# A Review of the Ecological Performance and Habitat Value of Standing versus Reefed Oil and Gas Platform Habitats in the Gulf of Mexico

Final Report

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**Executive Summary**

In the northern Gulf of Mexico (GOM), approximately 1,800 oil and gas production platforms (hereafter "standing platforms") function as de facto artificial reefs. As a large number of platforms are reaching the end of their production lifespans, some of these structures will be converted to permanent artificial reefs via state Rigs-to-Reefs (RTR) programs (many others have already been "reefed"), which involve partial removal or toppling of the platforms (hereafter "reefed platforms") either in place or moved to alternate approved locations. The conversion of standing platforms into artificial reefs results in a structure with a lower vertical relief, and no physical connection to the upper water column. As decommissioned standing platforms are increasingly converted into artificial reefs, it is important to evaluate the ecological effects of this physical transformation on platform-associated communities. Furthermore, the number of standing platforms in the northern GOM continues to rapidly decline as removals through the decommissioning process exceed new installations. Thus, there is a central need for science-based decision making on the proper use of these structures and to establish the best management practices to maximize RTR programmatic goals. Here, we review the current state of scientific knowledge comparing the ecological function and habitat value of standing and reefed platforms in the northern GOM and identify critical information gaps in need of future research with special emphasis on the ecological functionality of standing platforms and performance related to upper-water column benefits.

Allowing platforms to remain standing would ameliorate the loss of biodiversity and fish biomass due to the loss of shallow water substrate. While the ~85-ft (26-m) clearance guidelines observed in current RTR practices reduce some aspects of biodiversity (e.g., upper water column species) associated with standing platforms; nevertheless, there is evidence to suggest that partially removed platforms do continue to provide an effective means of preserving the community structure and ecological functions associated with standing platforms, particularly for economically important species. Furthermore, reefed platforms retain the majority of the fish community in the lower depth strata, including species that are targeted by recreational and commercial fisheries. As a result, studies evaluating how standing and reefed platforms function to support fish populations in the GOM have primarily focused on the biological characteristics of the economically important red snapper (*Lutjanus campechanus*) given this species iconic status and importance as the most valuable reef fish in the GOM. As a demersal species, both standing and reefed platforms appear to provide suitable habitat with sufficient resources to support its biological needs. Though, the lack of similar trends among artificial and natural habitats in the northwestern and north-central GOM highlights the complex nature of habitat- and region-specific contributions to the GOM red snapper stock and warrants further investigation, especially into the loss of structure and function of habitat as well as los of species in the upper water column. Nevertheless, increased emphasis on a wider range of species, including other broadly distributed fisheries species of commercial and/or recreational value (e.g., greater amberjack, *Seriola dumerili*), and on whole-community and functional approaches will build towards a more mechanistic understanding of the broader ecosystem values provided by both standing and reefed platforms.

The extensive variability in marine life and environmental conditions such as water depth, distance from shore, size, and many other characteristics associated with existing standing platforms makes it difficult to establish a generic set of predictions regarding the ecological consequences of

different decommissioning alternatives. Hence, decisions should be made on a case-by-case basis using all available scientific information. As standing platforms in the GOM reach the end of their productive lives at an increasing rate, long-term monitoring studies are critically needed to empirically assess changes to community structure and functionality prior to and following reefing or complete removal. These studies will ensure that RTR programs are operating at maximum efficiency and performance as it relates to reefing goals, and facilitate data-driven decisions to determine which standing platforms would be most economically and ecologically viable to remain standing and/or converted to artificial reefs.

In summary, this comprehensive literature review identified several key findings comparing the ecological function and habitat value of standing and reefed platforms in the GOM:

- Allowing platforms to remain standing would ameliorate the decline in biodiversity and fish biomass due to the loss of shallow water (<26 m) substrate.
- Reefed platforms, especially partially removed platforms, continue to provide an effective means of preserving the community structure and ecological functions associated with standing platforms, particularly for economically important species. Thus, even some structure retained is highly valuable.
- At this time, the ecological consequences of different decommissioning alternatives and decisions should be made on a case-by-case basis by the platform owner in conjunction with resource managers until a scientifically informed set of predictions can be formulated based on short- and long-term monitoring studies.
- Future research, including long-term monitoring studies and increased emphasis on a wider range of species, is critically needed to fully understand the impact of decommissioning standing platforms and different reef configurations on the ecology and productivity of the GOM.

## Introduction

The continental shelf of the northern Gulf of Mexico (GOM) is composed primarily of soft-bottom habitat with few distinct areas of high-relief natural reef, particularly in the northwestern region (Parker et al. 1983; Rezak et al. 1985). As of April 2019, there are 1,862 oil and gas production platforms[1] (hereafter "standing platforms"; BSEE 2020b) in the northern GOM (Fig. 1) that function as de facto artificial reefs by providing high-relief, hard substrate and the habitat complexity necessary for associated marine communities to thrive. As 'Idle Iron' policies have a large number of standing platforms that are reaching the end of their production lifespans slated for removal (Pulsipher et al. 2001; BSEE 2020a), some of these structures will be converted to permanent artificial reefs (hereafter "reefed platforms") via state Rigs-to-Reefs (RTR) programs as a means to mitigate habitat loss. Decommissioned standing platforms have been converted to artificial reefs in the United States (U.S.), Brunei, and Malaysia and potential RTR options are currently being evaluated and conducted in other regions (Bull and Love 2019). Though, RTR programs have been most popular in the northern GOM where, as of April 2018, 532 decommissioned standing platforms (~11% of total decommissioned platforms since 1986[2]) have been "reefed" under state artificial reef plans (Bull and Love 2019; BSEE 2020c), with Louisiana and Texas having the largest RTR programs (Kaiser and Pulsipher 2005; Kaiser et al. 2020; Fig. 1). Collectively, these standing and reefed platforms along with other reefed materials (e.g., ships, prefabricated concrete pyramids, reef balls, etc.) comprise the largest artificial reef complex in the world (Dauterive 2000).

The conversion of standing platforms into artificial reefs results in a structure with a lower vertical relief and no physical connection to the upper water column. Current RTR guidelines generally require reefed platforms to maintain 26 m of clearance depth below the sea surface (without the installation and maintenance of navigational aids) to avoid navigational hazards to large vessels. This is accomplished by either: (1) partial platform removal (cut-off); (2) toppling the structure in place; or, (3) toppling the structure after towing to a designated reefing site (Dauterive 2000). As decommissioned standing platforms are increasingly converted into artificial reefs, it is important to evaluate the ecological effects of this physical transformation on platform-associated communities. Furthermore, the number of standing platforms in the northern GOM continues to decline as removals through the decommissioning process exceed new installations (Pulsipher et al. 2001; Kaiser et al. 2020). Thus, there is a central need for science-based decision making on the proper use of these structures and to establish the best management practices for RTR programs. In other regions of the U.S. and the world, many scientists, managers, and stakeholders look to policies in the GOM to help inform decisions related to decommissioning strategies elsewhere (e.g., Aabel et al. 1997; Jagerroos and Krause 2016).

With a growing source of material for RTR programs worldwide, the ecological benefits provided by standing and reefed platforms compared to the complete removal of platform structures, while debated (Gallaway et al. 2009; Shipp and Bortone 2009; Cowan et al. 2011; Quirolo and Charter 2014; Cowan and Rose 2016), have been thoroughly reviewed (e.g., Schroeder and Love 2004; Scarborough-Bull et al. 2008; Versar 2008; Macreadie et al. 2011; Fortune and Paterson 2018;

[1]Includes approximately 456 caissons (~24%; BOEM 2020) that are deemed not suitable reef material and are rarely reefed (Kaiser et al. 2020).

[2]Increases to ~19% of total decommissioned platforms when excluding caissons (Kaiser et al. 2020).

Fowler et al. 2018; Fowler et al. 2020; Bull and Love 2019; Sommer et al. 2019; van Elden et al. 2019). However, there is presently a limited understanding of the habitat value retained by leaving a standing platform in place as an alternative to current RTR guidelines. Therefore, additional studies, starting with a comprehensive literature review of the current state of scientific knowledge, that compare the ecological function of standing and reefed platforms are especially important and timely. Thus, the **goal** of this review is *to synthesize the results of previous biological studies comparing the habitat value of standing and reefed platforms in the northern GOM and identify critical information gaps in need of future research*.

