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Artificial Reefs as Juvenile Fish Habitats in Marinas

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HALMOS COLLEGE OF NATURAL SCIENCES AND OCEANOGRAPHY

Artificial Reefs as Juvenile Fish Habitats in Marinas

By

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Abstract

Coastal infrastructure has replaced many vital fish nursery habitats with structures designed without fully mitigating for the loss of the natural ecosystems. This thesis details research focused on the use of small, inexpensive, artificial reef modules as replacement juvenile fish habitat within marinas. My research hypothesis was that the placement of small, structurally complex artificial reef modules would increase fish abundance and species richness relative to unmodified marina seawalls. Non-destructive visual surveys of fishes were completed monthly for 14 months for 12 artificial reef sites and 12 control (unmodified) sites within the Nova Southeastern University Guy Harvey Oceanographic Center (NSU-GHOC) marina. Divers recorded species, abundance, and size class (0-2 cm, >2-5 cm, >5-10 cm, >10-20 cm, >20-30 cm, >30-50 cm, >50 cm) for all sites. Data was statistically analyzed using analysis of variance (ANOVA) and post-hoc Student Newman-Keuls (SNK) tests to explore differences in mean abundance, mean species richness, and mean abundance and species richness by size class and month. Total mean fish abundance and mean species richness (all months and sizes combined) were both significantly higher at artificial reef sites than at control sites. Artificial reef sites were consistently higher in total abundance and species richness when analyzed by month. Analysis of mean abundance by size class found the >2-5 cm, >5-10 cm, >10-20 cm and >20-30 cm classes were significantly higher for artificial reef sites. Species richness analysis by size class found classes >2-5 cm, >5-10 cm, >10-20 cm, and >20-30 cm were significantly higher at artificial reef sites. Fishes from the grunt (Haemulidae) and snapper (Lutjanidae) families contributed the most to the total abundance for both types of sites. These results support my hypothesis and have important implications for mitigating ecological impact to coastal fish nursery areas with the use of artificial structure.

Keywords: *restoration, marine construction, coral reef fishes, marine mitigation*

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1.0 Introduction

1.1 Background

In the United States, an estimated 123.3 million people resided in coastal shoreline counties in 2010, accounting for 10% of the continental population (Crossett et al., 2013). In Florida, the third most populous state in the country, the majority of the population lives in coastal counties which hold over half a million housing units, including homes, condos, and resorts (Wilson & Fischetti, 2010; Crossett et al., 2013). These highly populated coastal areas have anthropogenic activities that negatively impact nearshore ecosystems, such as construction, port expansion, land reclamation, beach re-nourishment, and dredging (Chapman & Bulleri, 2003; Clynick, 2006).

Nearshore ecosystems, including estuarine and marine habitats, are areas of high productivity critical to fisheries. In Florida 80% of all marine species of recreational or commercial value use mangrove habitats during some period of their life cycle (Moberg & Rönnbäck, 2003). Habitats such as mangroves, coral reefs, and seagrass beds are vital nursery resources for many juvenile fish species worldwide (Blaber & Blaber, 1980; Laegdsgaard & Johnson, 2001). Nursery habitats have qualities differing from offshore habitats such as shallow waters, high turbidity, abundant food availability, protection from predation, and are associated with high growth rates and density of juvenile fishes (Blaber & Blaber, 1980; Laegdsgaard & Johnson, 2001). Such habitat is critical in the life history of many coral reef fishes that initially settle in nursery areas to survive and grow before moving offshore (de la Morinière et al., 2003; Faunce & Serafy, 2007; Grol, Rypel, & Nagelkerken (2014).

1.2 Importance of Study

Mitigating for the loss of coastal habitat is problematic. Replacing vital nursery habitats with artificial surrogates in dissimilar locations does not mitigate effectively for lost habitat. Many projects mitigating habitat destruction result in dubious returns of ecosystem services, fail to meet project goals of restoring or replacing target ecosystems, or have negative environmental impacts (Young, 2000; Naughton & Jokiel, 2001; Morley et al., 2008). Attempting to replace the functionality of different types of habitat is challenging, and the use of dissimilar habitats (e.g. artificial boulder reefs as replacement for lost hardbottom nursery habitats) at a separate, often distant location, is controversial (Kilfoyle et al., 2013). Increasing human coastal populations will continue to require coastal construction projects, and therefore continue to impact juvenile fish habitat (Burt et al., 2009; Levrel, Pioch, & Spieler, 2012). By 2060, almost 7 million acres of Florida land are projected to be converted to urban use (Figure 1)(Cerulean, 2008). Few studies, however, look at the potential of including mitigation efforts directly within coastal construction zones (Glasby & Connell, 1999; Pioch et al., 2011a; Pioch et al., 2011b; Pastor et al., 2013). The placement of artificial reef modules tailored to provide juvenile fish habitat in coastal areas impacted by infrastructure could provide a preemptive move towards restoring some essential fish habitat and the reduction of non-equitable mitigation.

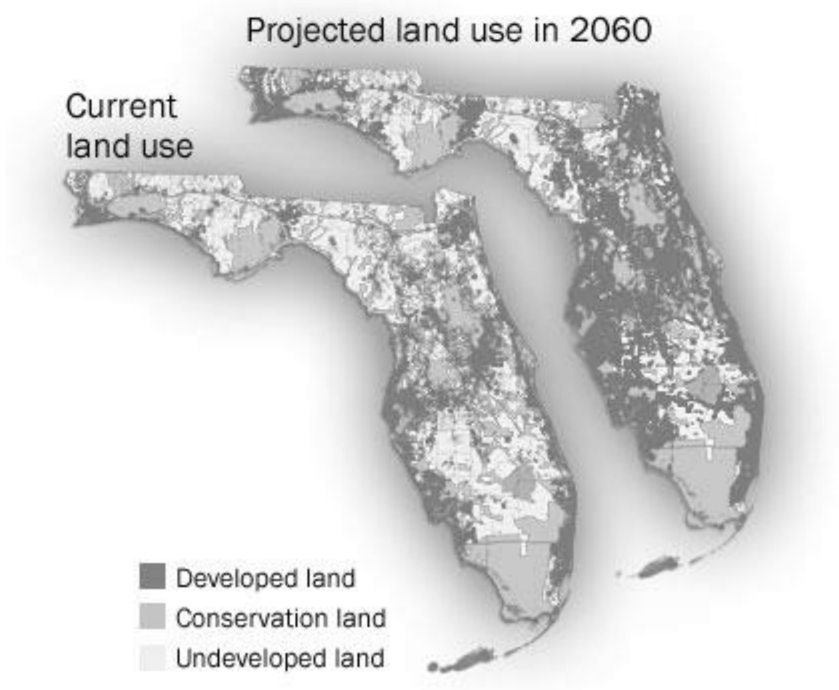

Figure 1. Florida Projected Development (Cerulean, 2008).

