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ARTICLE

Designing Cost-Effective Artificial Reefs: Fine-Scale Movement and Habitat Use of Red Snapper around a Nearshore Artificial Reef Complex

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Abstract
Artificial reefs are commonly used to provide structured habitat in areas with limited natural habitat to enhance the environment. Creating artificial reefs is expensive, and materials are often limited; thus, discussions are needed regarding the best material and design to maximize reefing efficiency while best meeting the goal of reefing programs. We tracked Red Snapper *Lutjanus campechanus*, an economically important and reef-dependent species, by using a Vemco Positioning System to determine fine-scale movements and habitat use around a nearshore reef comprised of three types of reefing structure: concrete reef pyramids, concrete culverts, and a sunken ship. Habitat use (core volume and home range, or the probability of a fish being absent 50% or 5% of the time, respectively) was significantly different by month, with the largest movements during summer months. Mean depth values also differed by study month (February–August), with Red Snapper residing deepest in the water column during August and shallowest during April. In the summer months, differences among structure types were observed in core volume use but not home range, suggesting that Red Snapper used similar-sized areas on all three structure types. A high reported recapture rate (77%; 10 of 13 fish) indicated that these easily accessible nearshore reefs undergo heavy fishing pressure. Half of the recaptures were reported as recaptured on a structure other than their tagging structure; however, tagged fish spent the greatest percentage of time on their tagging structure. Red Snapper habitat use was influenced more by the presence of structure than by the type of reefing structure. Using the results from this study combined with a cost comparison of reef types, we argue that use of the least expensive reefing material that covers the largest area may be the best policy in designing future artificial reefs.

Artificial reefs have often been used to increase the amount of structured habitat, which is generally sparse in the western Gulf of Mexico, especially off the Texas coast (Jorgensen 2009). These reefs are created from a variety of materials, including oil and gas platforms, ships, concrete structures (e.g., pyramids and culverts), tanks, and discarded appliances (Baine 2001; Boswell et al. 2010; Broughton 2012; Ajemian et al. 2015; Jaxion-Harm and Szedlmayer 2015). Each material has its drawbacks and benefits. For example, concrete structures are cost effective, durable, stable, and often designed specifically for reefing, as the material can be readily shaped into the desired size, complexity, or design. However, these structures can be heavy and require substantial construction and logistics prior to deployment (Broughton 2012). Ships used for reefing offer unique diving experiences and attract both pelagic and demersal fishes, but acquisition and preparation for reefing (e.g., removal of hazardous materials) can be costly (Broughton 2012). The variety and increase of available materials have sparked discussions on the best design (i.e., longevity and cost) and size, material, and location for artificial reefs to meet specific reefing goals—typically increasing fisheries habitat and production and providing alternative management tools (e.g.,

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Strelcheck et al. 2005; Broughton 2012; Sammarco et al. 2014; Harrison 2015; Jaxion-Harm and Szedlmayer 2015; Schuett et al. 2016).

One of the most economically important and reef-dependent fishery species in the Gulf of Mexico is the Red Snapper *Lutjanus campechanus*, which was classified in 1988 as overfished and undergoing overfishing, although the stock is now showing signs of recovering (Goodyear 1988; SEDAR 2018). As a result, Red Snapper have been the focus of intensive management and numerous and extensive scientific studies, especially regarding their use of artificial reefs throughout various stages of their life (Gallaway et al. 2009; Streich et al. 2017). The association of age-0 to age-8 Red Snapper with artificial reefs has been well documented, although this association may weaken throughout the life of the fish. Structures may provide benefits such as increased prey accessibility and protection from predators for younger and smaller fish (Bohnsack 1989; Szedlmayer 1997, 2007; Ouzts and Szedlmayer 2003; Gallaway et al. 2009; Streich et al. 2017). However, site fidelity to artificial reefs is very uncertain based on the wide range reported in the literature. Red Snapper were reported to have extended residency (>200 d) at two reefs off south Texas, with a higher long-term residency on the reef comprised of multiple materials (i.e., sunken tugboat and concrete culverts; Garcia 2013). In multiple long-term studies (>1 year), Red Snapper tagged off Alabama were reported to have long-term residency (>1,099 d) on steel-cage artificial reefs (Szedlmayer 1997; Szedlmayer and Schroepfer 2005; Topping and Szedlmayer 2011a, 2011b). However, Peabody (2004) reported that Red Snapper on oil and gas platforms in Louisiana initially demonstrated site fidelity (~70 d) to their release location, but this decreased over time to lower site fidelity in the long term (>200 d). Residency time may be influenced not only by environmental factors (e.g., depth, season, thermoclines, etc.) but also by reef type, size, and complexity (Froehlich et al. 2021), which should be considered when designing artificial reefs, especially if the goal is to increase habitat and therefore biomass for specific species.

Acoustic telemetry has been used to evaluate movements of Red Snapper, but the results of the studies vary greatly (Schroepfer and Szedlmayer 2006; Strelcheck et al. 2007; Topping and Szedlmayer 2011a, 2011b; Piraino and Szedlmayer 2014; Williams-Grove and Szedlmayer 2017; Froehlich et al. 2019, 2021; Bohaboy et al. 2020; Bacheler et al. 2021). Previous long-term studies found no seasonal differences in habitat use (kernel density estimates), but seasonal emigrations by some individuals were observed (Topping and Szedlmayer 2011b; Froelich et al. 2021). However, other studies found monthly and seasonal differences in habitat use by Red Snapper, which corresponded with water temperatures (Piraino and Szedlmayer 2014; Williams-Grove and Szedlmayer 2017). Despite the extensive research on Red Snapper, most earlier studies used two-dimensional (2D) location patterns to determine their fine-scale movement patterns. This ignores that the environment used by fish is three-dimensional (3D; Simpfendorfer et al. 2012). Recent developments in technology have allowed an increase in studies to focus on the entire 3D environment used by fish (Piranio and Szedlmayer 2014; Williams-Grove and Szedlmayer 2017; Bacheler et al. 2019, 2021; Bohaboy et al. 2020). The Vemco Positioning System (VPS; Vemco Ltd., Halifax, Novia Scotia) is an acoustic positioning system that is able to triangulate more accurate positions that can include depth estimations (i.e., 2D and 3D positions) and is used to track fine-scale movements of fish and other marine animals over long periods of time (Espinoza et al. 2011). Using a VPS array, legal-sized Red Snapper in Alabama were reported to differ in monthly depth patterns and area use (2D and 3D; Piranio and Szedlmayer 2014; Williams-Grove and Szedlmayer 2017). However, these reefs consisted of a single reefed object of one type: a steel cage. Reefs that comprise a suite of materials of varying heights, densities, and complexities may provide increased habitat (vertically and horizontally) and refuge from predators, ultimately increasing fish abundance on these reefs (Lingo and Szedlmayer 2006; Piko and Szedlmayer 2007).