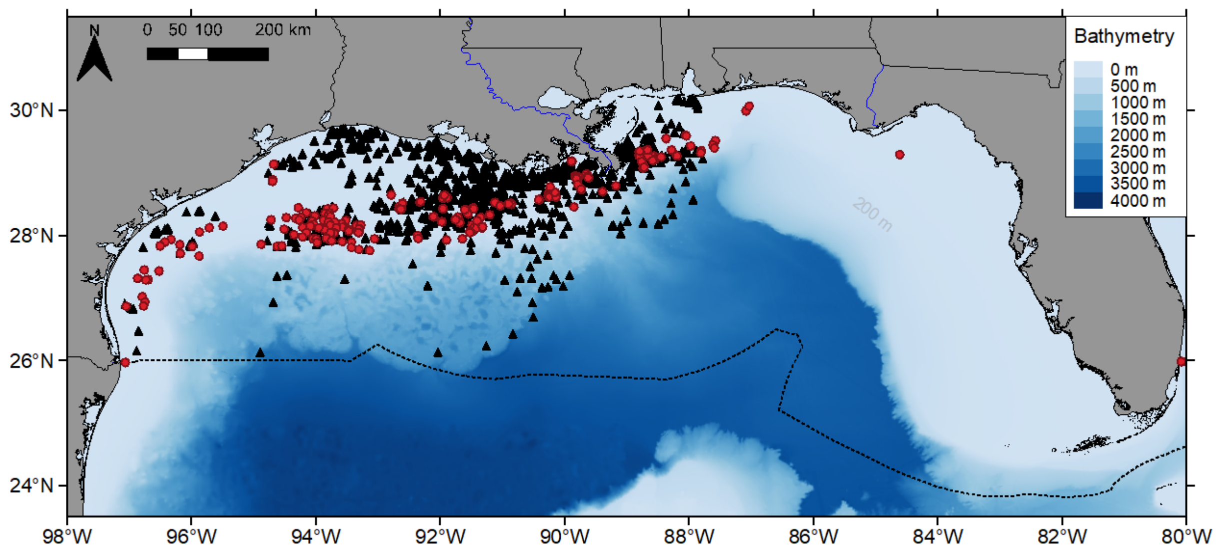


**Figure 1.** Location of standing oil and gas production platforms (black triangles) and Rigs-to-Reefs structures (red circles) in the northern Gulf of Mexico. Data were obtained from the Bureau of Ocean Energy Management (BOEM 2020) and National Oceanic and Atmospheric Administration (NOAA 2020). The 200 m isobath of the Outer Continental Shelf and the United States Exclusive Economic Zone are indicated by a gray solid line and black dotted line, respectively.

## Methods

The Google Scholar™ database was accessed up to May 2020, to search for peer-reviewed journal publications, book chapters, and gray literature that compared standing and reefed platforms using the keyword combinations "standing toppled oil platform", "partial removal oil platform", and "Rigs-to-Reefs". When available, peer-reviewed publications were the preferred source of information. The topic of oil and gas platforms as de facto artificial reefs and decommissioning strategies is a popular topic across multiple disciplines. The focus of this review is to compare ecological performance and habitat value among standing and reefed platforms in the northern GOM; therefore, we only reviewed biological studies and excluded other disciplines (e.g., socio-economic, political, legal, and engineering studies).

## Literature Search Results

The literature search identified 123 publications between 1979 and 2020 focusing on the biological implications of standing platforms and RTR programs (Table A1, Appendix). The majority of these studies (76%) have been published since 2010, highlighting the growing importance of evaluating decommissioning strategies and the need for further research. By region, a total of 93 studies (76%) were conducted in the U.S. with 64 (52%) and 29 (24%) studies focused in the GOM and Southern California Bight (SCB), respectively. Out of 123 publications identified in the literature search, 19 studies (15%) directly compared standing and reefed platforms. We note a few studies combined standing and reefed platforms into a single artificial reef (e.g., Glenn et al. 2017; Schwartzkopf et al. 2017; Schwartzkopf et al. 2017) or platform (e.g., Sluis et al. 2013) category and do not make direct comparisons between them. While acknowledging some degree of overlap, these studies can be best summarized into three main categories: community composition and structure, fish biomass and density, and snapper (family Lutjanidae) biology.

## Summary of Comparative Standing vs. Reefed Platform Research in the Gulf of Mexico

### Community Composition and Structure

In the northern GOM, community composition and structure associated with standing and reefed platforms has been primarily quantified using visual census techniques combined with SCUBA diver-based surveys, manned submersibles, remotely operated vehicles (ROVs), and/or baited remote underwater video (BRUV) arrays. Dokken et al. (2000) was the first to compare standing and reefed platform communities for development of the most effective management strategies for the Texas Artificial Reef Program. Specifically, Dokken et al. (2000) compared epibenthic (e.g., sessile invertebrates and algae) and fish communities using SCUBA diver-based surveys across five standing platforms and two reefed platforms (toppled in place and cut-off) off the Texas coast. The cut-off platform (North Padre Island [NPI] 72A) was surveyed one year before being converted into an artificial reef (pre-cut), two-weeks post-cut, and one-year post-cut, allowing comparison of pre- and post-cut communities. Epibenthic and fish communities were similarly grouped based on a shallow to deep-water transition (with a few exceptions) across sites. Species diversity and richness declined slightly as soon as NPI 72A was cut-off, due to the physical loss of species (e.g., tree oysters, *Isognomon* spp.) that are confined to the upper portion of the structure; however, both diversity and richness increased one year after it was cut-off. Though, the epibenthic community composition underwent substantial change and may be indicative of successional change due to removal of the upper portion of the structure. The fish community of NPI 72A was overwhelmingly dominated by a large school of lookdowns (*Selene vomer*) occupying the upper portion of the structure during the pre-cut survey, whereas horse-eye jacks (*Caranx latus*) and other pelagic fish species increased in abundance during the post-cut surveys resulting in a more diverse fish community. In addition, some of the non-pelagic reef species encountered most frequently at shallower depths in the pre-cut survey increased in numbers at the deeper depths in the post-cut surveys due to removal of reef habitat above 28 m.

The high fish abundance observed on standing and reefed platforms relative to open, soft-bottom habitats may result in prey depletion as reef-associated predators forage near platforms. Daigle (2011) compared benthic and demersal communities at two standing and two toppled platforms off the coast of Louisiana to assess potential prey depletion or other platform effects. Benthic and demersal communities were sampled using ponar grabs and bottom trawls, respectively, at sites near (0.25 km) and far (1.5 km) from each platform to evaluate potential differences with regards to distance and platform type. No discernable differences were observed in the benthic and demersal communities surrounding standing and toppled platforms; however, diel and seasonal patterns were detected. Logistical constraints prevented bottom trawls within 0.25 km of the toppled platforms; therefore, additional research is needed to further examine potential platform effects (e.g., prey depletion) on benthic and demersal communities in the area immediately adjacent to platforms (e.g., Montagna et al. 2002).

It is well established that standing platforms in the northern GOM support substantial coral communities (reviewed by Sammarco 2014). Though, there is limited information on the efficacy of lower-relief reefed platforms to support the growth and development of coral populations. Sammarco et al. (2014a) compared coral communities using ROV surveys across two standing platforms and five toppled platforms off the Texas and Louisiana coast. In contrast to Dokken et al. (2000), ROVs offer a robust survey tool for quantifying community composition and structure across a broader range of depths (>40 m) that are inaccessible to most conventional SCUBA diver-based surveys (Andaloro et al. 2013; Wetz et al. 2020). Overall coral density did not change between standing and toppled platforms due to varying species-specific abundances; however, there were differences in coral community structure as a result of toppling of the platforms. For example, hermatypic (reef-building) ten-ray star coral (*Madracis decactis)* densities did not vary between the two structure types given they are located in shallow water (≤50 m bottom depth). In contrast, ten-ray star coral colonies on standing platforms that are transported into deeper waters (>50 m) upon toppling will likely not survive due to colder temperatures and less light availability. Interestingly, some ahermatypic (non-reef-building) coral species (e.g., orange cup coral, *Tubastraea coccinea*) seem to thrive better on toppled platforms compared to standing platforms given their ability to grow particularly well in disturbed habitats. A toppled platform may be considered a disturbed habitat given the mode of severing a standing platform from the seafloor often uses explosives set around the base of the major support pilings. Explosive severance would dislodge and/or kill sessile epibenthic organisms, thus creating newly available space for settlement by incoming larvae or expansion by more robust surviving species (Bull and Kendall 1994). Corals were also distributed more deeply on standing platforms than toppled platforms, which is also likely a result of explosive severance. However, it is important to note that the platforms are not absolutely comparable with respect to date of toppling or whether the reefed platforms were relocated or toppled in place as these factors can influence ecological succession and benthic community structure. Nevertheless, it is clear that toppling of platforms dramatically affects the coral communities on the platforms, changing the species composition and diversity with depth.