Historically, coastal infrastructure has seldom been designed with fish or invertebrate species in mind, however, these areas are still inhabited by marine organisms (Pioch et al., 2011a; Pioch et al., 2011b). More recently there has been considerable interest in incorporating ecological engineering in new coastal structure, but this has primarily involved coastal armoring studies and not marinas or the like (Firth et al., 2014; Dafforn et al., 2015; Coombes et al., 2015; Sella & Perkol-Finkel, 2015). Marinas and associated structures may be capable of hosting large abundances of small juvenile fish, and may potentially act as nursery areas (Able et al., 1998; Clynick, 2006; Pastor et al., 2013). Studies conducted in marinas show that fish may be attracted to the structure provided by jetties, pilings, and pontoons (Coleman & Connell, 2001; Moreau et al., 2008; Pastor et al., 2013). However, few studies discuss the potential of adding additional structure into preexisting infrastructure in order to increase potential fish habitat (Lacroix & Pioch, 2011; Pioch et al., 2011a). An apparently neglected study published in 1984 illustrated a simple yet effective habitat improvement technique to mitigate habitat loss by marina development. The authors placed boulders under three docks inside a marina in Biscayne Bay, FL, and recorded a significant increase in the number and density of fish and invertebrates (Iversen & Bannerot, 1984). In a freshwater reservoir study, Barwick et al. (2004) attached plastic pallets to piers in North and South Carolina and found higher fish abundances and total fish biomass associated with sites containing plastic pallets as opposed to control sites. These two studies imply that the addition of purpose-built artificial structure into pre-existing coastal infrastructure can have positive effects on fish abundance.

1.3 Statement of Purpose

My research focused on the potential to use small, inexpensive artificial reef modules as replacement juvenile fish habitat within marinas. I hypothesized that areas within the Nova Southeastern University Guy Harvey Oceanographic Center (NSU-GHOC) boat basin containing artificial reef modules would have a higher abundance of juvenile fish than areas without modules due to increased structural complexity and enhanced opportunities for predator evasion.

2.0 Materials & Methods

2.1 Study Area

This study took place in the NSU-GHOC boat basin in Broward County, Florida, located 800m from the mouth of Port Everglades (Figure 2). Although many shorelines within the port are hardened by seawalls or rip-rap, mangrove and seagrass habitats still exist. Port Everglades acts as an essential fish habitat to many different species, providing the substrate and habitats necessary to allow for fish "spawning, breeding, feeding, or growth to maturity" (Karazsia & Pace, 2011). The inshore area of the port supports juveniles and sub-adults of 43 out of the 71 species named by the Snapper-Grouper Fisheries Management Plan (Karazsia & Pace, 2011).

The NSU-GHOC boat basin accommodates a maximum of 26 vessels up to 12 m in length, and has a maximum depth of 3 m at high tide. Direct access to Port Everglades allows for easy access between the boat basin, nearshore, and offshore habitats. The NSU-GHOC boat basin is typically characterized by having high turbidity levels due to an influx of turbid water from Port Everglades combined with a shallow, silt-covered bottom. This increased turbidity is attractive for many juvenile fish species, as suspended particulates increase food availability and decrease the visual acuity and hunting ability of many predators (Swenson, 1978; Blaber & Blaber, 1980). Paddle Seagrass (*Halophila decipiens*) and occasional blooms of filamentous algae sparsely populate open areas within the boat basin (Karazsia & Pace, 2011). In addition, the shallow depth of the boat basin restricts the areas in which most larger predators can travel (Blaber & Blaber, 1980). The NSU-GHOC boat basin also has weak, tidal-driven currents that are favorable for juvenile fish feeding behavior.

Figure 2. NSU-GHOC Boat Basin, Port Everglades. The study area is situated next to the port's mouth, allowing for easy access to nearshore habitats.

2.2 Module Design

The artificial reef module design used in this study was adapted from the Gilliam-Spieler 'fish condo' design (Sherman, 2000). Four 0.51 m^2 square concrete pavers, weighing 22.7 kg each, make up the base and three levels of the module (Figure 2). Five 4 cm tall concrete bricks separate each level, with one brick per corner and one brick centered on the paver. All bricks were oriented in the same direction to allow for an unrestricted view into the module. The overall result was an approximately 136.1 kg cube, 0.51 m in width and length and 0.66 m in height. This design provides internal space for smaller fish with internal structure and shading effect. The small size of the modules allowed them to easily fit between the batters of the seawall, which are 1.5 m apart from one another.

The modules were constructed on February 23 and 24, 2015. All artificial reef modules were constructed on land, using a cement mixture to attach the layers together.

The cement was allowed to harden for a minimum of 24 hours. On February 25th, 2015, the modules were lowered into their respective positions in the boat basin using a forklift and a rope cradle (Figure 3). A diver assisted with the placement of the modules in order to adjust module position before permanent settling. The modules were deployed 18 m apart from each other within the boat basin, located equidistant between two batters and 0.5 m away from the seawall.

Figure 3. Artificial reef modules were deployed into the NSU-GHOC boat basin by forklift. A diver in the water assisted with module placement.

A total of 24 survey sites were designated for this study, 12 control (C) sites and 12 Artificial Reef (AR) sites (Figure 4). Control sites contained no modification, while artificial reef sites contained one artificial reef module within the survey area. Sites were labeled C1 through C12 for control sites and AR1 through AR12 for artificial reef sites. Control sites were located 9m from each artificial reef module, and consisted of 1.5 m^3 sections within the harbor that did not receive habitat modifications. Due to variations in bottom depth, each module was placed at a depth ranging between 1 m to 3 m deep.

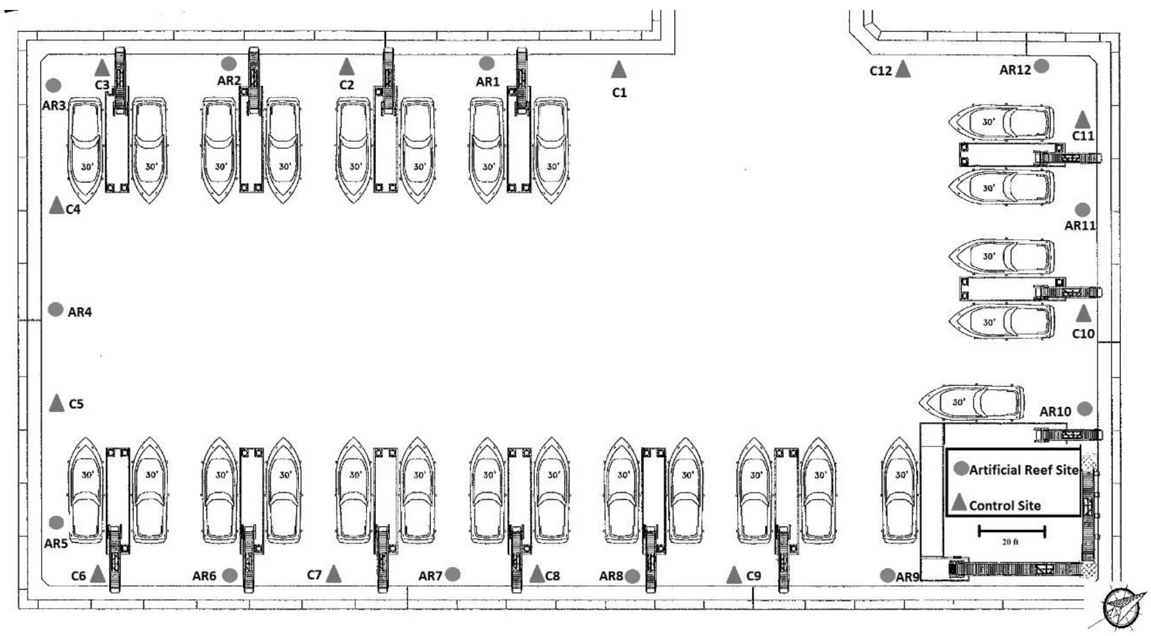

Figure 4. Artificial reef and control site locations within the NSU-GHOC boat basin

2.3 Survey Methodology

A visual census, modified from the method described by Bannerot & Bohnsack (1986) was conducted on every module and control site once a month for a period of fourteen months. Diver A began at site C1 and worked counterclockwise, while Diver B began at site C12 and worked clockwise. The survey covered a rectangular area from the substrate to the water surface, and included all areas between the batters to the seawall. Divers initially positioned themselves near the bottom 1-2 m away from the survey area to observe the entire area, and then moved closer to inspect the area behind the modules and up against the seawall. Data recorded included number of individuals by size class (0-2 cm, >2-5 cm, >5-10 cm, >10-20 cm, >20-30 cm, >30-50 cm, >50 cm estimated total length) within the target area. Surveys took place for a total of three minutes or until all fish species had been recorded. A watcher on the seawall followed divers from the surface as a safety precaution.