The purpose of the current study was to examine fine-scale movements and habitat selection of Red Snapper on a nearshore Texas reef comprised of multiple reefing materials. Specific objectives were to (1) determine the influence of reef structure type on habitat use patterns by Red Snapper and (2) determine the best reef type when considering cost and habitat selection. This information will assist managers in designing cost-effective artificial reefs to provide additional habitat for Red Snapper.

METHODS

Study site.— The Corpus Christi Nearshore Reef (CCNR; block number MU-775) is an artificial reef located in state waters about 23 m deep and is approximately 15 km southeast of Port Aransas, Texas. This site was selected for study because of its unique design and reefing material used in constructing the artificial reef (Figure 1). In 2013, 470 prefabricated reef pyramids (~3.0-m base × ~2.5 m tall) were deployed in the northwest corner of the permitted reef block, along with 203 concrete culverts of various sizes (from 1.2 × 1.2 m to 3.0 × 3.0 m) in the middle of the reef block. A few pyramids were deployed in the middle of the culvert field and were assumed to not greatly influence the results of this study. In 2014, a 47.2-m steel cargo ship, the M/V *Kinta S* (hereafter, "the *Kinta*"), was sunk in the southeast corner of the reef block, standing about 12 m off the seafloor at the tallest point. A distinct space (~60 m between the

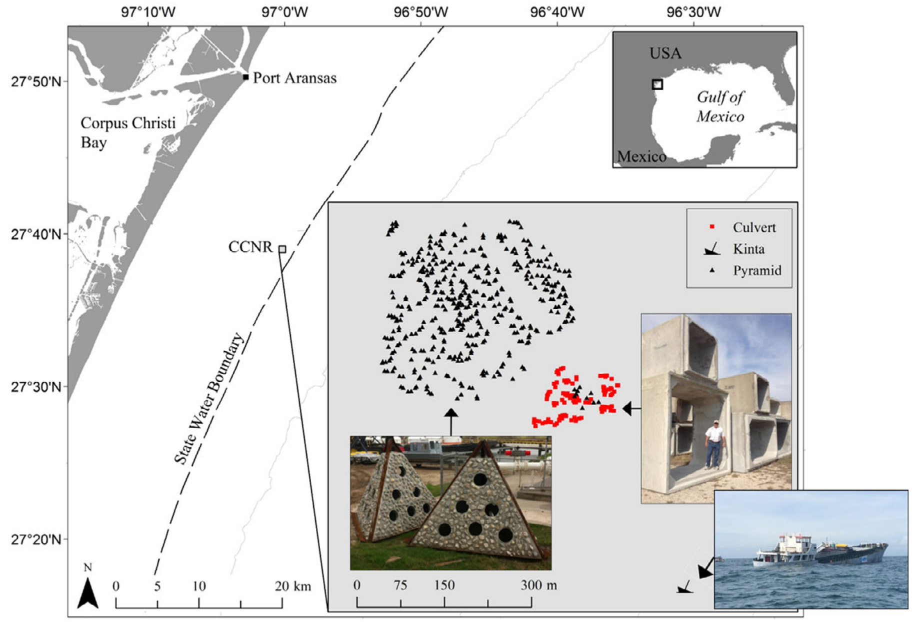

FIGURE 1. The Corpus Christi Nearshore Reef (CCNR) location off the Texas coast and the enlarged reef site, displaying the arrangement of the reefing material within the reef block. The closest port to the reef location was Port Aransas, Texas (black square). Pyramids (~2.5 m tall) had six similar-sized holes on each side compared to the large, single openings in the culverts. Culverts were also approximately 2.5 m tall. The man pictured standing inside the culverts was about 1.8 m tall. (Reproduced from Streich et al. 2017).

pyramids and culverts and ~330 m between the culverts and the *Kinta*) separates each reefing material grouping or field, making this an ideal design for studying fine-scale movements and habitat preferences of Red Snapper on nearshore artificial reefs. Environmental properties (e.g., prey availability, substrate, physical water properties, etc.) were assumed to be similar among reef structure types within the 1-km^2 reefing block.

Fine-scale tracking.— The VPS was used to evaluate fine-scale movement and habitat selection of acoustic-tagged Red Snapper at the CCNR using an array of 20 submersible hydrophone receivers (12 Vemco VR2W and 8 Vemco VR2AR receivers) placed approximately 150 m apart (Figure 2). Receivers were moored to the seafloor using concrete anchors (≥45.36 kg [≥100 lb] in water weight) with angle iron recessed into the concrete. Galvanized pipe was anchored to the angle iron, with a receiver attached to the top of each pipe. A 2-m segment of polypropylene rope leading to an 8.16-kg (18-lb) trawl float was attached to the receivers. Range tests to determine the distance at which the receivers detected acoustic tags were conducted in situ using a reference tag (Vemco V9-2x-069k-3; transmission delay = 500–700 s) that was deployed near the center of each reefing material field. Sentinel tags (Vemco V16-069k-2; transmission delay = 500–700 s) were deployed on the 2-m rope segment to synchronize internal clocks on each receiver and to confirm continuous data collection throughout the study. To identify potential low-detection zones, spatial variation in array efficiency was assessed by calculating the proportion of successful detections at each station from neighboring sentinel tags and interpolating across the VPS array in ArcMap version 10.5 (ESRI, Redlands, California; Tin-Han et al. 2018). Array efficiency was calculated from the day after completion of array deployment (September 9, 2016) until the conclusion of this study (August 24, 2017) using the sentinel tags associated with the nearest neighboring receivers that were recovered. Receivers and associated sentinel tags that were determined by Vemco's proprietary positioning software to have shifted during the study were removed from further spatial detection efficiency analysis on the date of movement as triangulated by the VPS array. Continuous water temperature monitoring occurred using the VR2AR receivers that contained a temperature sensor.