Ajemian et al. (2015a) assessed fish communities using ROVs at an array of artificial reef types including fourteen reefed platforms (seven cut-off and seven toppled) and three standing platforms broadly distributed over the Texas continental shelf. Given the visibility constraints on the lower portion of the water column at some locales (i.e., benthic nepheloid layer) and preference for these habitats by demersal red snapper (*Lutjanus campechanus*; Dokken et al. 2000; Ajemian et al. 2015b), Ajemian et al. (2015a) supplemented their ROV methods with fishery-independent vertical line surveys (sensu Gregalis et al. 2012) to estimate the abundance and size of red snapper across artificial structures. Their findings suggest that the conversion of standing platforms into artificial reefs may significantly alter fish community structure, supporting previous studies (Dokken et al. 2000; Wilson et al. 2003). While overall species diversity, richness, and evenness were stable among standing and reefed platforms, there were key assemblage differences. For example, fish communities at standing platforms were dominated by Bermuda chub (*Kyphosus sectatrix*), a schooling, pelagic herbivore with low economic value. While fish assemblages were different between standing and toppled platforms, no significant differences were observed between standing and cut-off platforms. This finding provides potential evidence that the community characteristics of standing platforms can be best retained by cut-off platforms that maintain an upright orientation and provide relatively high vertical relief. Overall, the effects of converting standing platforms into completely submerged artificial reefs with lower vertical relief are generally limited to pelagic planktivores and piscivores that use the upper water column, and do not affect demersal species (Wilson et al. 2003). For example, there was no strong evidence of structure type affecting demersal red snapper abundance (via ROV and vertical line surveys), biomass (total weight per set), or mean size. Importantly, while structure type and vertical relief were shown to influence species richness and community structure, major trends in species composition were largely explained by the bottom depth where these structures occurred.

As decommissioned standing platforms are increasingly converted into artificial reefs, it is important to evaluate the ecological effects of this physical transformation on platform-associated epibenthic communities and food webs. Rezek et al. (2018) used a combination of stable isotope and community analyses to evaluate the structure and food web functioning of epibenthic communities among two standing platforms at 5 m and 30 m depths and three reefed platforms (one cut-off and two toppled) at 30 m depths (near the top of the structure) off the Texas coast. Standing and reefed platforms supported structurally similar communities at equivalent depths (30 m), which indicate that comparable communities are able to develop at this depth regardless of physical links to shallow substrate. In contrast, the distinct compositional characteristics of shallow (5 m) platform communities are likely to be lost or diminished when standing platforms are converted into artificial reefs. Interestingly, stable isotope analyses revealed epibenthic communities in deep (30 m) standing and reefed platform sites relied on similar food sources as the shallower (5 m) standing platform sites, despite the variation in community composition between these depth zones. These findings demonstrate that the current reefing practice of removal of the upper ~26 m of the structure does not substantially influence the ecological functionality of these systems. Moreover, the retained structure preserves suitable habitat for epibenthic communities and forage resources for important fisheries species (e.g., gray triggerfish [*Balistes capriscus*] and sheepshead [*Archosargus probatocephalus*]) and non-targeted reef-associated species (Daigle et al. 2013; Cowan and Rose 2016; Reeves et al. 2019).

<u>Fish Biomass and Density</u>

The spatial distribution of fish biomass, density, and size associated with standing and reefed platforms has been quantified using hydroacoustic surveys. These non-invasive techniques offer unique advantages over visual census methods by sampling the entire water column at a high spatial and temporal resolution over large areas (Boswell et al. 2010; Reynolds et al. 2018). In addition, studies that contemporaneously collect hydroacoustic and video data can determine the relative contribution of an individual species to the acoustic biomass (Reynolds et al. 2018).

Wilson et al. (2003) was the first to compare fish communities, density and biomass associated with a standing platform, two reefed platforms (toppled and cut-off), and a nearby, large natural reef, the West Flower Garden Banks, using a combination of hydroacoustic and ROV sampling methods off the Texas and Louisiana coast. Overall, Wilson et al. (2003) found that species composition at the standing and reefed platforms were fairly similar at depth but differed from the West Flower Garden Banks. However, fish biomass and density around the standing platform was an order of magnitude higher than the reefed platforms or West Flower Garden Banks. Fish density and size was greater near the surface than the bottom (~90 m) at the standing platform, whereas fish densities at the cut-off and toppled platforms were highest in the lower portion of the water column (>50 m). Though, the cut-off platform also had high fish densities closer to the surface than the toppled platform resembling fish distribution at the standing platform. Similar to Ajemian et al. (2015a), when a standing platform is converted into an artificial reef, it appears that the pelagic planktivores (e.g., Bermuda chub and blue runner [*Caranx crysos*]) make up the greatest biomass that is lost. However, fish biomass and species composition around the reefed platforms was fundamentally similar to the lower portion (>50 m) of the standing platform and included important recreational and commercial reef-associated species such as red snapper, gray triggerfish, greater amberjack (*Seriola dumerili*), and almaco jack (*Seriola rivoliana*). These data suggest that the fish community in the lower depth strata may be uncoupled from the community found in the upper strata and that reefed platforms retain the majority of species targeted by recreational and commercial fisheries after the decommissioning process.

Simonsen (2013) examined the spatial and temporal distribution of fish biomass around two standing and two toppled platforms off the Louisiana coast. In the absence of video data, Simonsen (2013) used a multifrequency hydroacoustic approach to broadly categorize organisms into four acoustic classes (sensu Korneliussen et al. 2009): large pelagic predators (e.g., sharks), schooling planktivores (e.g., Bermuda chub and blue runner), fish (excluded from previous classes), and zooplankton scattering layer. Similar to Wilson et al. (2003), standing platforms supported roughly two times higher fish biomass than toppled platforms. Differences in biomass between structures were observed only in the upper and middle water column and were largely due to the higher observed biomass of large pelagic predators, schooling planktivores, and zooplankton classes at the standing platforms. In contrast, the similarities observed in the lower water column between standing and reefed platforms and across seasons indicate that demersal fish species are likely to be found at both habitats. Similar to the findings described above, Simonsen (2013) demonstrated that the conversion of standing platforms into artificial reef structures will differentially affect species, or classes, of reef-associated fishes.

Harwell (2013) assessed fish density before and after a standing platform was reefed in relation to modifying habitat complexity – defined by vertical relief, footprint and volume of the structure. In contrast to Wilson et al. (2003) and Simonsen (2013), Harwell (2013) examined changes in fish density at the same site before and after reefing using a nearby standing platform as a control. The standing platform was reefed by removing the deck and the upper ~32 m of the jacket (legs) and placing the jacket material on the seafloor approximately 15 m from the original structure. A separate decommissioned standing platform had the deck removed and placed on the seafloor adjacent to the study site after reefing, thus creating a large and complex artificial reef. After reefing, the structure had a vertical relief of 37 m from a bottom depth of ~72 m, which resulted in a 54% decrease in vertical relief compared to the original standing platform and an overall decline in fish density. However, there was an increase in fish density between 40-60 m, which comprised the highest percentage (~70%) of the reefed platform volume. Although the percent increase in overall footprint (1024%) was an order of magnitude higher than volume (55%) after reefing, ultimately volume accounted for the greatest variability among fish densities. The additional substrate material (platform deck) from the separate decommissioned platform increased the overall volume and provided additional habitat and structural complexity at the site. Similarly, Ajemian et al. (2015a) observed the highest average species richness from a reefed platform deck suggesting that this structure type could provide a high habitat value for fish communities (given more efficient cleaning methods).

Reynolds et al. (2018) expanded on the methodology of Simonsen (2013) by integrating video and hydroacoustic data to determine relative species contribution to biomass observed at three standing and two toppled platforms off the Louisiana coast. Similar to previous results, Reynolds et al. (2018) observed higher species richness, evenness and diversity at standing platforms compared to toppled platforms. Yet, only four species (red snapper, greater amberjack, horse-eye jack, and little tunny [*Euthynnus alletteratus*]) contributed to 90% of fishes observed at both toppled and standing platforms, and fish biomass was highest in the lower portion of the water column (>60 m) across sites. While overall mean biomass remained relatively consistent across seasons, different species contributed to community structure depending on season and depth. Red snapper was the dominant species across seasons at standing and reefed platforms at depths >60 m and in 30-60 m (except during summer), whereas the fish communities changed at depths between 0-30 m during each season. The integration of video and hydroacoustic data to ground-truth which species contributed to relative acoustic biomass at standing and toppled platforms is an important step in understanding the efficacy of these structures as ecological and economically valuable habitat.

Snapper Biology

Red snapper and vermilion snapper (*Rhomboplites aurorubens*) are among the most economically important reef fishes in the northern GOM. These lutjanids associate with hard substrate, occupying natural banks, ridges, and reefs (Gledhill 2001; Wilson et al. 2006; Wells and Cowan 2007; Patterson et al. 2014; Karnauskas et al. 2017; Streich et al. 2017b), and are dominant reef fish species observed at standing and reefed platforms (Stanley and Wilson 1997; Wilson et al. 2003; Ajemian et al. 2015a; Reynolds et al. 2018; Streich et al. 2018; LGL 2019). Given both species are federally managed, and that the GOM red snapper stock continues to rebuild from overfished conditions (Strelcheck and Hood 2007; SEDAR 2018), evaluating potential biological differences among habitats is critical for accurate assessments of stock status and management recommendations (Streich et al. 2017c; Moncrief et al. 2018). To date, Moncrief et al. (2018) is the only study to evaluate how standing and reefed platforms function to support the GOM vermilion snapper stock by comparing the reproductive potential of females among standing and reefed platforms with natural reefs in the north-central GOM. The highest percentage of actively spawning females (26.5%) were captured on natural reefs despite natural reefs containing the lowest percentage of spawning capable females (6.2%). Moreover, the percentage of actively spawning (14.5%, 16.4%) and spawning capable (11.1%, 11.5%) females were similar for reefed and standing platforms, respectively. In comparison, several studies (n = 7) have evaluated how standing and reefed platforms function to support the GOM red snapper stock, including age and growth (Saari 2011; Streich et al. 2017c), reproductive biology (Kulaw 2012; Downey et al. 2018), trophic ecology (Simonsen et al. 2015; Brewton et al. 2020), and movement (Westmeyer et al. 2007).