2.4 Statistical Analysis

The sampling protocol intentionally resulted in duplicate counts for each module and control site each month, with a few exceptions when extenuating circumstances were a factor (i.e., safety concerns, weather, illness) and only a single count per site was possible. To account for the duplicate surveys, the analysis was performed on the mean values taken from both Diver A and B at each site. This strategy allowed for some of the more reclusive species to be observed that may have been missed by one survey diver. A parametric one-way ANOVA was used to determine significance of mean abundance, species richness, and size class using the program Statistica V13 (Statsoft Inc., Tulsa, Oklahoma, USA). Abundance data underwent a log(x+1) transformation before analysis to homogenize variances. A post-hoc Student Newman-Keuls (SNK) test was used to test for differences between treatments and months. An Alpha level of $p<0.05$ was accepted as a significant difference. Percent occurrence was also calculated for each species by dividing the total number of times the species occurred in surveys by the total number of surveys completed. This provides the likelihood of each species being present in any given survey. A multidimensional scaling (MDS) plot created in Primer v6 (Clark & Gorley, 2006) was used to compare artificial reef and control locations for all 336 surveys.

3.0 Results

3.1 General

A total of 14 survey events were conducted monthly between March 2015 and May 2016, resulting in 336 surveys for analysis once the duplicates were combined. Of these 336 surveys, 168 occurred at artificial reef sites and 168 occurred at control sites. No survey was conducted during May of 2015 due to sustained inclement weather and excessive turbidity. A combined total of 2,269 fish were counted at all sites during the 14 month period.

Overall, 65 species from 25 different families were observed during survey events (Table 1). The five most frequently observed species in terms of percent occurrence at both artificial reef and control sites combined were: *Lutjanus griseus* (51.2%), *Anisotremus virginicus* (40.2%), *Lutjanus synagris* (29.5%), *Abudefduf saxatilis* (27.1%), and *Lutjanus apodus* (25.9%). Fifteen of the observed species fall within the Snapper-Grouper Fishery Management Plan (Karazsia & Pace, 2011). Out of the total number of fishes counted, 1,079 (47.6%) were grunts (Haemulidae) and 512 (22.5%) were snappers (Lutjanidae), making these two families responsible for a larger portion of the dataset than any other families.

Table 1. List of observed fish species, total abundance, and percent occurrence for artificial reef (AR) and control sites.

Scientific Name	Common Name	Combined Total Abundance	AR Total Abundance	Control Total Abundance	AR % Occurrence	Control % Occurrence
Pomacanthidae	**Angelfish**					
Pomacanthus arcuatus	Gray Angelfish	8	5.5	2.5	4.17%	1.79%
Sphyraenidae	**Barracuda**					
Sphyraena barracuda	Great Barracuda	2	2	0	2.38%	0.00%
Clinidae	**Clinids**					
Labrisomus nuchipinnis	Hairy Blenny	2	1.5	0.5	1.19%	0.60%
Malacoctenus macropus	Rosy Blenny	2	0	2	0.00%	2.38%
Blennidae	**Blennies**					
Hypleurochilus geminatus	Crested Blenny	1.5	1	0.5	0.60%	0.60%
Parablennius marmoreus	Seaweed Blenny	2	0	2	0.00%	1.79%
Pomacentridae	**Damselfish**					
Abudefduf saxatilis	Sergeant Major	116.5	80	36.5	32.74%	21.43%
Stegastes adustus	Dusky Damselfish	1	0	1	0.00%	0.60%
Stegastes leucostictus	Beaugregory	0.5	0.5	0	0.60%	0.00%
Stegastes variabilis	Bicolor Damselfish	1.5	1.5	0	1.79%	0.00%
Sciaenidae	**Drums**					
Odontoscion dentex	Reef Croaker	1	1	0	0.60%	0.00%
Pareques acuminatus	Highhat	3.5	3.5	0	3.57%	0.00%
Gobiidae	**Gobies**					
Coryphopterus glaucofraenum	Bridled Goby	3	0.5	2.5	0.60%	2.98%
Ctenogobius saepepallens	Dash Goby	9	1.5	7.5	1.19%	5.95%
Elacatinus oceanops	Neon Goby	3	3	0	1.79%	0.00%
Gobiosoma grosvenori	Rockcut Goby	0.5	0.5	0	0.60%	0.00%
Gobiosoma robustum	Code Goby	3	0.5	2.5	0.60%	2.98%
Lophogobius cyprinoides	Crested Goby	5	1	4	1.19%	2.98%
Microgobius microlepis	Banner Goby	6.5	1.5	5	1.19%	2.98%
Haemulidae	**Grunts**					
Anisotremus virginicus	Porkfish	180.5	143.5	37	54.17%	26.19%
Haemulon aurolineatum	Tomtate	25.5	17.5	8	6.55%	2.38%
Haemulon carbonarium	Caesar Grunt	4.5	4.5	0	2.98%	0.00%
Haemulon flavolineatum	French Grunt	169	124	45	31.55%	11.31%
Haemulon macrostomum	Spanish Grunt	0.5	0.5	0	0.60%	0.00%
Haemulon parra	Sailor's Choice	16	12	4	10.12%	3.57%
Haemulon plumierii	White Grunt	17	12	5	8.33%	3.57%
Haemulon sciurus	Bluestriped Grunt	96	85	11	35.12%	7.14%
Haemulon spp.	Grunt spp.	570	461.5	108.5	22.02%	17.86%