The number of Red Snapper tagged within the array was limited to 21 fish, which was determined as the maximum number of tags for the size of this system before acoustic transmission collisions start reducing array performance (http://vemco.com/collision-calculator/). Sublegal-sized Red Snapper for Texas state waters (<381 mm TL) were targeted for this study to reduce the likelihood of fishing mortality. Seven fish were tagged per reef type (i.e., pyramids, culverts, or the *Kinta*). For the pyramid and

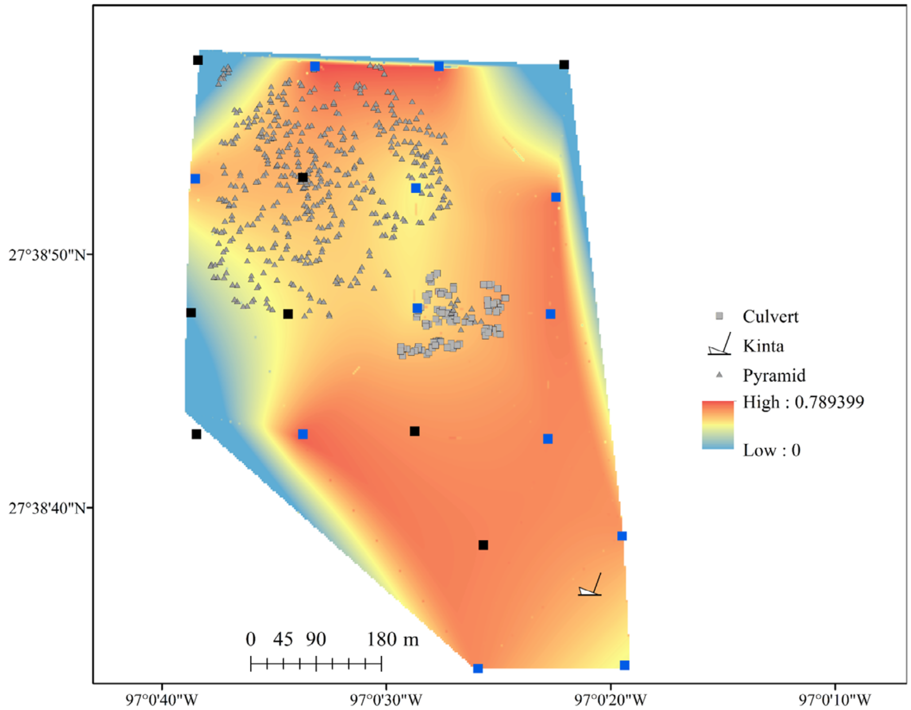

FIGURE 2. The Vemco Positioning System array at the Corpus Christi Nearshore Reef consisted of 20 receivers; the receivers that were retrieved are represented by blue squares. Only retrieved receivers were used in calculating the array efficiency. Black squares represent receivers that could not be retrieved at the conclusion of the study. The color gradient depicts array efficiency.

culvert fields, fish were released as close to their capture location as possible but may not have been released on the exact structure at which they were caught. Red Snapper were surgically implanted with Vemco V9P acoustic transmitters (V9P-2x-069k-1; transmission delay = 155–215 s; battery life = 366 d), which contain a built-in pressure sensor to help determine fine-scale horizontal and vertical movements around the CCNR. A single 15-mm incision was made ventrally above the midline, and a V9P transmitter was placed into the peritoneal cavity. The incision was closed with two sutures (Ethicon Vicryl Plus Antibacterial 2-0, metric 3; Institutional Animal Care and Use Committee, Texas A&M University–Corpus Christi, Animal Use Protocol 10-14; Topping and Szedlmayer 2011b). Fish were externally tagged below the dorsal fin with a dart tag (Hallprint Pty. Ltd., Hindmarsh Valley, South Australia) for reporting recaptures by anglers. External tags had a phone number, e-mail address, unique identification number, and “REWARD” printed on the tag for reporting recaptures. Once tagged, each fish was held for recovery (mean ± SE = 23 ± 3 min) in an aerated, 150-L tank aboard the vessel prior to release. Red Snapper were considered to have recovered when active operculum and fin movement resumed, with the appearance of normal behavior. To decrease the likelihood of predation and any barotrauma effects, Red Snapper were released slightly above the seafloor using a SeaQualizer fish descender (depth release setting was 21.34 m [70 ft]). The descender device was attached to the lower jaw of the fish, which was returned to depth rapidly using a weighted line.

Red Snapper were tracked on the CCNR for 10 months (January–October 2017), with continuous data collection. To exclude any behavior altered by the tagging event, the first 11 d after tagging were omitted from analysis (Topping and Szedlmayer 2011b, 2013). On August 25, 2017, Hurricane Harvey passed through the study area and resulted in displacement of the resident fish on the CCNR. Due to this unpredictable event, Red Snapper fine-scale movement and habitat selection for this study were analyzed through August 24, 2017. Topping and Szedlmayer (2011a) found that Red Snapper emigrated from artificial reefs during or following major storm events, and emigration rates for other reef-dependent fish, such as Gray Triggerfish *Balistes capriscus*, have been reported to increase 100–2,550% during storms compared to days with no storm activity (Bacheler et al. 2019).

Data analysis.— The data analysis for the VPS array requires proprietary positioning software. Therefore, data downloaded from receivers were sent to Vemco for data processing, and the triangulated positions were returned for in-house analysis. Assuming no acoustic tag loss, the array was used to categorize the fate of tagged fish as active (continuously swimming), emigrated (tracked for some time before leaving the array), or deceased (the tag became stationary at a continuous depth or showed a predatory profile; Curtis et al. 2015). Residence time was defined as the time period when 50% of the active tagged Red Snapper were still detected within the array (Williams-Grove and Szedlmayer 2017). Habitat use patterns (core volume use and home range volume) were determined using kernel utilization distribution (KUD) analysis (Simpfendorfer et al. 2012), which estimates the probability of detecting a tagged fish in a particular area. Core volume use is defined as the 50% KUD, or the probability of the tagged fish being absent from the area half of the time, while home range is defined as the 95% KUD, or the probability of the tagged fish being absent from a particular area 5% of the time (Piraino and Szedlmayer 2014). We used KUD calculations because they are robust to spatial autocorrelation and outlying positions (Worton 1989; Seaman and Powell 1996; De Solla et al. 1999).