*Age and growth*

While numerous studies have aged red snapper, Saari (2011) was the first to simultaneously compare age structure, size, and growth rates of red snapper among two standing and two toppled platforms with four natural hard-bottom shelf-edge banks on Louisiana's outer continental shelf. Saari (2011) found no difference in the ratio of males to females, mean age, and age frequency between standing and toppled platforms. Red snapper at toppled platforms were on average longer than those from standing platforms; however, there was no difference in terms of weight. Further, no consistent pattern in mean size-at-age was observed between red snapper from standing and toppled platforms. However, total length and total weight at age indicated significantly faster growth rates for red snapper from toppled platforms compared to standing platforms. While these results indicate some habitat-specific differences in red snapper size and growth rates among standing and toppled platforms, the mechanisms underlying these differences remain largely unknown.

Streich et al. (2017c) provided new information for the northwestern GOM by conducting vertical line surveys to assess red snapper relative abundance, size and age structure, and growth parameters at three standing platforms, three reefed platforms (two cut-off and one toppled), and three natural banks off the Texas coast. Red snapper relative abundance (i.e., catch per unit effort) was similar among standing platforms, reefed platforms, and natural banks – a finding that is inconsistent with previous studies demonstrating higher relative abundance of red snapper at artificial habitats than at natural habitats (Patterson et al. 2014; Karnauskas et al. 2017; Streich et al. 2017b). For example, ROV surveys conducted at artificial reefs and natural banks in the same region estimated that red snapper abundance was nearly eight times greater at artificial reefs (Streich et al. 2017b). Video-based surveys are generally less affected by gear saturation (see Streich et al. 2018) and may provide less-biased indices of abundance given adequate visibility (Harvey et al. 2012; Ajemian et al. 2015b). Overall mean red snapper size (length and weight) and age was similar among all three habitat types; however, size and age frequencies revealed that natural banks supported a greater proportion of large and relatively old fish compared to standing or reefed platforms. Moreover, weight frequency distributions were more similar between standing and reefed platforms, as both were dominated by smaller fish. However, growth models suggested that fish from reefed platforms reached larger sizes at age than fish from either standing platforms or natural banks. Importantly, these results indicate that all three habitat types could contribute similarly to GOM red snapper stock productivity on a per-unit-area basis.

*Reproductive biology*

To better understand the functional role of standing and reefed platforms in supporting the GOM red snapper stock, it is essential to understand whether fish using these different habitat types have similar reproductive potential (Downey et al. 2018). In a companion study to Saari (2011), Kulaw (2012) was the first to compare reproductive biology estimates of female red snapper among standing and toppled platforms with natural hard-bottom shelf-edge banks on Louisiana's outer continental shelf. Specifically, Kulaw (2012) compared sex ratios, gonadosomatic indices (GSI), size and age at maturity, and spawning frequency among habitats. Similar to Saari (2011), Kulaw (2012) found no difference in the ratio of males to females among standing and toppled platforms. Females at standing platforms were significantly younger and smaller compared to females at toppled platforms and yielded relatively low GSI estimates, which indicates a reduced spawning capacity. In addition, females from standing platforms reached maturity at a slower pace compared to females from toppled platforms. Collectively, these results suggest a reduced spawning frequency at standing platforms compared to toppled platforms.

In a companion study to Streich et al. (2017c), Downey et al. (2018) further examined the habitat-specific reproductive potential of red snapper at standing and reefed platforms relative to natural banks off the Texas coast. Comparisons of sex ratios, GSI, fecundity, spawning frequency, and number of spawning-capable individuals indicated that red snapper reproductive biology was similar among standing platforms, reefed platforms, and natural banks. These results suggest that reproductive traits of similar age classes of red snapper are functionally comparable among platform and natural bank habitats. The contrasting results of this study and Kulaw (2012) in the central GOM highlights regional differences in reproductive potential of red snapper among habitat types that warrant further investigation.

*Trophic ecology*

There has been extensive research on how artificial reefs function in the feeding ecology of red snapper (e.g., Ouzts and Szedlmayer 2003; McCawley and Cowan 2007; Wells et al. 2008; Schwartzkopf et al. 2017; Dance et al. 2018). Though, Simonsen et al. (2015) was the first study to compare the dietary preferences of red snapper associated with standing platforms, toppled platforms, and natural reefs on Louisiana's outer continental shelf using a combination of stomach gut and stable isotope analyses. Stomach gut contents provide an accurate description of recent (hours to days) feeding habits, while stable isotopes are incorporated over several months and therefore provide an integrated assessment of diet over time. While diets of red snapper were more diverse at the natural reefs, they consisted of similar prey items found at the standing and reefed platforms. Fish dominated diets at all three habitat types; however, habitat-specific differences existed in the contribution of major prey items. For example, red snapper collected from standing platforms consumed primarily fish, squid, and shrimp, while greater amounts of crabs, shrimp, and other crustaceans were consumed at toppled platforms. On the natural reefs, diets varied the most, consisting of both fish and crustaceans. Stable isotope analyses revealed red snapper from standing platforms were more enriched in nitrogen, indicating feeding at a higher trophic level compared to other habitats. Though, the diets of red snapper were overall similar among habitat types and are consistently sourced from the surrounding water column and seafloor, as evidenced by phytoplankton serving as the dominant basal resource (see Daigle et al. 2013).

Streich et al. (2017c) demonstrated that reefed platforms in the western GOM support larger size-at-age red snapper relative to natural reefs or standing platforms and that older, larger fish are found on natural reefs. Interestingly, a companion study by Downey et al. (2018) revealed no differences in relative weight or reproductive potential for red snapper among these three habitat types. Thus, while these faster growth rates on reefed platforms do not also translate to significantly improved reproductive capacity or condition, it is possible that they are explained by higher-quality prey resources at these habitats. In a companion study, Brewton et al. (2020) evaluated the potential trophic enhancement provided by reefed platforms by comparing annual, ontogenetic, and habitat-specific diet and stable isotope signatures of adult red snapper from relic coralgal natural reefs to those from standing and reefed platforms off the Texas coast. Relic coralgal natural reefs supported a more diverse diet for red snapper in the intermediate size class corroborating previous findings on natural salt dome reefs near Louisiana (Simonsen et al. 2015; Schwartzkopf et al. 2017). In contrast to Simonsen et al. (2015), Brewton et al. (2020) identified unique prey items at standing and reefed platforms, which suggests that these artificial habitats may provide red snapper with unique foraging opportunities. For example, the greatest trophic diversity was observed for larger red snapper at reefed platforms. Moreover, reefed platforms supported a more varied prey base compared to standing platforms likely due to their unique structure that combines characteristics of standing platforms and natural low-relief habitats. Furthermore, these results may explain the higher growth rates previously observed for older red snapper at these reefed platforms (Streich et al. 2017c). Yet, standing platforms may provide a more consistent, higher trophic level food resource throughout ontogeny resulting in increased nitrogen enrichment consistent with previous studies (Simonsen et al. 2015; Schwartzkopf et al. 2017). Overall, these findings suggest that region- and habitat-specific effects on red snapper trophic ecology are more complex than previously considered in the GOM, and that reefed platforms provide foraging opportunities more similar to natural reefs than standing platforms.

*Movement*

Information on red snapper site fidelity and movement patterns around artificial reefs is critical to elucidate the relative importance of these structures as effective fishery enhancement tools. While conventional mark-recapture studies can be informative depending upon the number of recaptures (e.g., Szedlmayer and Shipp 1994; Patterson et al. 2001; Patterson and Cowan 2003; Diamond et al. 2007; Strelcheck et al. 2007), the advent of acoustic telemetry has greatly improved the spatial and temporal resolution of red snapper movement studies. The fidelity and movement patterns of red snapper around standing platforms (McDonough and Cowan 2007; Westmeyer et al. 2007; Curtis 2014; Everett 2018), reefed platforms (Getz and Kline 2019), and low-relief artificial reefs (Szedlmayer and Schroepfer 2005; Schroepfer and Szedlmayer 2006; Topping and Szedlmayer 2011; Piraino and Szedlmayer 2014; Williams-Grove and Szedlmayer 2016; Williams-Grove and Szedlmayer 2017; Froehlich et al. 2019) has been examined using acoustic telemetry with varying results. Though, Westmeyer et al. (2007) is the only study to date that compared red snapper site fidelity and movements between standing and toppled platforms. Red snapper had high initial fidelity to release locations that subsequently decreased over time (over a period of months) and exhibited little movement between platforms in the study area. These results are consistent with several previous studies that reported low site fidelity to artificial structures for red snapper (Patterson et al. 2001; Patterson and Cowan 2003; McDonough and Cowan 2007; Westmeyer et al. 2007), whereas others have suggested red snapper exhibit high site fidelity (Szedlmayer and Shipp 1994; Szedlmayer and Schroepfer 2005; Schroepfer and Szedlmayer 2006; Topping and Szedlmayer 2011; Curtis 2014; Piraino and Szedlmayer 2014; Williams-Grove and Szedlmayer 2016; Williams-Grove and Szedlmayer 2017; Froehlich et al. 2019). Though, the methods (mark-recapture versus acoustic telemetry), habitat type, study length, and spatial scales varied among these studies and may affect estimates of site fidelity (Patterson 2007). Furthermore, these varying results suggest individual variability in site fidelity and movements among red snapper (Diamond et al. 2007). Westmeyer et al. (2007) found relocated red snapper exhibited lower site fidelity and lacked evidence of homing behavior to original capture locations. In addition, red snapper exhibited a diel pattern of movement away from the structures at night which was attributed to foraging excursions. In this study, red snapper movements were monitored at a single toppled platform and seven standing platforms. Therefore, future research evaluating the habitat value of standing and reefed platforms requires additional structures to clarify the site fidelity and connectivity of red snapper, and other species, to these structures.