Scientific Name	Common Name	Combined Total Abundance	Artificial Reef Total Abundance	Control Total Abundance	Artificial Reef % Occurrence	Control % Occurrence
Carangidae	**Jacks**					
Caranx crysos	Blue Runner	2	1.5	0.5	1.19%	0.60%
Caranx hippos	Crevalle Jack	11.5	3.5	8	1.79%	2.98%
Selene vomer	Lookdown	39	33.5	5.5	5.36%	1.79%
Balistidae	**Triggerfish**					
Balistes capriscus	Gray Triggerfish	3.5	2.5	1	2.38%	1.19%
Gerreidae	**Mojarra**					
Gerres spp.	Mojarra spp.	202	84	118	12.50%	20.24%
Muraenidae	**Moray Eel**					
Gymnothorax funebris	Green Moray	2	2	0	1.19%	0.00%
Gymnothorax moringa	Spotted Moray	0.5	0.5	0	0.60%	0.00%
Ginglymostomatidae	**Nurse Sharks**					
Ginglymostoma cirratum	Nurse Sharks	3.5	3.5	0	1.79%	0.00%
Scaridae	**Parrotfish**					
Scarus guacamaia	Rainbow Parrotfish	5.5	3.5	2	1.79%	1.79%
Scarus iseri	Striped Parrotfish	0.5	0	0.5	0.00%	0.60%
Sparisoma aurofrenatum	Redband Parrotfish	2	0.5	1.5	0.60%	1.79%
Sparisoma chrysopterum	Redtail Parrotfish	3	0.5	2.5	0.60%	2.98%
Sparisoma rubripinne	Yellowtail Parrotfish	10.5	4	6.5	2.38%	1.79%
Sparisoma viride	Stoplight Parrotfish	1	1	0	0.60%	0.00%
Sparidae	**Porgies**					
Archosargus probatocephalus	Sheepshead	3	2	1	2.38%	1.19%
Archosargus rhomboidalis	Seabream	22.5	12	10.5	8.33%	7.74%
Diplodus holbrookii	Spottail Pinfish	67.5	39	28.5	14.29%	13.10%
Lagodon rhomboides	Pinfish	1.5	1.5	0	0.60%	0.00%
Tetraodontidae	**Pufferfish**					
Canthigaster rostrata	Sharpnose Puffer	3	1.5	1.5	1.79%	1.79%
Sphoeroides spengleri	Bandtail Puffer	14	6	8	5.95%	7.74%
Sphoeroides testudineus	Checkered Puffer	13	7.5	5.5	7.74%	5.95%
Serranidae	**Sea Bass**					
Epinephelus morio	Red Grouper	0.5	0	0.5	0.00%	0.60%
Scorpaenidae	**Scorpionfish**					
Scorpaena plumieri	Spotted Scorpionfish	1.5	1	0.5	1.19%	0.60%
Lutjanidae	**Snapper**					
Lutjanus analis	Mutton Snapper	0.5	0.5	0	0.60%	0.00%
Lutjanus apodus	Schoolmaster Snapper	91.5	71.5	20	36.31%	15.48%
Lutjanus griseus	Gray Snapper	285	210.5	74.5	66.67%	35.71%
Lutjanus synagris	Lane Snapper	129	98.5	30.5	38.10%	20.83%
Ocyurus chrysurus	Yellowtail Snapper	6.5	2.5	4	2.38%	1.19%

Scientific Name	Common Name	Combined Total Abundance	Artificial Reef Total Abundance	Control Total Abundance	Artificial Reef % Occurrence	Control % Occurrence
Centropomidae	**Snook**					
Centropomus undecimalis	Snook	48.5	43	5.5	6.55%	2.98%
Diodontidae	**Porcupinefish**					
Chilomycterus schoepfi	Striped Burrfish	0.5	0.5	0	0.60%	0.00%
Diodon hystrix	Porcupinefish	0.5	0	0.5	0.00%	0.60%
Dasyatidae	**Stingrays**					
Urobatis jamaicensis	Yellow Stingray	2	1	1	1.19%	1.19%
Acanthuridae	**Surgeonfish**					
Acanthurus bahianus	Ocean Surgeonfish	15	2	13	2.38%	4.17%
Acanthurus chirurgus	Doctofish	24	6.5	17.5	6.55%	3.57%
Acanthurus coeruleus	Blue Tang	2	1	1	1.19%	0.60%
Labridae	**Wrasses**					
Halichoeres bivittatus	Slippery Dick	0.5	0	0.5	0.00%	0.60%
Total		**2269**	**1614**	**655**		

3.2 Mean Fish Abundance

With all 14 months combined, mean fish abundance was found to be significant ($p<0.01$) greater at artificial reef sites compared to control sites (Figure 5). Combined surveys resulted in a total of 1,614 fish counted at artificial reef sites and 655 at control sites. Mean abundance at artificial reef sites was 9.6 (±1.1 SEM) fish per site, while mean abundance at control sites was 4.0 (±0.4 SEM) fish per site.

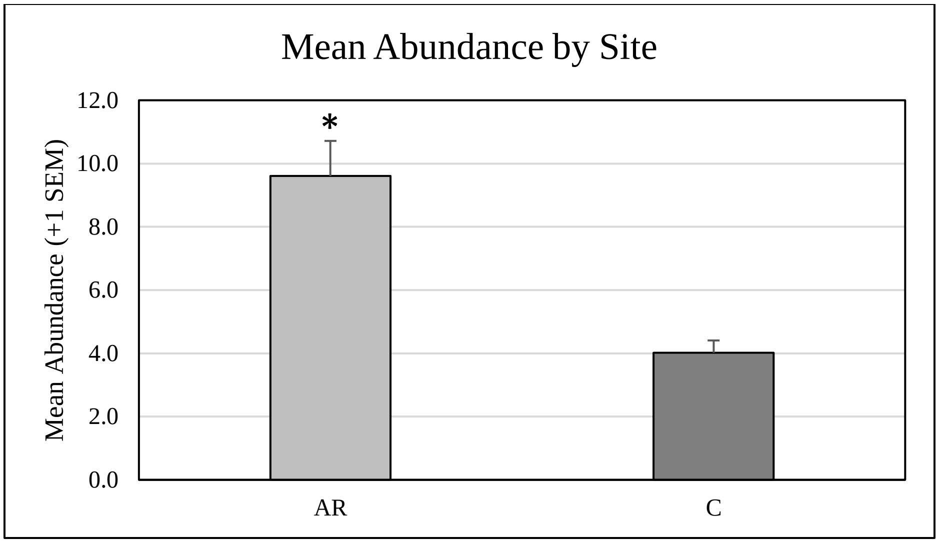

Figure 5. Mean fish abundance by treatment for artificial reefs (AR) and control sites. AR mean is significantly greater than control (ANOVA, p<0.05).

3.3 Mean Species Richness

Species richness was also found to be significantly higher (p<0.01) at artificial reef sites compared to control sites (Figure 6). Mean species richness at artificial reef sites was 3.5 (±0.2 SEM) fish per site, while mean abundance at control sites was 1.8 (±0.1 SEM) fish per site. Out of the 65 observed species, 42 were observed at higher abundances at artificial reef sites. In addition, out of the 65 total species recorded from all surveys, 42 species were surveyed at both artificial reef and control sites, 16 species recorded exclusively at artificial reef sites, and 7 species only noted on control sites.

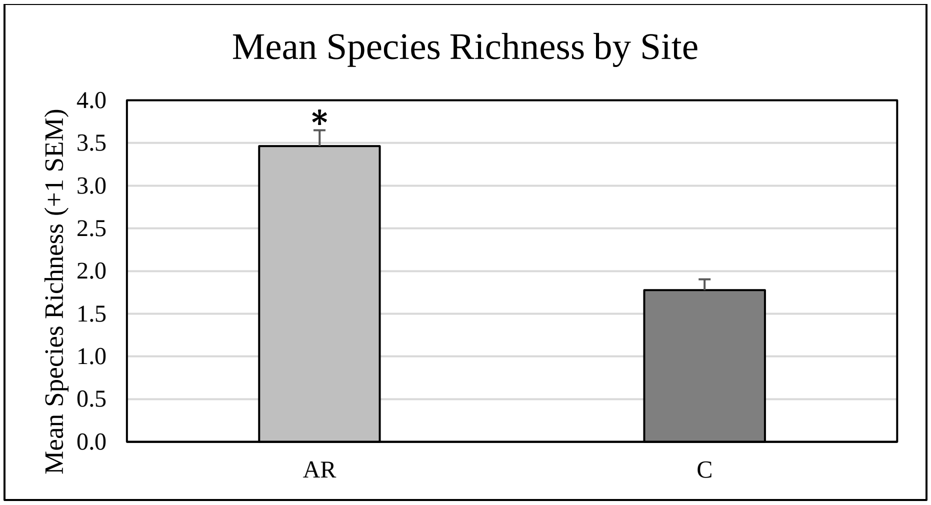

Figure 6. Mean species richness by treatment for artificial reefs (AR) and control sites. AR mean is significantly greater than control (ANOVA, $p<0.05$).