Statistical analyses were completed in R version 3.5.0 (R Core Team 2014), and 3D KUDs were calculated following Simpfendorfer et al. (2012) by using the *ks* package with a plug-in bandwidth selector to estimate the smoothing factor matrix (Duong 2007). A blocking ANOVA with fish as the random factor and month as the blocked variable was used to test for differences in habitat use among open habitat (i.e., positions triangulated over open bottom outside a structure field) and the three reef structure types (i.e., pyramids, culverts, and the *Kinta*). If significant differences were found between structure and open bottom, then the open-bottom habitat was removed from further habitat preference analyses to explore the influence of structure type. Monthly effects on habitat use were tested by using one-way, repeated-measures ANOVA, with fish as the random factor and month as the repeated measure (Zar 2010). Habitat preference and diel period effects on habitat use were each tested using a one-way ANOVA, with fish as the random factor. Additionally, time spent in each habitat field was calculated using percent detections for each habitat structure type. Depth patterns were also tested using repeated-measures ANOVA, with fish as the random factor and month as the repeated measure. If significant differences were detected, those differences were parsed using a Tukey–Kramer multiple comparison test. A Kruskal–Wallis rank-sum test was used to examine the effects of diel period on depth patterns. Variations around the mean were evaluated by using Levene's test. Linear regression was used to compare core volumes and home ranges to water temperature, habitat field area, and Red Snapper TL. To conduct the cost–benefit analysis, data were obtained from the Texas Parks and Wildlife Department (TPWD) Artificial Reef Program (Shively 2014), and cost per area by structure field and cost per individual structure were calculated. Data were assessed for homogeneity of variance and normality of residuals and were log-transformed if necessary. All tests were conducted at the significance level α of 0.05.

RESULTS

Tagged Red Snapper ranged from 221 to 370 mm TL (mean $\pm$ SD = 297 ± 46 mm TL; Table 1). Of the 21 Red Snapper that were tagged, 8 fish (38%) either suffered a mortality event (e.g., predation or release mortality) or emigrated immediately after release (i.e., tagging-induced emigration). Those fish were omitted from further analysis. Based on depth plots, four of the eight fish were suspected to have been consumed by predators immediately following release. The remaining 13 Red Snapper were used to evaluate fine-scale movements and habitat preferences on the three reef types (culverts: $n = 5$ fish; pyramids: $n = 2$ fish; *Kinta*: $n = 6$ fish). These fish were tracked for 205 d (February 1–August 24), with mean residence time calculated at 135 d.

Fine-Scale Tracking

Twenty receivers were deployed in the VPS array, but due to the effects of the hurricane, only 12 receivers were recovered. Despite this loss, the array provided sufficient coverage and acoustic overlap for position triangulation, with a mean detection efficiency of 0.6867 for the array (Figure 2). Over 1,172,700 detections resulting in nearly 140,000 triangulated positions were used to analyze Red Snapper fine-scale 3D movement patterns at the CCNR. Overall, 86.6% of sentinel tag transmissions were logged on three or more of the recovered receivers. Reference tags showed a mean ($\pm$SD) horizontal (latitude and longitude) accuracy of 2.5 ± 2.4 m, and depth sensors in the acoustic release receivers showed a vertical position accuracy of less than 1 m. Fates of each Red Snapper were determined based on recapture reports, depth plots, and tracks. At the conclusion of the study, three Red Snapper remained present on site, one had suffered a postrelease mortality event after recapture, one was caught and retained by an angler, and six had emigrated (Figure 3). Two fish were originally classified as emigrated based on tracks but were reported as recaptured within the array over 5 months after the last triangulated position or detection event within the array (see Recaptures for more detail). Red Snapper were detected throughout the study duration, but several fish emigrated and returned at least twice prior to the conclusion of the study (Figure 3). Red Snapper that were tagged at the CCNR would need to travel several miles to reach the next closest known structure. Unfortunately, surrounding reef blocks did not have receivers deployed on them during the study period, meaning that once a tagged Red Snapper left the VPS array, its locations were unknown unless the individual was recaptured and reported.

TABLE 1. Movement of Red Snapper on the Vemco Positioning System (VPS) array at the Corpus Christi Nearshore Reef (CCNR). Release structure was the structure type where the fish was caught and released after tagging. Days at liberty were calculated from the date of release (January 20, 2017) until the date of the last triangulated position or harvested recapture. Recapture days at liberty were calculated from the date of release until the date of recapture. Recapture fate and structure were reported by the angler that recaptured the fish, and the structure was confirmed via coordinates submitted by anglers unless noted (†), where recapture location was estimated by triangulated positions. Fate of each fish was determined on the last day of study (August 24, 2017) and is denoted by letters (H = fishing mortality; R = released; E = emigration; M = mortality; P = present on site). Asterisks denote the two fish that were reported as recaptured at the VPS months after their last detection.

Fish number	Release structure	TL (mm)	Days at liberty	Recapture fate	Recapture days at liberty	Recapture structure	Fate at end of study
1	Culvert	221					E
2	Culvert	273	212	H	212	Culvert†	M
3	Culvert	225					M
4	Culvert	270	1				M
5	Culvert	282					M
6	*Kinta*	235					M
7	*Kinta*	293	203	R	13	*Kinta*	E
8	*Kinta*	350	135				E
9	*Kinta*	329	217				P
10	*Kinta*	318	282				P
11	*Kinta*	343	97				E
12	*Kinta*	300	217				P
13	Culvert	246	2				M
14	Culvert	324	177	R	103	Culvert	E
				R	138	Culvert	
15	Pyramid	360	54	R	54	Pyramid	M
16*	Pyramid	289	55	H	317	Pyramid	M
17*	Pyramid	330	66	H	205	CCNR	M
18	Pyramid	242					M
19	Pyramid	282					M
20	Pyramid	370	64	R	33	Culvert	E
21	Pyramid	354	68	R	54	*Kinta*	E

Emigration from the site may be due to the size of Red Snapper, as fish on this site have been previously reported to emigrate at around age 2–3 (Streich et al. 2017).

Significant differences were detected for habitat use between structured habitat and open bottom (core volume use: $F_{3,31} = 5.919$, $P < 0.01$; home range: $F_{3,24.4} = 9.390$, $P < 0.001$); therefore, positions that were triangulated over open bottom were omitted from future analyses. Red Snapper movement increased with warmer water temperatures. Habitat use varied significantly by month (core volume use: $F_{1,6} = 6.147$, $P < 0.001$; home range: $F_{1,6} = 4.024$, $P < 0.01$) and was positively correlated with increasing mean monthly water temperature (Pearson's product-moment correlation, core volume use: $r = 0.939$, $P < 0.001$; home range: $r = 0.779$, $P < 0.05$; Figure 4). Fish used more of the reef in spring and summer months (April–July), with the largest mean KUDs in July (core volume use [mean ± SE] = $18{,}588 \pm 6{,}459$ m^3; home range = $196{,}997 \pm 46{,}084$ m^3), corresponding with warmer temperatures (range = 23.2–30.1°C). The smallest mean core volume uses were observed in February ($2{,}890 \pm 555$ m^3), while the smallest home ranges were observed in March ($43{,}769 \pm 6{,}990$ m^3), when temperatures were cooler (range = 18.6–21.2°C).