Comparison with Natural Habitats

Comparisons of standing and reefed platforms with natural habitats are critically needed to contextualize the ecological function and value of these artificial structures. Although several studies have directly compared either standing or reefed platforms with natural habitats (e.g., Rooker et al. 1997; Wilson et al. 2006; Patterson et al. 2014; Streich et al. 2017b), relatively few have contemporaneously compared all three habitat types. Wilson et al. (2003) reported the fish community and biomass associated with standing and reefed platforms differed from the West Flower Garden Banks and recommended future research efforts toward determining the fundamental reasons for this difference. Though, the Flower Garden Banks are unique coral reef habitats that are not representative of other natural banks, ridges, and reefs in the northern GOM (Rezak et al. 1985).

Other than Wilson et al. (2003), previous studies directly comparing standing and reefed platforms to natural habitats in the northern GOM have primarily focused on the biological characteristics of red snapper (but see Moncrief et al. 2018). Recent studies in the northwestern GOM have shown that reefed platforms support larger size-at-age red snapper relative to relic coralgal natural reefs or standing platforms and that older, larger fish are found on natural reefs (Streich et al. 2017c). Though, reproductive characteristics were similar for this same collection of red snapper among habitats (Downey et al. 2018). Furthermore, a companion study by Brewton et al. (2020) revealed trophic similarities between reefed platforms and natural reefs compared to standing platforms, which may translate into the faster growth rates reported by Streich et al. (2017c).

However, some region-specific differences in growth rates (Saari 2011), reproductive characteristics (Kulaw 2012; Glenn et al. 2017), and trophic ecology (Simonsen et al. 2015; Schwartzkopf et al. 2017) have been reported for red snapper inhabiting natural salt dome reefs, standing platforms, and reefed platforms in the north-central GOM. For example, Saari (2011) documented no difference in age frequencies of red snapper among these habitat types off the coast of Louisiana, whereas Kulaw (2012) and Glenn et al. (2017) reported differences in reproductive biology. Specifically, natural salt dome reefs yielded the highest GSI estimates for red snapper among habitats (Kulaw 2012) and annual fecundity estimates were almost 20-fold higher in fish collected from these natural habitats (Glenn et al. 2017). In addition, natural salt dome reefs supported a more diverse red snapper diet (Simonsen et al. 2015; Schwartzkopf et al. 2017), which mirrors what has been found on relic coralgal reefs in the northwestern GOM near Texas (Brewton et al. 2020). These corroborating studies reveal that multiple types of natural reefs support a broader prey base than do artificial habitats. Moreover, there was no evidence of prey items specific to the artificial structures as compared to the natural habitat on the Louisiana shelf edge

(Simonsen et al. 2015); however, prey items unique to artificial structures were identified off the coast of Texas (Brewton et al. 2020). Lastly, reefed platforms supported a more varied prey base than did standing platforms (Simonsen et al. 2015; Brewton et al. 2020) suggesting the lower relief of reefed platforms may better mimic natural reef habitats.

The differences between these studies may be influenced by the disparate characteristics of each habitat type (e.g., bottom depth, footprint, vertical relief) and documented differences in fish community structure between natural and artificial habitats across the GOM (Rooker et al. 1997; Wilson et al. 2006; Patterson et al. 2014; Streich et al. 2017b). For example, the relic coralgal reefs surveyed in the northwestern GOM are geologically distinct from the salt dome reefs in the north-central GOM (Rezak et al. 1985) and occur in shallower water (72-84 m) compared to the deeper shelf-edge banks (90-150 m) surveyed off Louisiana (Streich et al. 2017c). The lack of similar trends among habitats in Louisiana and Texas highlights the complex nature of habitat- and region-specific contributions to the GOM red snapper stock (e.g., Saari et al. 2014; Kulaw et al. 2017; Brown-Peterson et al. 2019).

**Comparison with California Platform Research**

Compared to the extensive array of 1,862 standing platforms in the GOM, there are currently 27 standing platforms in the in the SCB (Bull and Love 2019). Communities associated with standing platforms in the SCB and GOM are characterized by distinct regional faunal assemblages and species associations (Scarborough-Bull et al. 2008; Love et al. 2019a; Love et al. 2019c; Page et al. 2019). For example, standing platforms in the SCB are characterized by three distinct fish assemblages: midwater, bottom, and shell mound, which are associated with these different microhabitats around the platform structure (Love et al. 2019a). Shell mounds are biogenic reefs that surround some of the standing platforms resulting from an accumulation of mollusk shells that have fallen from the shallow portions of the platforms. Further, standing platforms in the SCB have the highest secondary fish production per square meter of seafloor of any marine habitat that has been studied, approximately an order of magnitude higher than fish communities from other marine ecosystems (Claisse et al. 2014). Although several platforms have been installed and removed in the SCB, none have been reefed. With the passage of the California Marine Resources Legacy Act in 2010, the State of California will allow consideration of the partial removal of decommissioned standing platforms as an alternative to complete removal. Because standing platforms in the SCB are scheduled for decommissioning in the near future, a model for estimating biological loss for partial and complete removal is needed to evaluate these decommissioning options (Claisse et al. 2015; Pondella et al. 2015).

Claisse et al. (2015) and Pondella et al. (2015) evaluated the potential effects of partial removal on the biomass and secondary production of fish communities associated with standing platforms in the SCB. Secondary production is the formation of new animal biomass from growth for all individuals in a given area and period of time (Claisse et al. 2014). While complete removal would likely eliminate most of the existing fish biomass and associated secondary production, the potential impacts of partial removal would likely be limited on almost all standing platforms in the SCB. On average 80% of fish biomass and 86% of annual secondary fish production would be retained after partial removal, with above 90% retention expected for both metrics on several platforms (Claisse et al. 2015). Further, these cut-off platforms would retain some of the highest secondary fish production values of any documented marine habitat globally (Claisse et al. 2014; Claisse et al. 2015). Partial removal would likely result in the loss of fish biomass and production for species typically found residing in the shallow portions of the platform structure. However, these species generally represent a small proportion of the fishes associated with these standing platforms compared to deeper-dwelling rockfishes (*Sebastes* spp.; Love et al. 2012; Love et al. 2019a). Furthermore, many platform-associated rockfishes are important to recreational and commercial fisheries and these results suggest that cut-off platforms will continue to remain viable habitats for these species. In addition, Claisse et al. (2015) found that shell mounds beneath the platform are moderately productive fish habitats, similar to or greater than natural rocky reefs in the region at comparable depths. However, partial removal will diminish the supply of falling mollusk shells from the shallow portions (<26 m) of the platform potentially resulting in reduced shell mound habitats and associated fish biomass and production (Meyer-Gutbrod et al. 2019b). Though, reductions in shell mound habitat and fish production may be mitigated by placing the partially removed portion or additional habitat enrichment material near the base of the existing structure (Claisse et al. 2015).