3.4 Size Class

Mean abundance by size class was tested for both artificial reef and control treatments (Figure 7). Abundance of size classes >2-5cm ($p=0.007$), >5-10 cm ($p<0.001$), >10-20 cm ($p<0.001$), and >20-30 cm ($p=0.02$) were found to be significantly higher for artificial reef treatments. Although the abundance of fishes observed at artificial reef sites for the 0-2 cm size class was greater than controls, this difference was not statistically significant ($p=0.49$).

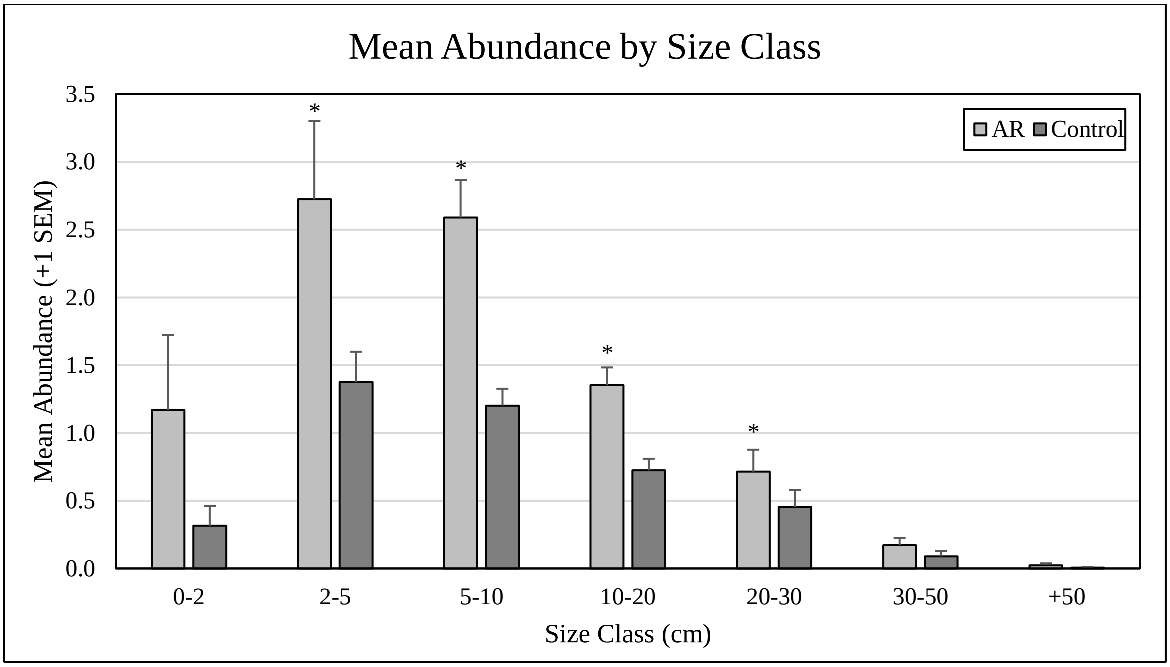

Figure 7. Mean abundance by size class for artificial reefs (AR) and control sites. Columns with an asterisk indicate a significant difference between AR and control within a size class (ANOVA, SNK, $p<0.05$).

Mean species richness by size class was analyzed by treatment (Figure 8). For size classes >2-5 cm (p=0.002), >5-10 cm (p<0.001), >10-20 cm (p<0.001), and >20-30 cm (p=0.046) artificial reef treatments had significantly more species. Size classes 0-2 cm (p=0.62), >30-50 cm (p=0.638), and 50+ cm (p=0.219) were not statistically significant between treatments.

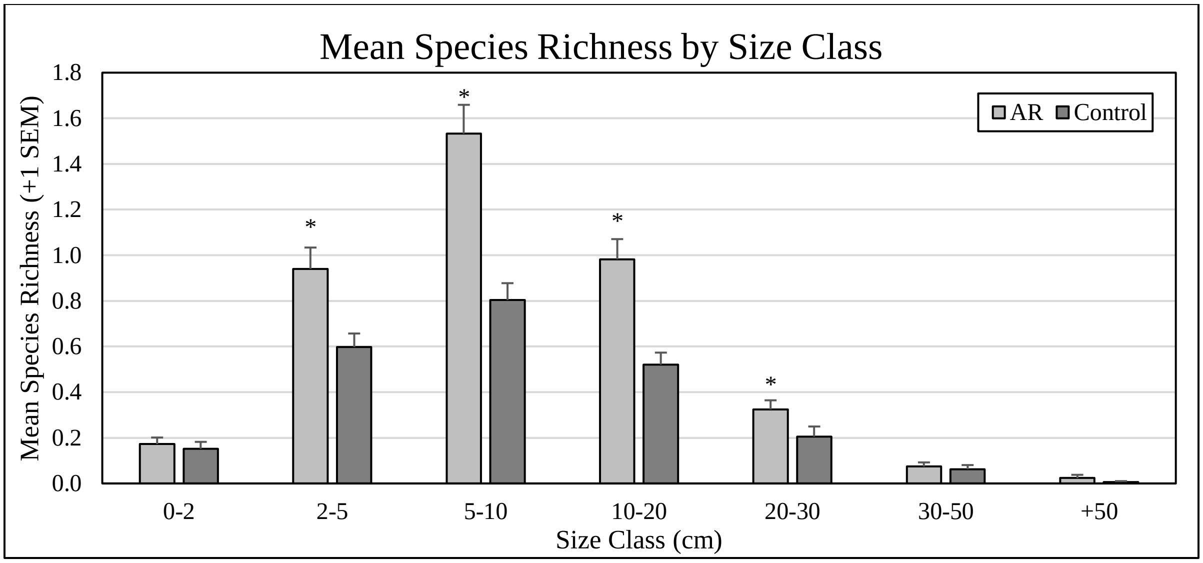

Figure 8. Mean species richness by size class for artificial reefs (AR) and control sites. Columns with an asterisk indicate a significant difference between AR and control within a size class (ANOVA, SNK, p<0.05).

3.5 Treatment by Month

During the 14 months of surveys, the highest fish abundance for artificial reef sites was observed in March 2015, with an average of 40.6 (±10.1 SEM) fish per site (Figure 9). The highest abundance for control sites was observed in August 2015, with an average 11.4 (± 2.3 SEM) fish per site. Out of 14 months, 10 months had significantly higher ($p<0.05$) abundances at artificial reef sites compared to control sites. Mean abundance by month was never higher for control treatments than artificial reef treatments, with the single exception of July 2015 which was not statistically significant ($p=0.96$).

