Nuttall MF, Hu X, Embesi JA, Hickerson EL, Schmahl GP (2021) Long-term monitoring at East and West Flower Garden Banks, 2019 Annual Report. Marine Sanctuaries Conservation Series ONMS-21-02. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX, p 92

Kaiser MJ, Pulsipher AJ (2005) Rigs-to-Reef programs in the Gulf of Mexico. Ocean Dev Int Law 36(2):119–134. https://doi.org/10.1080/00908320590943990

Kohler KE, Gill SM (2006) Coral point count with Excel extensions (CPCe): A Visual Basic program for the determination of coral and substrate coverage using random point count methodology. Comput Geosci 32:1259–1269

Kolian SR, Sammarco PW, Porter SA (2017) Abundance of Corals on Offshore Oil and Gas Platforms in the Gulf of Mexico. Environ Manag 60:357–366

Luecke C, Wurtsbaugh WA (1993) Effects of moon and daylight on hydroacoustic estimates of pelagic fish abundance. Trans Am Fish Soc 122:112–120

NOAA (National Oceanic and Atmospheric Administration) (2022) Gulf of Mexico Reef Fish Fishery Management Plan. NOAA Fisheries. Accessed 06/10/2022. https://www.fisheries.noaa.gov/management-plan/gulf-mexico-reef-fish-fishery-management-plan

ONMS (Office of National Marine Sanctuaries) (2008) Flower Garden Banks National Marine Sanctuary Condition Report 2008. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD, p 49

Paxton AB, Shertzer KW, Bacheler NM, Kellison GT, Riley KL, Taylor JC (2020) Meta-Analysis Reveals Artificial Reefs Can Be Effective Tools for Fish Community Enhancement but Are Not One-Size-Fits-All. Front Mar Sci 7:282. https://doi.org/10.3389/fmars.2020.00282

Precht WF, Hickerson EL, Schmahl GP, Aronson RB (2014) The invasive coral *Tubastraea coccinea* (Lesson, 1829): Implications for natural habitats in the Gulf of Mexico and the Florida Keys. Gulf Mex Sci 32:1

REEF (Reef Environmental Education Foundation) (2019) Reef Environmental Education Foundation interpreting REEF data. Accessed 12/9/2019. https://www.reef.org/interpreting-reef-data.

Rezak R, Gittings SR, Bright TJ (1990) Biological Assemblages and Ecological Controls on Reefs and Banks in the Northwestern Gulf of Mexico. Am Zool 30:23–35

Robins CR, Ray GC (1986) A field guide to Atlantic coast fishes of North America. Houghton Mifflin Company, Boston, MA, p 354

Rooker JR, Dokken QR, Pattengill CV, Holt GJ (1997) Fish assemblages on artificial and natural reefs in the Flower Garden Banks National Marine Sanctuary, USA. Coral Reefs 16:83–92

Sammarco PW, Atchison A, Boland GS (2004) Expansion of coral communities within the northern Gulf of Mexico via offshore oil and gas platforms. Mar Ecol Prog Ser 280:129–143

Sammarco PW, Brazeau DA, Sinclair J (2012) Genetic Connectivity in Scleractinian Corals across the Northern Gulf of Mexico: Oil/Gas Platforms, and Relationship to the Flower Garden Banks. PLOS ONE 7(4):e30144

Sammarco PW, Lirette A, Tung YF, Boland GS, Genazzio M, Sinclair J (2014a) Coral communities on artificial reefs in the Gulf of Mexico: standing vs. toppled oil platforms. J Mar Sci 71:417–426

Sammarco PW, Porter S, Sinclair J, Genazzio M (2014b) Population expansion of a new invasive coral species, Tubastraea micranthus, in the northern Gulf of Mexico. Mar Ecol Prog Ser 495:161–173. https://doi.org/10.3354/meps10576

Schmitt EF, Sullivan KM (1996) Analysis of a volunteer method for collecting fish presence and abundance data in the Florida Keys. Bull Mar Sci 59(2):404–416

Sheehy DJ, Vik SF (2010) The role of constructed reefs in non-indigenous species introductions and range expansions. Ecol Eng 36:1–11

Stanley DR, Wilson CA (1997) Seasonal and spatial variation in the abundance and size distribution of fishes associated with a petroleum platform in the northern Gulf of Mexico. Can J Fish Aquat Sci. https://doi.org/10.1139/f97-005

Stunz GW, Coffey DM (2020). A review of the ecological performance and habitat value of standing versus reefed oil and gas platform habitats in the Gulf of Mexico. Gulf Offshore Research Institute Technical Report. pp. 1-40

Sward D, Monk J, Barrett N (2019) A Systematic Review of Remotely Operated Vehicle Surveys for Visually Assessing Fish Assemblages. Front Mar Sci 6:134. https://doi.org/10.3389/fmars.2019.00134

Thanner SE, McIntosh TL, Blair SM (2006) Development of benthic and fish assemblages on artificial reef materials compared to adjacent natural reef assemblages in Miami-Dade County, Florida. Bull Mar Sci 78(1):57–70

Wetmore LS, Dance MA, Hill RL, Rooker J (2020) Community dynamics of fish assemblages on mid-shelf and outer-shelf coral reefs in the Northwestern Gulf of Mexico. Front Mar Sci 7:1–15

Wetz JJ, Ajemian MJ, Shipley B, Stunz GW (2020) An assessment of two visual survey methods for documenting fish community structure on artificial platform reefs in the Gulf of Mexico. Fish Res 225. https://doi.org/10.1016/j.fishres.2020.105492