**Current Research Gaps and Future Directions**

Despite the vast amount of research on platform and artificial reef habitats in the northern GOM, relatively few studies have directly compared the ecological functions of standing and reefed platforms. While the studies reviewed here were seminal and informative, most did not account for seasonal changes (but see Simonsen (2013) and Reynolds et al. (2018)) and drew comparisons from a relatively small set of sites and reef configurations, largely due to sampling logistics related to offshore field studies. Moreover, several companion studies were conducted contemporaneously at the same sites off Louisiana (Daigle 2011; Daigle et al. 2013; Saari 2011; Kulaw 2012; Simonsen 2013; Simonsen et al. 2015) and Texas (Streich et al. 2017c; Downey et al. 2018; Rezek et al. 2018; Brewton et al. 2020). Ajemian et al. (2015a) provided the most comprehensive comparison of standing and reefed platform-associated fish communities to date; yet, this study was focused solely in the northwestern GOM and relied on ROV methods supplemented with opportunistic vertical line surveys. Ultimately, understanding the association of fish community structure, biomass, density, and size estimates relative to reef configuration will provide a better understanding of the role of standing and reefed platforms as fishery management tools and guide future decommissioning strategies (Boswell et al. 2010; Reynolds et al. 2018; LGL 2019). Therefore, it must be taken into consideration that these studies may not be representative of the entire (sub)region, and inferences regarding the patterns described should be interpreted with regard to the season, spatial extent, and sampling methods of the respective studies. For example, seasonal and oceanographic variability across the northern GOM can have a substantial influence on the vertical distribution of fishes in the water column (Stanley and Wilson 2004; Williams-Grove and Szedlmayer 2017; Reeves et al. 2018c), community composition (Stanley and Wilson 1997; Reynolds et al. 2018), and fish condition (McCawley and Cowan 2007; Schwartzkopf and Cowan 2017). Research directed towards understanding the temporal dynamics of platform-associated communities will greatly inform our understanding of decommissioning decisions. Moreover, future studies may benefit from combining standardized sampling efforts across the GOM to increase the temporal and spatial extent of sampling and help refine our understanding of the ecological function of different habitats.

The results of this comprehensive literature review identified several research needs and goals for standing and reefed platforms in the GOM including:

- Comprehensive information on ecosystem structure and function
- Understanding the connectivity between habitats
- Improving assessments of fishing pressure and their biological implications
- Addressing the relative importance of attraction versus production
- Optimal artificial reef design
- Establishing long-term monitoring programs

Ecosystem Structure and Function

In general, research into the ecology of platform structures has primarily focused on only a few descriptive aspects such as fish biomass, density, community composition and structure, which currently limits an overall ecosystem understanding on the effects of decommissioning strategies. More comprehensive studies investigating the functional impacts of different reefing options have done so primarily in relation to the biological characteristics (e.g., life history, trophic ecology) of red snapper. As a demersal species, both standing and reefed platforms appear to provide suitable habitat with sufficient resources to support its biological needs. Increased emphasis on a wider range of species, including other broadly distributed fisheries species of commercial and/or recreational value (e.g., greater amberjack), and on whole-community and functional approaches will build towards a more mechanistic understanding of the broader ecosystem values provided by standing and reefed platforms. For example, Rooker et al. (1997) and Beaver (2002) established the importance of the epibenthic fouling community to provide shelter and forage resources to the fish community. Furthermore, compositional dissimilarity in fish assemblages associated with standing and reefed platforms have been documented, with greater abundance of pelagic schooling planktivores and large, mobile piscivores reported on standing platforms (Wilson et al. 2003; Simonsen 2013; Ajemian et al. 2015a; Reynolds et al. 2018). Yet, important questions remain for these distinct shallow fish assemblages and their subsequent decline in abundance during the decommissioning process. For example, what is the mechanism of attraction/ association? How does the presence of artificial lighting on operating standing platforms influence concealment and foraging behaviors at night (e.g., Rooker et al. 1997; Dokken et al. 2000; Keenan et al. 2007; Foss 2016; Barker and Cowan 2018)? Where do these shallow species go after reefing and do they survive? Does the increased presence of large, mobile piscivores observed at standing platforms influence the movements of reef-associated prey away from refuge (e.g., Rooker et al. 1997)? How does reefing influence predation mortality rates on the remaining species?

Connectivity

Fish and invertebrate species observed at both artificial structures and natural reefs may not reside in these habitats for their entire life history as various developmental stages (egg, larval, juvenile, or adult) may populate different depths or habitats (Cowen and Sponaugle 2009; Bishop et al. 2017; Henry et al. 2018; van der Molen et al. 2018; Nishimoto et al. 2019a; Nishimoto et al. 2019b). Therefore, artificial structures and decommissioning strategies do not only produce localized impacts at the sites of their placement/removal, but may also produce larger-scale impacts through their influence on biological connectivity (i.e., the exchange of individuals among marine populations; Cowen and Sponaugle 2009). The influence of artificial structures on biological connectivity within and among populations will vary according to the life history of each species, oceanographic patterns, and distribution of natural and artificial habitats (Adams et al. 2014). For example, biological and oceanographic data have been combined to investigate the extent of potential larval connectivity between artificial structures and natural habitat (Lugo-Fernández et al. 2001; Toland 2001) and also how artificial structures may provide patches of habitat or "stepping stones" that facilitate the dispersal of species into new areas (Gallaway and Lewbel 1982; Sammarco et al. 2004; Sammarco et al. 2012a). Genetic and geochemical (e.g., otolith chemistry) techniques to identify source populations and dispersal distances are also utilized in this effort (Atchison et al. 2008; Patterson et al. 2008; Sammarco et al. 2012b; Sluis et al. 2013; Sluis et al. 2015; Puritz et al. 2016). Moreover, conventional and electronic tagging techniques have investigated potential connectivity between artificial and natural habitats by providing direct estimates of movement, site fidelity, and dispersal (e.g., Patterson 2007; Westmeyer et al. 2007; Topping and Szedlmayer 2011). Changes to connectivity may, in turn, influence the genetic structure and size of populations, the distribution of species, and community structure and ecological functioning (Bishop et al. 2017). The presence of standing platforms in the northern GOM have also facilitated the introduction or range expansion of non-native and invasive species (Villareal et al. 2007; Sheehy and Vik 2010; Sammarco et al. 2014b; Bennett et al. 2019). Despite the growing awareness of the capacity of standing platforms to influence biological connectivity, we lack a comprehensive understanding of the spatial and temporal extent to which the present array of standing and reefed platforms, and natural habitats, in the GOM are biologically connected and the consequences of different decommissioning strategies (e.g., Pondella et al. 2015).

Fishing Pressure

In the GOM, standing and reefed platforms inadvertently function as closed reserves to commercial shrimp trawling due to navigational and entanglement hazards; however, they are open to recreational and commercial fishing pressure (Ditton and Auyong 1985). Standing and reefed platforms and other artificial reefs have been suggested to severely increase the vulnerability of red snapper (and other species) to fishing by aggregating fish closer to shore (Cowan et al. 2011; Cowan and Rose 2016). In contrast, others contend the presence of artificial structures serve as fishery enhancement tools by increasing the abundance and harvest potential of economically important species (Gallaway et al. 2009; Shipp and Bortone 2009). Moreover, the conspicuousness of standing and reefed platforms may also direct fishing pressure away from natural reefs, which may help to preserve these natural habitats (Streich et al. 2017b; Brewton et al. 2020). This inference is supported by a recent survey of recreational boaters and anglers in Texas, which reported that ~55% of respondents used artificial reefs, with nearly 40% and 12% primarily targeting standing and reefed platforms, respectively, compared to 21% targeting natural habitats (Schuett et al. 2015). The use of artificial reefs was largely attributed to greater fishing opportunities. Similarly, Reggio (1987) and Gordon (1993) estimated that 70% and 61%, respectively, of recreational fishing trips off Louisiana principally target standing platforms. Moreover, Gordon (1993) reported that nearly 75% off all recreational anglers tie to platforms at some time during the year. Hiett and Milon (2002) also reported over 20% of all recreational fishing trips (including 20% of small private trips, 32% of charter trips, and 51% of head boat trips) and ~94% of dive trips across Texas, Louisiana, Mississippi, and Alabama target standing platforms. Thus, there is a critical need to accurately assess recreational and commercial fishing pressures and their biological implications among natural habitats, standing platforms, and reefed platforms (e.g., Stanley and Wilson 1989; Stanley and Wilson 1990; Nieland and Wilson 2003; Garner and Patterson 2015; Cowan and Rose 2016; Everett 2018). Furthermore, the role of standing and reefed platforms as pelagic fishery enhancement tools warrants further study including the efficacy of these structures as fish aggregating devices for highly mobile species (Franks 2000) and associated depredation rates (e.g., Hoolihan et al. 2014).

Attraction versus Production

Questions surrounding the ecological value of standing and reefed platforms fall within the broader attraction versus production artificial reef debate (Bohnsack 1989; Gallaway et al. 2009; Shipp and Bortone 2009; Cowan et al. 2011; Cowan and Rose 2016). A key finding from numerous studies are that these two alternatives of attraction versus production are not mutually exclusive and operate along a continuum as some species may be merely attracted to artificial structures, whereas other species may benefit from increased secondary production (Bohnsack 1989). In contrast to fish communities, the epibenthic communities that colonize artificial structures require hard substrate to exist and subsequently increase production at platforms (Beaver et al. 2003; Daigle et al. 2013; Reeves et al. 2018a; Rezek et al. 2018). Thus, the issue of greatest scientific interest is how platform decommissioning strategies may affect existing fish biomass and secondary production. Versar (2008) and Cowan and Rose (2016) estimated fish production attributable to a standing platform based on five abundant species (red snapper, blue runner, sheepshead, Atlantic spadefish [*Chaetodipterus faber*], and bluefish [*Pomatomus saltatrix*]) with sufficient data. Red snapper, bluefish, and blue runner are less dependent upon reef-associated prey and thus had low annual production estimates compared to Atlantic spadefish and sheepshead that depend heavily upon the platform-associated epibenthic community. Furthermore, the net effect on red snapper production is negative when fishing morality is considered (Versar 2008; Cowan and Rose 2016). Versar (2008) and Gomez (2020) further evaluated the impacts of standing platform removal on red snapper productivity by simulating different scenarios of platform removal, which overall decreased red snapper biomass and production. Because standing platforms attract mostly the younger age-classes of red snapper, their contribution to red snapper biomass and spawning potential is relatively low compared to natural habitats (Karnauskas et al. 2017). Therefore, the simulated removal of standing platforms resulted in relatively minor changes in overall GOM red snapper biomass (Gomez 2020). Despite these results, Versar (2008) and Cowan and Rose (2016) caution against drawing inference about the role of platforms as habitat for red snapper given that much of the work has been done on relatively small, low-relief artificial reefs. Moreover, recent work (as reviewed above) comparing the ecological performance of standing and reefed platforms with natural habitats in the northern GOM has highlighted habitat- and region-specific variation in red snapper biology that must be taken into account.