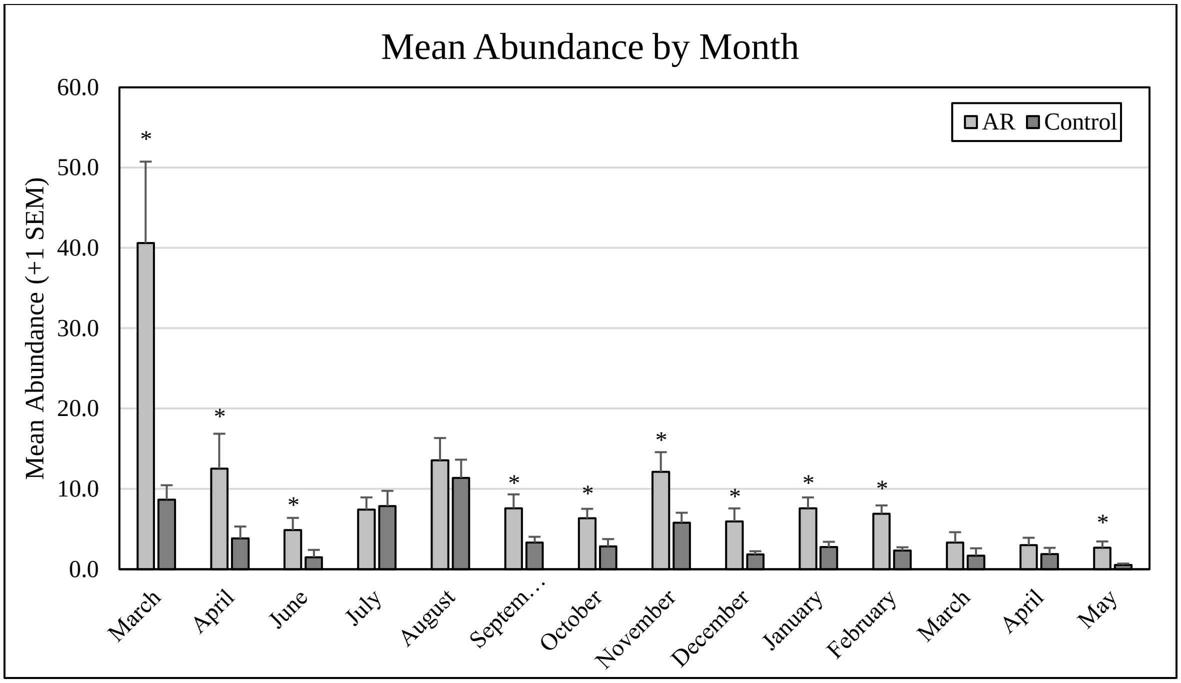

Figure 9. Mean abundance by month for artificial reefs (AR) and control sites. Columns with an asterisk indicate a significant difference between AR and control within a size class (ANOVA, SNK, p<0.05).

Mean species richness was determined by month with regards to treatment (Figure 10). The highest species richness for artificial reef sites was observed in March 2015, with an average 3.5 (± 1.0 SEM) species per site, followed by August and November. The highest richness for control sites was observed in August 2015, with an average 3.3 (± 0.3 SEM) species per site. Species richness was significantly higher ($p<0.05$) for artificial reef sites in 10 out of 14 months. Mean species richness by month was never higher for control treatments than for artificial reef treatments.

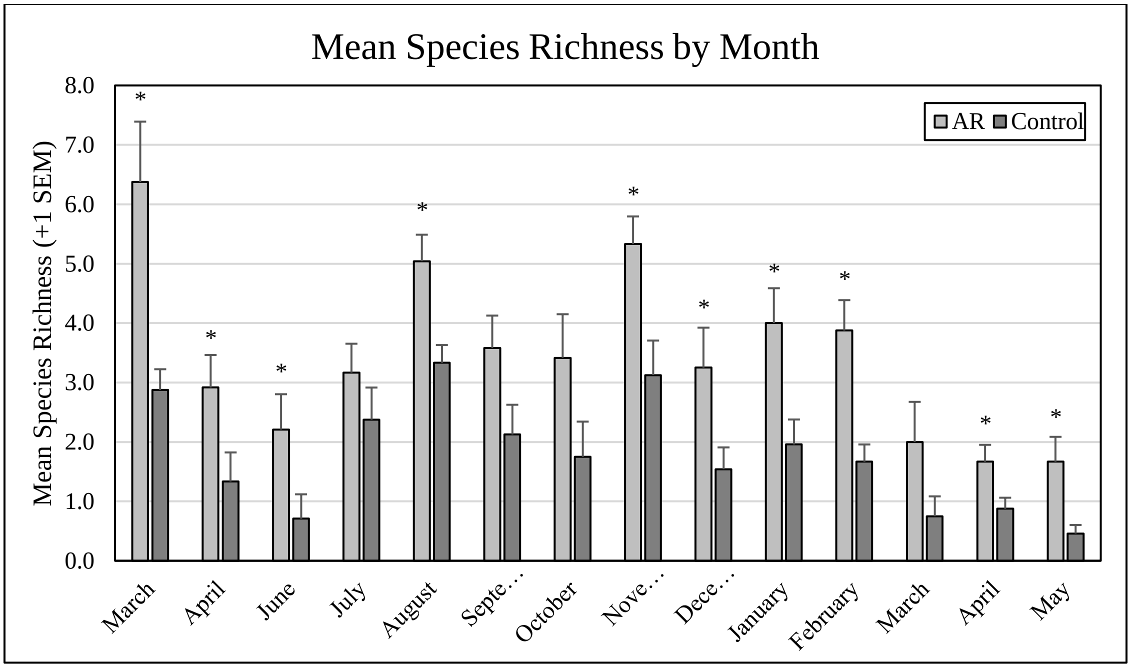

Figure 10. Mean species richness by month for artificial reefs (AR) and control sites. Columns with an asterisk indicate a significant difference between AR and control within a size class (ANOVA, SNK, p<0.05).

3.6 MDS Plot

A MDS plot (Figure 11) of the dataset indicated no major differences between treatments. However, even though there is no distinct clustering apparent between treatments, they are not completely intermingled and the results suggest that there is some difference in assemblage structure. Given the significant differences in abundances and richness between the two treatments, this is to be expected.