Red Snapper movements were also influenced by time of day. There were no significant differences for diel patterns in core volume use ($F_{1,298} = 0.230$, $P = 0.632$), but differences were observed in home range ($F_{1,298} = 59.73$, $P < 0.0001$). Red Snapper had larger-volume movements during the day (0600–2000 hours; mean ± SE = $105{,}164 \pm 7{,}838$ m^3) than during the night (2100–0500 hours; $63{,}789 \pm 5{,}465$ m^3; Figure 5).

Red Snapper used most of the water column from near the surface (1.5 m) to the seafloor (23 m), with a mean (±SD) depth of 18.5 ± 0.641 m. Red Snapper mean depth was not significantly different between diel periods (Kruskal–Wallis rank-sum test: $H = 3.47$, df = 1, $P = 0.062$) or among habitat types ($F_{1,3} = 1.994$, $P = 0.134$) despite vertical relief differences in structure type. Although variation in depth use was not significant for habitat type ($P = 0.293$), significant differences in variation were observed for diel periods ($P < 0.0001$), with fish using a wider range

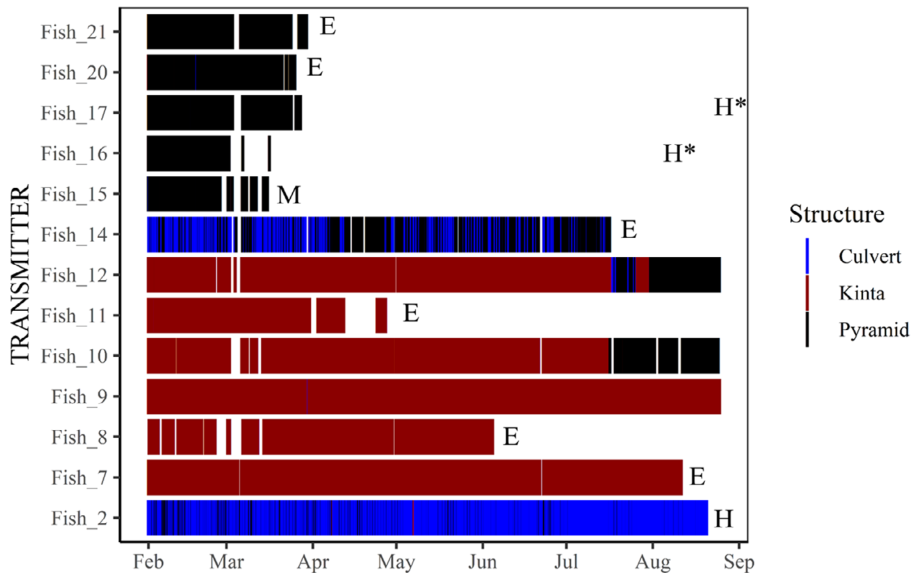

FIGURE 3. Tracking periods for transmitter-tagged Red Snapper on the Vemco Positioning System (VPS) array at the Corpus Christi Nearshore Reef after an 11-d post-tracking recovery period. Fish present after the last day of tracking (August 24, 2017) were all active. The colored bars represent the structure on which the tagged Red Snapper was positioned during the active tracking period. Letters denote the fates of fish on the VPS site (H = fishing mortality; E = emigration; M = mortality). Asterisks denote the two fish that were reported as recaptured at the VPS array months after their last detection.

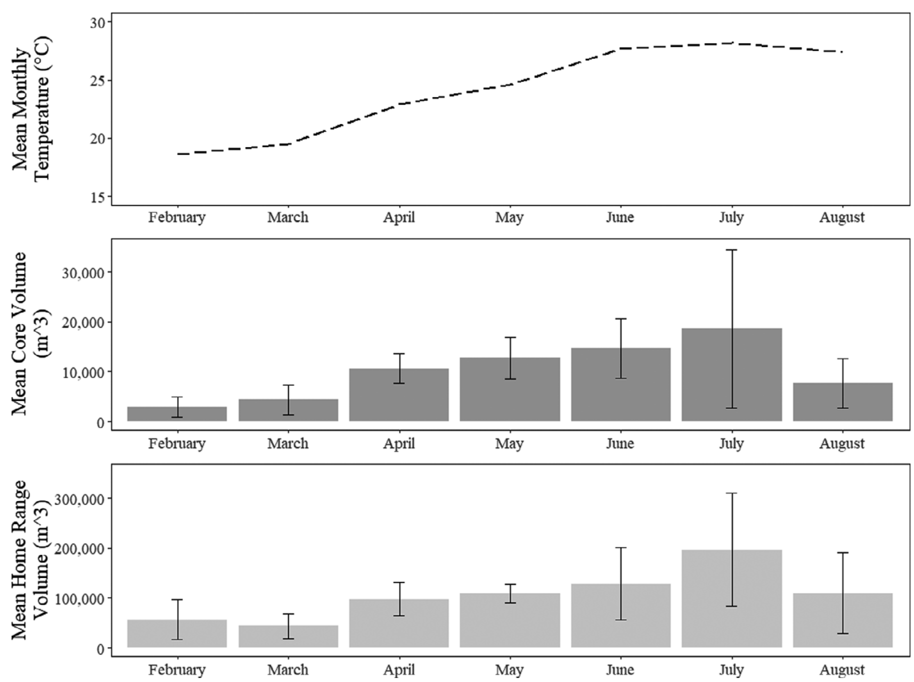

FIGURE 4. Comparison of water temperature with mean monthly core volumes (50% kernel utilization distribution [KUD]) and home ranges (95% KUD) of Red Snapper around the Corpus Christi Nearshore Reef (dark gray bars = core volume; light gray bars = home range; error bars = SE; black dotted line = temperature at depth as recorded by the receivers in the Vemco Positioning System array).

of depths during the day. Monthly changes in depth use were significantly different ($F_{1,7} = 7.205$, $P < 0.0001$) and correlated with water temperature (Pearson's product-moment correlation: $r = 0.764$, $P < 0.05$). Mean (±SE) depth was shallowest in April (17.5 ± 0.440 m) and deepest in August (19.4 ± 0.669 m; Figure 6).