While complete removal would likely reduce or eliminate most of the existing fish biomass and associated secondary production on standing platforms, the potential impacts of reefing in the northern GOM have only been evaluated for epibenthic communities (Rezek et al. 2018). Claisse et al. (2015) and Pondella et al. (2015) estimated the potential impacts of partial removal on the biomass and secondary production of platform-associated fish communities would likely be limited on almost all standing platforms in the SCB. Though, fish production supported by platforms may vary substantially between structures (Claisse et al. 2014) and regions; therefore, these results should not be used to inform RTR policies in the GOM or other regions of the world (Fowler et al. 2015). Therefore, future research efforts should be focused towards direct measures of ecosystem productivity for standing and reefed platforms in comparison to natural habitats and to quantify the potential impacts of different decommissioning strategies.

## Optimal Artificial Reef Design

Artificial structure type and location play an important role in determining the associated fish community (Ajemian et al. 2015a). Studies suggest that optimal artificial reef configurations exist, but vary depending on the target species (Bohnsack and Sutherland 1985; Pickering and Whitmarsh 1997; Campbell et al. 2011; Shipley and Cowan 2011). An evaluation of possible platform orientations (i.e. standing, cut-off, toppled), structural complexity (Wilson et al. 2003; Love et al. 2019b; Meyer-Gutbrod et al. 2019a), and placement (water depth, distance from shore, proximity to natural reefs, number of structures per reef site) warrants further research in order to establish the best management practices for RTR programs. For example, Dokken et al. (2000) suggested having a standing platform as a center point in a designated reefing area in order to maximize vertical relief and supplying additional reefed platforms or smaller-scale habitat enrichment material to enhance fish production. Although the 26 m clearance guidelines observed in current RTR practices may reduce some aspects of biodiversity associated with standing platforms, cut-off platforms may retain similar functionality of standing platforms (Daigle et al. 2013; Rezek et al. 2018). Compared to toppled platforms, cut-off platforms retain higher vertical relief and undergo less disturbance as communities below 26 m are relatively undisturbed during the conversion process and maintain their position in the water column. Moreover, in a partial removal option, the vertical conductor pipes, the conduits carrying the oil and gas to the topside platform structure from below the seafloor, may be left in place and cut off at the same depth as the jacket base (≥26 m), depending on Bureau of Safety and Environmental Enforcement (BSEE) approval (Dauterive 2000; Kaiser et al. 2020). Retention of the conductors provides additional habitat complexity and surface area to the remaining structure and eliminates the need for explosive or mechanical severance below the seafloor, which overall diminishes negative impacts to platform-associated communities (Dauterive 2000; Schroeder and 2004; Bull and Love 2019). In addition, placing the cut-off portion adjacent to the remaining standing structure creates additional habitat augmentation on the seafloor and increases the structural footprint (e.g., Harwell 2013), which is the overall benefit attributed to toppled platforms. The number of structures on a designated reefing site may also influence the resulting fish community. Further investigation into structure density effects and optimal network design of artificial reefs is needed as these materials are considerably larger than most artificial reefs examined in previous studies (e.g., Gallaway et al. 1999; Strelcheck et al. 2005; Campbell et al. 2011; Mudrak and Szedlmayer 2012; Froehlich and Kline 2015; but see Shipley et al. 2018).

## Long-term Monitoring

Long-term monitoring of standing and reefed platforms is essential and will greatly enhance our understanding of the ecological function and habitat value of these artificial structures, including the ecological succession of marine communities following decommissioning (Sommer et al. 2019). From a technical perspective, reefing a platform in place or towing it to an existing reef site is dependent on the size of the structure, clearance requirements, proximity to navigational safety fairways, water depth, and tow distance (Kaiser et al. 2020). In addition, individual platforms should be assessed for their ecological performance and habitat value before decommissioning decisions are made (Fowler et al. 2014; Sammarco 2014; Henrion et al. 2015; FGBNMS 2017; Sommer et al. 2019). A model example is the long-term monitoring of standing platform High Island A-389A (HI-A-389A) that was originally installed in 1981 by Mobile Oil and enclosed within the Flower Garden Banks National Marine Sanctuary boundaries in 1992 (Boland et al. 1983; Rooker et al. 1997; Boland 2002). HI-A-389A was recently converted into a cut-off platform in 2018 as part of the Texas Artificial Reef Program and will undergo annual biological monitoring moving forward (FGBNMS 2017). However, not all platforms are good candidates to remain standing or be converted into artificial reefs. For example, some platforms may be exposed to particularly high sediment and nutrient loads derived from the Mississippi River resulting in hypoxic zones (Stanley and Wilson 2004; Reeves et al. 2018c; Munnelly et al. 2019) or suboptimal salinity and winter temperatures for epibenthic community growth and survival (Sammarco et al. 2012a). Moreover, platforms in place for under 15 years will likely have less-developed reef communities and thus may be less environmentally valuable than others (Sammarco et al. 2004; Kolian and Sammarco 2019).

Surveying communities prior to decommissioning would permit a before-after control-impact study design to directly quantify the effects of different decommissioning options to the existing community and monitor ecological succession (Harwell 2013; Versar 2008; Streich et al. 2017a). Similarly, this methodological approach can be used prior to the placement of new structures such as the construction of a new standing platform (e.g., Todd et al. 2019) or at the designated reefing site where a tow-and-toppled platform will be placed. Using this approach, platform-associated communities would be evaluated for a minimum of one year to account for seasonality in which a given platform or group of platforms were in place. Marine communities would then be compared to the same area after the platforms had been removed or reefed and to nearby control areas that were unchanged to judge temporal trends.

## Summary and Conclusions

These results have important implications for marine resource management, as it demonstrates the potential for reefed platforms left in place to retain habitat value and ecological functions that would otherwise be lost when decommissioned platforms are removed. Overall, allowing platforms to remain standing would ameliorate the decline in biodiversity and fish biomass due to the loss of shallow water substrate. However, the extensive variability in marine life and environmental conditions observed around standing platforms prohibits a generic set of predictions across large ocean basins regarding the ecological consequences of different decommissioning alternatives and decisions should be made on a case-by-case basis (Schroeder and Love 2004) after scientific evaluation. Although the 26-m clearance guidelines observed in current RTR practices may reduce some aspects of biodiversity associated with standing platforms, there is evidence to suggest that partially removed platforms continue to provide an effective means of preserving the ecological functions associated with standing platforms (Ajemian et al. 2015a; Rezek et al. 2018); although, the trade-off is a loss to species richness and diversity. Though, some studies show toppled platforms may better reflect the vertical relief (Versar 2008) and functionality (Simonsen et al. 2015) of low-relief natural reefs. Thus, preserving at least a portion of the structure is highly valuable.

This literature review highlights critical knowledge gaps and research needs to fully understand the impact of decommissioning standing platforms and different reef configurations on the ecology and productivity of the GOM. As standing platforms in the GOM reach the end of their productive lives at an increasing rate, long-term monitoring studies are needed to empirically assess changes to community structure and functionality prior to and following reefing or complete removal. These studies will ensure that RTR programs are operating at maximum efficiency and facilitate data-driven decisions to determine which standing platforms would be most economically and ecologically viable to remain standing and/or converted to artificial reefs.

U.S. federal regulations require that a state agency responsible for managing natural resources assume all liability and costs associated with maintaining standing platforms as artificial reefs in perpetuity (Kaiser and Pulsipher 2005). Alternatively, decommissioned standing platforms may be repurposed for alternative uses such as research, monitoring stations, aquaculture, and a variety of other uses (e.g., Schroeder and Love 2004; FGBNMSAC 2013). Many of these would greatly reduce the logistical challenges associated with traditional ship-based offshore research activities. Although, the cost and benefit considerations must be given to navigational safety, rate of deterioration, cathodic protection and maintenance, increased risk during storm events, and technical feasibility (Schroeder and Love 2004; Bull and Love 2019). Thus, the high costs associated with maintaining decommissioned standing platforms as artificial reefs, or alternate use, have the potential precluded these activities (Schroeder and Love 2004; FGBNMS 2017). However, maintenance costs may be partially or entirely subsidized through alternative uses such as aquaculture and offshore renewable energy (Schroeder and Love 2004; Kaiser et al. 2011; Kolian et al. 2019). Currently, there are programs in the GOM that are showing much promise for viable alternative uses for repurposing standing platforms, and these should be further explored. One such program is the Gulf Offshore Research Institute which has partnered with Peregrine Oil & Gas to apply for a Right of Use and Easement (RUE) from the Bureau of Ocean Energy Management (BOEM) to convert three offshore standing platforms to alternative marine uses.