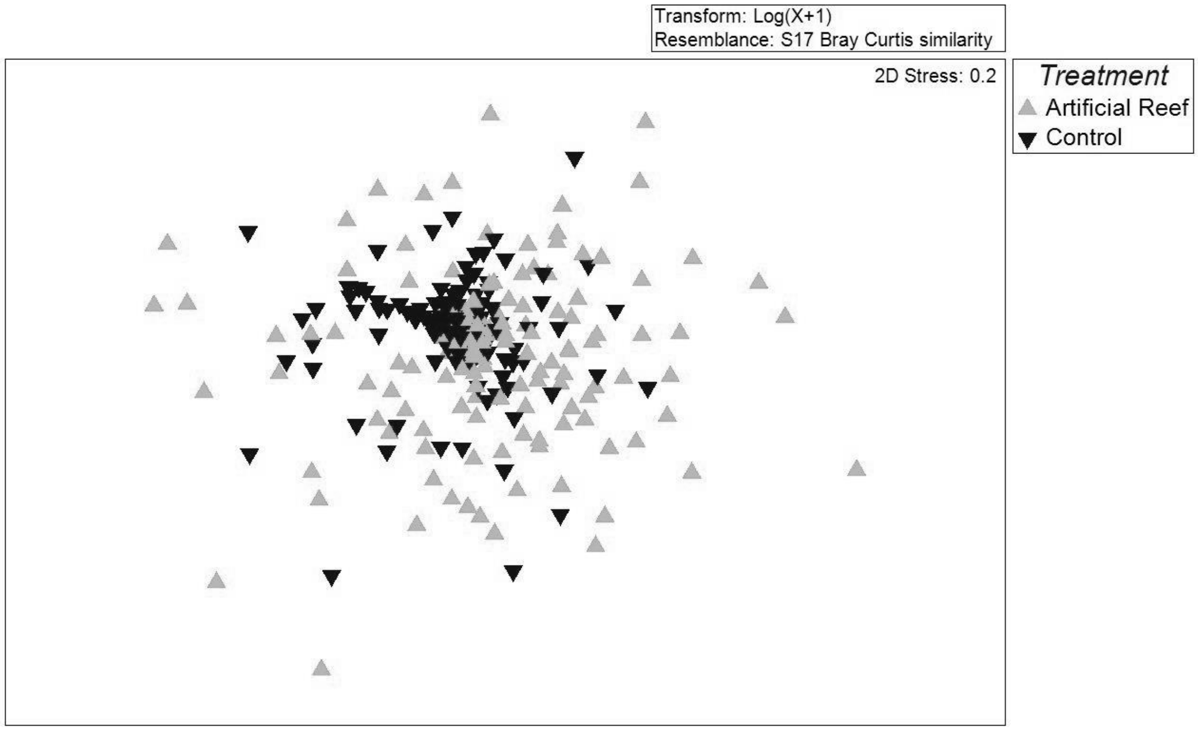

Figure 11. 2D MDS plot comparing individual site by treatment. Artificial reef points are in grey, control points are in black.

3.7 Haemulidae & Lutjanidae

The grunts (Family Haemulidae) and snappers (Family Lutjanidae) were the dominant families recorded during this study and made up more than 70% of the dataset. These two families also have a well-established prey-predator relationship (Shulman et al., 1983; Shulman & Ogden, 1987). Therefore, in an effort to gain a measure of insight into the interaction between members of these two families I examined their size class and monthly abundances separately.

Of the nine total grunt species observed, four species were in the top ten species surveyed by total percent occurrence (*A. virginicus*, 40.2%; *H. flavolineatum*, 21.4%; *H. sciurus*, 21.1%; *Haemulon* spp., 19.9%) (Figure 13). Grunts were significantly higher at artificial reef sites than at control site for size classes >2-5 cm ($p<0.001$), >5-10 ($p>0.001$), and 10-20 ($p<0.001$) (Figure 12). Treatment by size class was not significant for classes 0-2 cm and >20-30 cm, and no individuals were observed for size classes >30-50 cm and >50 cm.

Out of the five snapper species observed, three were in the top five species surveyed by total percent occurrence (*L. griseus*, 51.2%; *L. synagris*, 29.5%; and *L. apodus*, 25.9%) (Figure 14). Individuals of the snapper family were significantly higher at artificial reef sites than at control sites for size classes >2-5 cm ($p<0.001$), >5-10 cm ($p<0.001$), >10-20 cm ($p<0.001$) and >30-50 cm ($p = 0.043$) (Figure 15). Individuals in the size class 0-2 cm were only observed during August 2015. Treatment by size class was not significant for classes 0-2 cm and >20-30 cm, and no individuals were observed for size classes >30-50 cm and >50 cm.

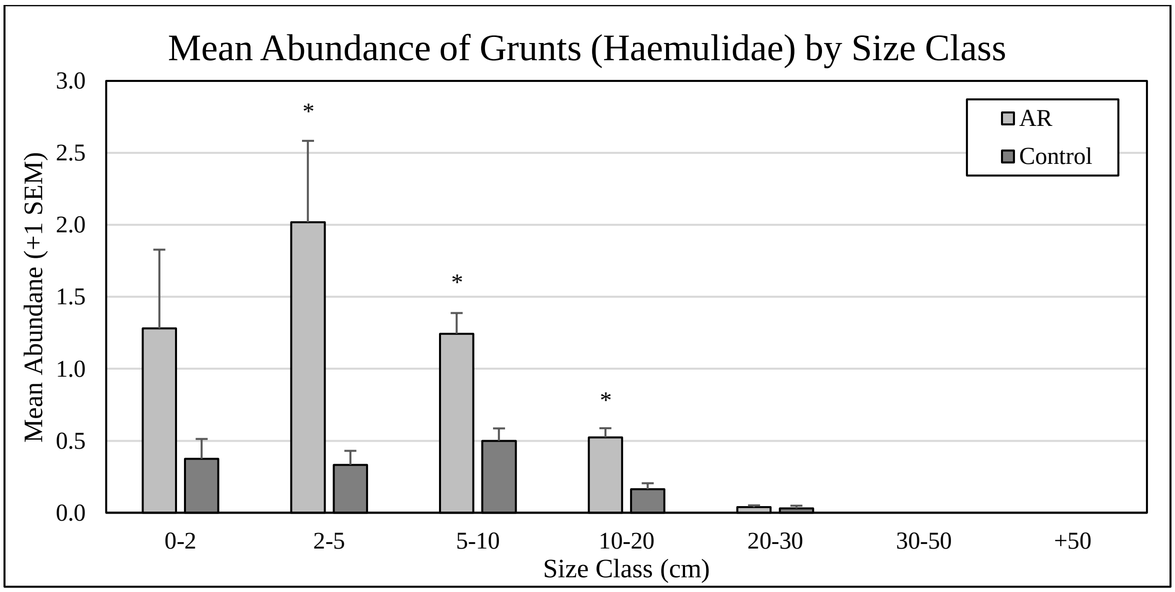

Figure 22. Mean abundance of grunts (Haemulidae) for size class by artificial reef (AR) and control sites.

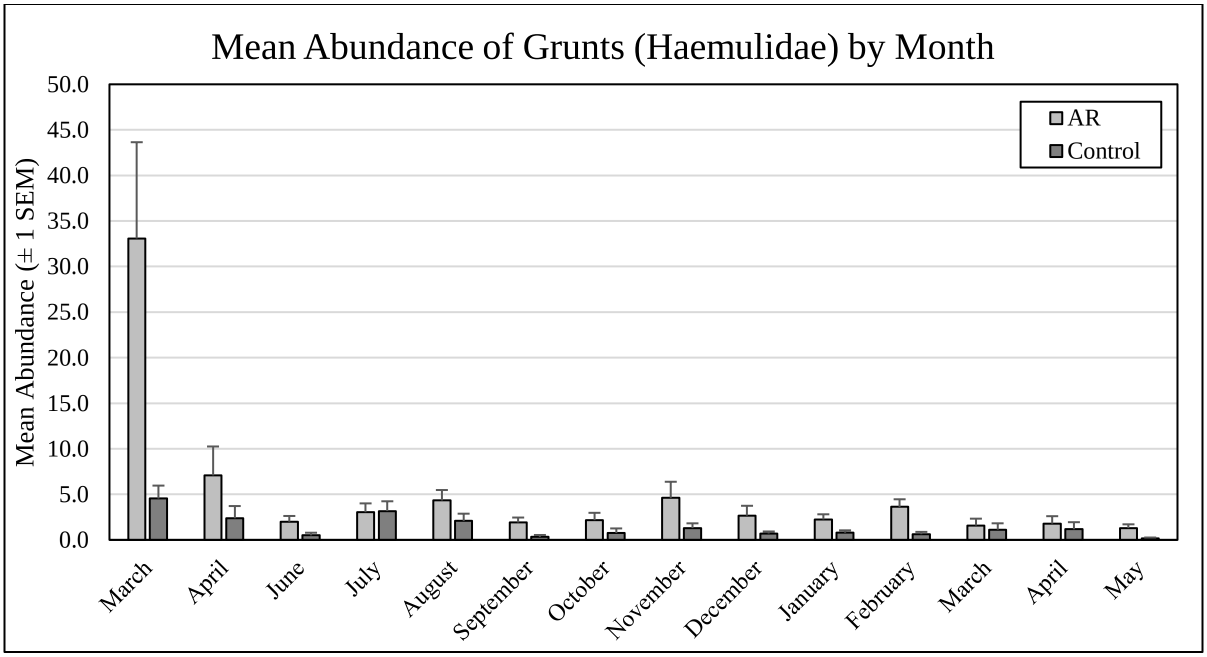

Figure 13. Mean abundance of grunts (Haemulidae) for month by artificial reef (AR) and control sites.