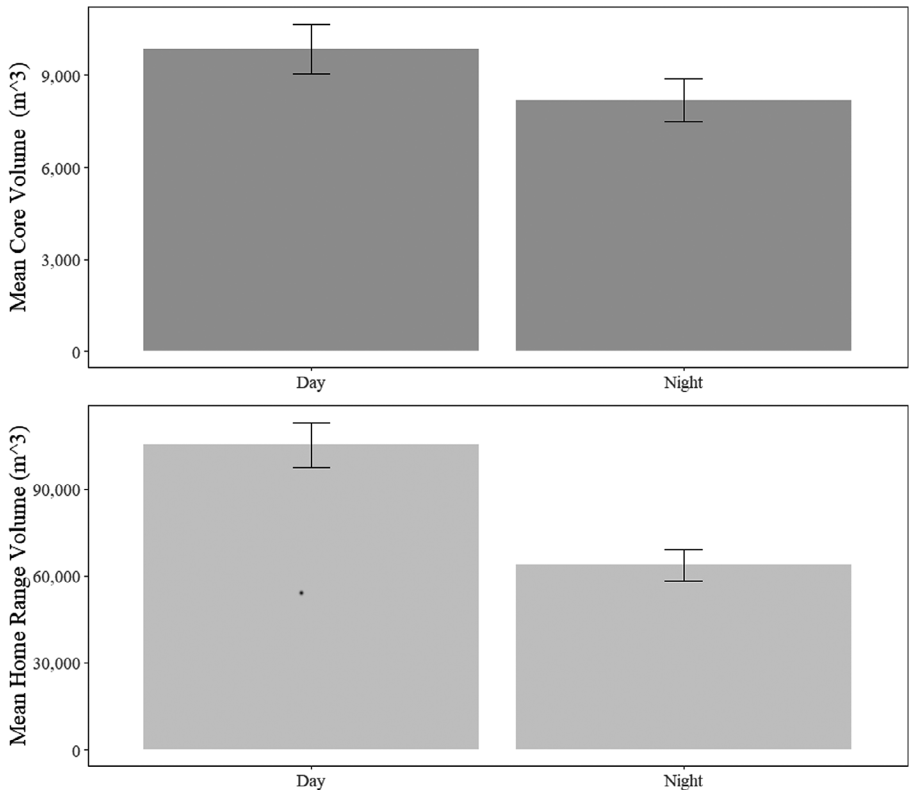

FIGURE 5. Diel movements by Red Snapper on the Corpus Christi Nearshore Reef. Home range (95% kernel utilization distribution [KUD]) was significantly different between diel periods, but core volume (50% KUD) was not. Red Snapper had larger movements during the day (0600–2000 hours) compared to night (2100–0500 hours).

Individual fish spent the greatest percentage of time on their tagging habitat compared to time spent on other habitat types (Figure 7). Fish that were tagged in the culverts moved more than other tagged fish and predominantly moved to the pyramids (Figure 3). When including all months of the study, no significant habitat preferences were detected in Red Snapper habitat use (core volume: $F_{2,18} = 1.371$, $P = 0.279$; home range: $F_{2,18} = 0.425$, $P = 0.660$). However, when examined seasonally, Red Snapper used more of the reef in late spring/summer months (April–July), and differences in core volume use ($F_{2,11.182} = 7.073$, $P < 0.05$) were detected between structure types. Volume used around the sunken vessel *Kinta* was larger than that used around the pyramids or culverts (core volume use: $P < 0.01$ and $P < 0.05$, respectively), but volume use around the pyramids and culverts was similar ($P = 0.205$). Core volume uses were largest over the *Kinta* (mean ± SE = $14{,}576 \pm 2{,}066$ m^3) and smallest over the culverts ($4{,}105 \pm 1{,}570$ m^3). Additionally, home range was not significantly different among habitat types for the summer months ($F_{2,14} = 0.893$, $P = 0.432$). Area covered by reefing material did not influence habitat use (core volume use: $P = 0.223$; home range: $P = 0.579$).

Recaptures

Of the 13 active tagged fish in the study, 10 (77%) were reported as recaptured, with half of those recaptures reported by a single charter headboat. The remaining recaptures were reported by private recreational anglers. Recaptured fish were at liberty for 13–317 d (January–October; mean = 146 d); 43% of the fish with verified recapture locations from angler reports were recaptured on a structure other than the initial tagging structure, including a nearby standing oil and gas platform approximately 4.83 km (3 mi) away. One Red Snapper was reported as recaptured twice in a 1-month period. All recaptured Red Snapper were reported to be released except four individuals, which were all reported to have shed the external Hallprint tags indicating that these fish were being tracked as part of a scientific study. The transmitters were found when fish were filleted, and the anglers reported the transmitters to the Center for Sportfish Science and Conservation (Texas A&M University–Corpus Christi) due to the center's close relationship with the angling community. Although these fish were below the minimum size for Texas state waters when initially tagged, they were above the minimum size when recaptured. One of the reported Red Snapper was recaptured in the

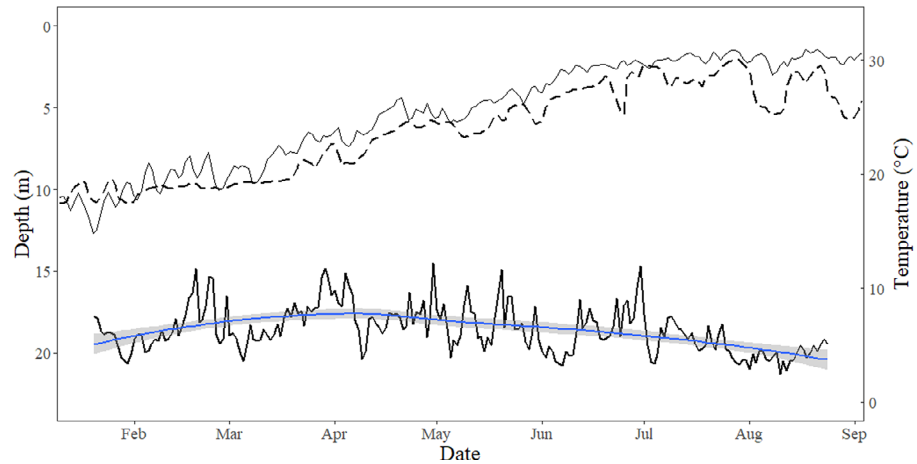

FIGURE 6. Comparison of water temperature by month with daily depths of all Red Snapper around the Corpus Christi Nearshore Reef. Fish were deeper in warmer months and shallower in the cooler months (solid bold line = mean daily depth; solid blue line = overall trend in depth across months, with 95% confidence interval [gray shaded area]; black dashed line = water temperature as recorded by the receivers in the Vemco Positioning System array; black thin line = projected thermocline [difference between mean monthly surface temperatures from the National Oceanic and Atmospheric Administration buoy 42020 and average temperature at depth from the receivers]).