Partnerships such as these should be further explored to fully understand and integrate various decommissioning options as alternate tools for managers and other decision-makers enabling full utilization of GOM resources.

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**Appendix**

**Table A1.** Summary of literature search results. References in the United States are assigned to the Gulf of Mexico (GOM) and Southern California Bight (SCB) regions. Study type assignments correspond to review, standing oil and gas production platforms, Rigs-to-Reefs (RTR) structures, other artificial reef materials, and natural habitats.

| Reference | Region | Study Type |
|---|---|---|
| Aabel et al. (1997) | North Sea | Review |
| Ajemian et al. (2015a) | GOM | Standing, RTR, Artificial |
| Ajemian et al. (2015b) | GOM | RTR, Artificial |
| Anthony et al. (2013) | SCB | Standing |
| Atchison et al. (2008) | GOM | Standing, Natural |
| Aziz (2019) | Persian Gulf | Standing |
| Barker and Cowan (2018) | GOM | Standing |
| Bergmark and Jørgensen (2014) | North Sea | Standing |
| Bernstein (2015a) | SCB | Review |
| Bernstein (2015b) | SCB | Review |
| Bolser et al. (2020) | GOM | Standing |
| Boswell et al. (2010) | GOM | RTR |
| Brewton et al. (2020) | GOM | Standing, RTR, Natural |
| Brown-Peterson et al. (2019) | GOM | Standing, RTR, Artificial[a] |
| Bull and Kendall (1994) | GOM | RTR, Natural |
| Bull and Love (2019) | SCB | Review |
| Claisse et al. (2014) | SCB | Standing, Natural |
| Claisse et al. (2015) | SCB | Standing, RTR |
| Claisse et al. (2019) | SCB | Standing, Natural |
| Consoli et al. (2013) | Mediterranean Sea | Standing |
| Cowan and Rose (2016) | GOM | Standing |
| Cripps and Aabel (2002) | North Sea | Review |
| Daigle (2011) | GOM | Standing, RTR |
| Daigle et al. (2013) | GOM | Standing |
| Dokken et al. (2000) | GOM | Standing, RTR |
| Downey et al. (2018) | GOM | Standing, RTR, Natural |
| Driessen (1986) | GOM | Review |
| Firth et al. (2016) | North Sea | Review |
| Fortune and Paterson (2018) | North Sea | Review |
| Foss (2016) | GOM | Standing |
| Fowler et al. (2014) | North Sea | Review |
| Fowler et al. (2015) | North Sea | Review |
| Fowler et al. (2018) | North Sea | Review |
| Fowler et al. (2020) | North Sea | Review |
| Friedlander et al. (2014) | West Africa | Standing |
| Getz and Kline (2019) | GOM | RTR, Artificial, Natural |

Table A1. continued.

| Reference | Region | Study Type |
|---|---|---|
| Gitschlag and Herczeg (1994) | GOM | Standing |
| Glenn et al. (2017) | GOM | Standing, RTR, Natural[b] |
| Goddard and Love (2010) | SCB | Standing |
| Gomez (2020) | GOM | Standing |
| Guerin (2009) | North Sea | Standing |
| Harwell (2013) | GOM | Standing, RTR |
| Henrion et al. (2015) | SCB | Review |
| Holbrook et al. (2000) | SCB | Review |
| Jagerroos and Krause (2016) | Southeast Asia | Review |
| Jensen et al. (2000) | North Sea | Review |
| Jones et al. (2019) | North Sea | Standing |
| Karnauskas et al. (2017) | GOM | Standing, RTR, Artificial, Natural[c] |
| Kasprzak (1998) | GOM | Review |
| Keenan et al. (2007) | GOM | Standing |
| Kolian (2011) | GOM | Review |
| Kolian et al. (2018) | GOM | Review |
| Kolian et al. (2019) | GOM | Review |
| Kulaw (2012) | GOM | Standing, RTR, Natural |
| Kulaw et al. (2017) | GOM | Standing, RTR, Artificial, Natural[a] |
| Lima et al. (2019) | SCB | Review |
| Love (20(19) | SCB | Review |
| Love and Goldberg (2009) | SCB | Standing, Natural |
| Love et al. (2003) | SCB | Review |
| Love et al. (2007) | SCB | Standing, Natural |
| Love et al. (2019a) | SCB | Standing |
| Love et al. (2019b) | SCB | Standing |
| Lowe et al. (2009) | SCB | Standing |
| Macreadie et al. (2011) | Australia | Review |
| Martin and Lowe (2010) | SCB | Standing |
| McLean et al. (2019) | Australia | Standing |
| Meyer-Gutbrod et al. (2019b) | SCB | Standing |
| Meyer-Gutbrod et al. (2019a) | SCB | Standing |
| Mireles et al. (2019) | SCB | Standing |
| Moncrief et al. (2018) | GOM | Standing, RTR, Natural |
| Munnelly et al. (2019) | GOM | Standing |
| Nishimoto et al. (2019a) | SCB | Standing |
| Nugraha et al. (2019) | Indonesia | Review |
| Page et al. (1999) | SCB | Standing |
| Page et al. (2019) | SCB | Standing |
| Plumlee et al. (2020) | GOM | RTR, Artificial |
| Pondella et al. (2015) | SCB | Standing, RTR |
| Quirolo and Charter (2014) | GOM | Review |

Table A1. continued.

| Reference | Region | Study Type |
|---|---|---|
| Reeves et al. (2018c) | GOM | Standing |
| Reeves et al. (2018a) | GOM | Standing |
| Reeves et al. (2018b) | GOM | Standing |
| Reeves et al. (2019) | GOM | Standing |
| Reggio (1987) | GOM | Review |
| Reynolds et al. (2018) | GOM | Standing, RTR |
| Rezek et al. (2018) | GOM | Standing, RTR |
| Saari (2011) | GOM | Standing, RTR, Natural |
| Sammarco (2014) | GOM | Review |
| Sammarco et al. (2010) | GOM | Standing |
| Sammarco et al. (2014a) | GOM | Standing, RTR |
| Sammarco et al. (2014b) | GOM | Standing |
| Sammarco et al. (2017) | GOM | Standing |
| Sayer and Baine (2002) | North Sea | Review |
| Scarborough-Bull et al. (2008) | SCB | Review |
| Schroeder and Love (2004) | SCB | Review |
| Schwartzkopf and Cowan (2017) | GOM | Standing, RTR, Natural[b] |
| Schwartzkopf et al. (2017) | GOM | Standing, RTR, Natural[b] |
| Sheehy and Vik (2010) | GOM | Review |
| Shipley et al. (2018) | GOM | Standing, RTR, Artificial[a] |
| Shively et al. (2003) | GOM | Review |
| Simonsen (2013) | GOM | Standing, RTR, Natural |
| Simonsen et al. (2015) | GOM | Standing, RTR, Natural |
| Sink et al. (2010) | South Africa | Standing, Natural |
| Sluis and Cowan (2013) | GOM | Standing |
| Sluis et al. (2013) | GOM | Standing, RTR, Artificial, Natural[b] |
| Soldal et al. (1998) | North Sea | Standing |
| Sommer et al. (2019) | Australia | Review |
| Stanley and Wilson (1998) | GOM | Standing |
| Streich et al. (2017b) | GOM | RTR, Natural |
| Streich et al. (2017c) | GOM | Standing, RTR, Natural |
| Streich et al. (2018) | GOM | Standing, RTR, Natural[d] |
| Thomson et al. (2018) | Australia | Standing |
| Todd et al. (2009) | North Sea | Standing |
| Todd et al. (2018) | North Sea | Standing |
| Todd et al. (2020) | North Sea | Standing |
| van der Stap et al. (2016) | North Sea | Standing |
| van Elden et al. (2019) | Australia | Review |
| Villareal et al. (2007) | GOM | Standing |
| Wells et al. (2018) | GOM | Standing, RTR, Artificial[a] |
| Westmeyer et al. (2007) | GOM | Standing, RTR |
| Wilson et al. (2003) | GOM | Standing, RTR, Natural |

Table A1. continued.

| Reference | Region | Study Type |
| --- | --- | --- |
| Wilson et al. (2006) | GOM | Standing, Natural |
| Wolfson et al. (1979) | SCB | Standing |
| Yeung et al. (2011) | Canada | Standing |

[a]No comparison between habitat types
[b]Standing oil and gas production platforms and RTR structures combined into a single category
[c]RTR structures and other artificial reef materials combined into a single category
[d]Companion study to Streich et al. (2017c)