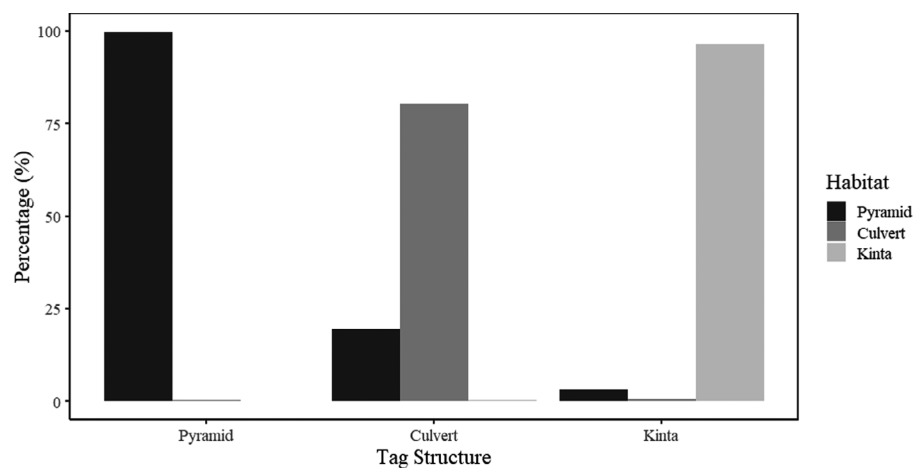

FIGURE 7. Percentage of time spent on each habitat type by Red Snapper (classified by tagging structure) for the entire study duration. Red Snapper spent most of their time on their tagging structure type (pyramids: $n = 5$ fish; culverts: $n = 2$ fish; *Kinta*: $n = 6$ fish). Fish that were tagged on the culverts moved to other reefing structures more than fish that were tagged on the pyramids or the *Kinta*.

pyramid field of the CCNR in December 2017, but the fish was last detected by the VPS array in March 2017 (Figure 3). A second fish was also reportedly recaptured at the study site, but its last detection was months before; however, the recapture location of this individual could not be verified, as coordinates could not be supplied with the recapture information. Depth plots for all fish did not show any unreported recaptures and did not confirm any known recapture events, but triangulated positions for fish 2 (Table 1) suggested that the recapture event occurred in the culvert fields, as this was the last detected position before vanishing from the array, although an exact location was not reported with the recapture information.

Reefing Material

For the purpose of our cost analysis, only the benefits and disadvantages of the reef structure type related to Red Snapper habitat selection were considered. The estimated total cost to deploy 674 reef structures at the CCNR was around US$1.5 million (D. Shively, TPWD, personal communication), with the reef comprised of three types of structure: prefabricated concrete pyramids, concrete culverts, and a sunken cargo ship, the *Kinta*. The total cost for deployment of 470 prefabricated pyramids was about $734,000. Each pyramid costs an estimated $1,600 from construction to reefing, and pyramids can be constructed in large orders and to desired specifications

(Shively 2014). Conversely, concrete culverts are usually donated free of charge to the TPWD Artificial Reef Program for the purpose of constructing artificial reefs; unfortunately, culverts are not readily obtainable, as they are provided when they are constructed incorrectly, resulting in a malformed structure such that the culverts are of various sizes and, unlike the pyramids, are nonuniform. Total cost of deployment for these culverts was \$248,878, resulting in an estimated \$1,250 per culvert to reef. Because the culverts are of various sizes, this cost per unit is an estimate that ignores size (i.e., the cost to reef each unit is assumed to be the same regardless of size). The largest solo structure in the CCNR is the 47.2-m *Kinta*, which was also the most expensive structure per unit to reef. The total cost to prepare and deploy the *Kinta* was about \$496,700 (Shively, personal communication). Ships cannot be reefed without first being cleaned of any harmful materials and chemicals before deployment; therefore, a cleaning and storage area is needed during this time, increasing the expense (Broughton 2012).

For the CCNR, reef structure was not equally represented at the artificial reef complex. The pyramid field covered the largest area (~129,440 m^2) and had the least cost per square meter reefed (~\$6/m^2), but the culverts, which covered less than 30% of the area (~35,870 m^2) of the pyramid field, had a cost per square meter (~\$7/m^2) similar to that of the pyramids. The most expensive structure to reef, the *Kinta*, covered the least amount of area (~7,500 m^2), resulting in an estimated cost of \$67/m^2.

DISCUSSION

This study demonstrated that the fine-scale movement patterns of young adult Red Snapper on a nearshore artificial reef complex were similar among multiple types of reef structure. Red Snapper had limited exchange among reef structures and exhibited fidelity to their initial tagging structures. Lack of difference in mean depths used by fish among habitat types indicated that differences in vertical relief of these material types (i.e., the *Kinta* had ~3× more vertical relief than the pyramids and culverts) may have limited influence on Red Snapper habitat use, especially for individuals just entering the recreational fishery. These results, along with the cost analysis of each reef structure type, suggested that the best policy for management in designing future artificial reefs should include low-cost material distributed over large areas.

Recaptures

The CCNR is an artificial reef located in Texas state waters, which are open 365 d/year for Red Snapper fishing (https://tpwd.texas.gov/regulations/outdoor-annual/fishing/saltwater-fishing/saltwater-bag-and-length-limits). As one of only 15 artificial reefing blocks in state waters (https://tpwd.texas.gov/gis/ris/artificialreefs/), this site is easily accessible to anglers and therefore is heavily fished for Red Snapper year-round by both state-permitted for-hire and private recreational anglers. For example, about 80% of the tagged fish were recaptured, with half of those recaptured by a single headboat. One of those recaptures was unsolicitedly reported while conversing with the headboat captain over the vessel radio. This reporting event, along with the external tag shedding reported by other anglers, suggests that the recapture rate may be higher than reported. The heavy fishing pressure demonstrates the importance of these easily accessible nearshore reefs for anglers and the need for designing artificial reefs that retain fish and provide necessary habitat to support healthy populations.

Fine-Scale Tracking

Collectively, Red Snapper did not select one structure type over another, suggesting that fish demonstrated fidelity to structure regardless of structure type. However, differences in core volume use among structures were detected when analyzing only warmer months (i.e., when fish exhibited increased habitat use). Fish used more volume around the *Kinta*, which covers a smaller geographical area, compared to the pyramids or the culverts, which cover a larger area. Red Snapper also interchanged more between the pyramids and culverts, although more fish from the culverts traveled to the pyramids than vice versa. Proximity was likely a large influence, as the *Kinta* is hundreds of meters away compared to the approximately 60-m space between the pyramids and the culverts. Pyramids may also provide the necessary complexity for protection due to their enclosed nature with small openings for smaller fish to hide within compared to the larger openings in the culverts, which provide less security (see photos in Figure 1). However, pyramids deployed at the CCNR have six similar-sized openings on each side, but no difference in Red Snapper size (TL) was found among structure types at the CCNR (Streich et al. 2017; G.W.S., unpublished data). Previous research has reported that more complex reefs had higher abundances of juvenile Red Snapper. This was purportedly due to the reduced predation success on these more complex reefs, which included increased availability of prey refuges in structure (holes similar to the body size of prey species; Hixon and Beets 1993; Lingo and Szedlmayer 2006; Piko and Szedlmayer 2007). Jaxion-Harm and Szedlmayer (2015) found a higher percentage of small Red Snapper (100–250 mm TL) on smaller reefs (e.g., pyramids and unpublished reefs) than on larger artificial reefs (e.g., tanks, ships, and oil platforms) and observed that pyramids had a higher percentage of larger Red Snapper than unpublished small reefs. This difference was attributed to the pyramids having prey refuges (i.e., one large opening [~30 cm] on each side of the pyramid). The lack of size difference at the CCNR may be due to the reef being comprised of multiple structures that are deployed closely together, creating additional complexity for the entire artificial reef complex compared to the singular structures in the previously published studies.

This study showed that the size of the reef does matter for habitat use. Larger mean core volumes and home range volumes found in the current study likely corresponded to the increased area of the artificial reef site, which consisted of 674 structures of various sizes in a 1-km^2 reef block. Williams-Grove and Szedlmayer (2017) reported smaller 3D KUDs on Alabama reefs consisting of a single steel cage ($2.5 \times 2.4 \times 1.3$ m). Similar to this study, Froehlich et al. (2019) reported that on a 0.8-km^2 reef comprising a variety of structure types, 2D KUDs were up to four times larger than those found in other studies (Szedlmayer and Schroepfer 2005; Topping and Szedlmayer 2011a; Piraino and Szedlmayer 2014; Williams-Grove and Szedlmayer 2016). However, depth was not included in their KUD analysis, and their study was limited to a 3-month tracking period (from the end of August to the beginning of November).

Red Snapper habitat use was also explained by water temperature and was significantly different by month, with fish staying deeper and using more of the reefing block in the warmer months (i.e., June and July) compared to cooler months (i.e., February and March). However, only core volume use was found to have a significant difference, suggesting that fish may be minimizing volume used with cooling water temperatures. Additionally, fish were deepest in August, when the highest water temperatures were observed and a compressed nepheloid layer is present. Red Snapper are often observed moving in and out of the nepheloid layer (Ajemian et al. 2015), and the CCNR is characterized by a thick nepheloid layer that changes depth throughout the year, decreasing in August to near the thermocline, usually around 15 m deep (G.W.S., unpublished data). Smaller Red Snapper are likely using this nepheloid layer to hide from predators, possibly explaining the deeper depths in August. Additionally, differences in water temperature may explain the deeper August depths, as Red Snapper may be staying in cooler water below the thermocline, which is on average 3°C cooler than the water temperature above the thermocline. Red Snapper were shallowest in April, which could be explained by the beginning of the spawning season. However, fish in the current study were small and nearing the size at maturity (Wilson and Nieland 2001). These shallower depths could also potentially be influenced by seasonal upwellings that occur off the Texas coast (Walker 2005). Bacheler et al. (2021) reported that vertical movements for Red Snapper could be explained by bottom upwelling events, which occurred sporadically in warmer months off the North Carolina coast.

Although this study provides valuable data for the design of future artificial reefs, there were some limitations. First, the sample size was limited to avoid acoustic transmission collisions that would decrease the VPS array performance and data collected. The sample size was then further decreased through delayed mortality, predation after release, or emigrations. Second, sublegal-sized Red Snapper were chosen for this study to minimize fishing mortality; thus, the results, although valuable, should be used with caution when extrapolating to larger, older fish, as Red Snapper behavior has been shown to change with age (Render 1995; Nieland and Wilson 2003). Fishing effort on this nearshore artificial reef was not known to be extremely high prior the start of the study but resulted in about 80% of the tagged fish being recaptured. Unfortunately, these recaptures did not readily appear in the depth plots; therefore, using transmitters that ping more frequently could have helped not only to reveal recapture events, but also to give insight into fish movement after release from those recaptures. Third, the timeline of the study was truncated to reduce any influence of the hurricane that passed through the study site, as major meteorological disturbances have been shown to greatly influence emigration rates of reef fish (Topping and Szedlmayer 2011b; Bacheler et al. 2019).

While seasonal differences in habitat use were detected in this study, no difference was detected among habitat types, suggesting that Red Snapper did not select one structure over another. Results from this study have important implications for reef science and management. The cost and availability of reef structures are often the limiting factors for reef deployment; thus, the results from this study indicate that reefing the most effective and least expensive material covering the largest area may be the best policy in designing future artificial reefs when considering Red Snapper habitat use. For the total cost to prepare and reef the *Kinta*, over 315 pyramids could be constructed and deployed or 405 culverts could be deployed, with both materials covering a larger area (17.3 and 4.8 times, respectively) than a single ship; hence, reefing of pyramids and culverts results in a larger area covered by structure for less cost. However, culverts cannot be made to order like pyramids, suggesting that availability and storage can become the limiting factors for that structure type. This would indicate that the readily available pyramids might be a better option costwise for creating reef structure. This would allow managers to create the most expansive reef or use materials in other areas to maximize habitat. Future research should explore in detail the spatial density of structures used in designing artificial reefs and the economic value of different artificial reef types.

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