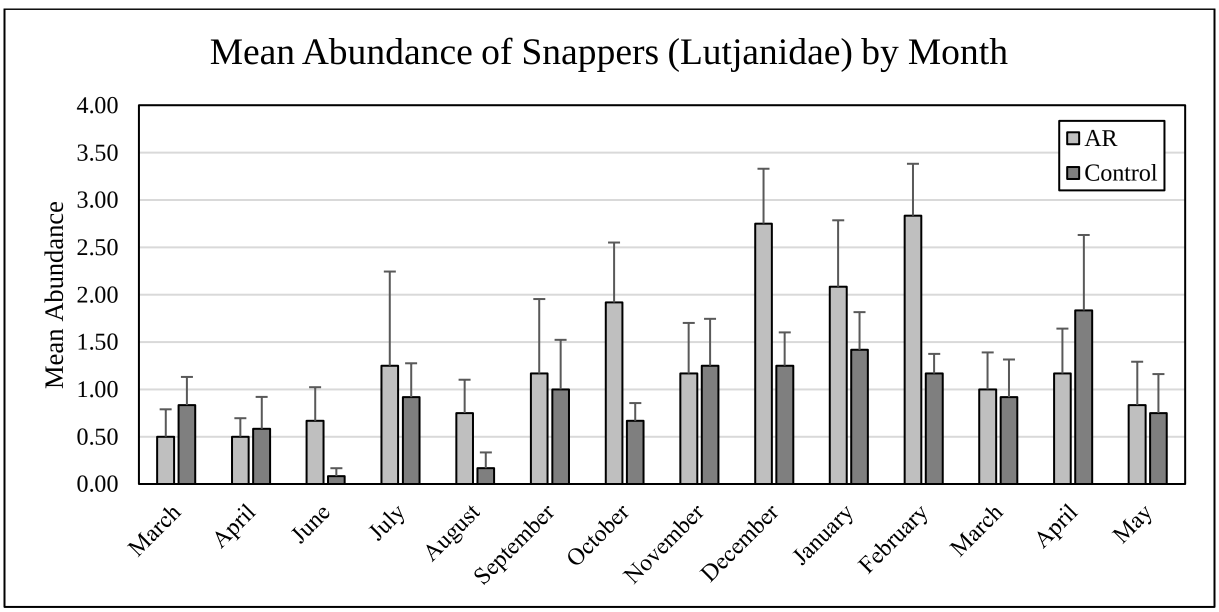

Figure 14. Mean abundance snappers (Lutjanidae) for month by artificial reef (AR) and control sites.

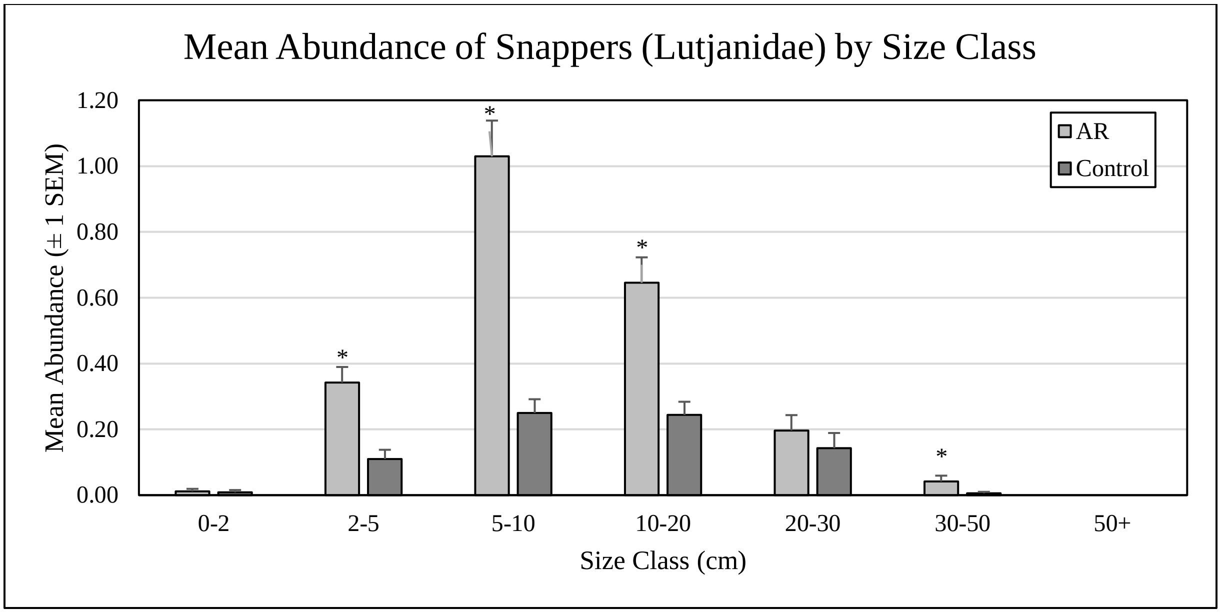

Figure 15. Mean abundance snappers (Lutjanidae) for size class by artificial reef (AR) and control sites.

4.0 Discussion

4.1 General

My hypothesis of artificial reefs acquiring a greater aggregation of fishes than the unmodified walls of the marina was strongly supported by the research results. Significantly higher fish abundance and species richness were found at artificial reef sites compared to control sites. However, mean fish abundance showed an unexpected decline over the 15-month survey period. The high fish abundance of the March 2015 survey resulted from a Haemulidae settling event immediately after the deployment of the artificial reef modules. The March 2016 count showed no evidence of a similar settling event, although April 2015 and 2016 also had small peaks.

The decline in fish abundance over time may be attributed to ontogenetic shifts, predation, or an unrecognized environmental impact (e.g., increased turbidity due to port dredging). Many species, including grunts and snappers, move offshore at species-specific size ranges and that may have occurred here (Beck et al., 2001; Pereira et al., 2014). Note that the smaller grunts dominated throughout the study with the highest numbers under 5 cm (Figure 11) which would support, in part, an ontogenic migration occurring at about 10 cm (Pereira et al., 2014). But this could not fully explain the decrease in abundance of the species relative to March 2015. Presumably, the migrants would be replaced by new recruits in that time interval. Thus, I posit that compensatory density dependence may have been, in part, responsible for the decline in abundance noted over the study period (Hixon & Jones, 2005). Note that the most abundant snapper size classes were larger than the grunts (>5-10 cm, >10-20 cm) and tellingly increased in abundance throughout the year from March to February on the artificial reefs but remained fairly constant on the control sites (Figures 13, 14). Possibly, the grunt recruitment density was offset by a compensatory increase in the number and size of their predators and this was further exacerbated by the artificial reef design which provided refuge for the juvenile predators.

Species richness was higher for artificial reef sites for the total species and for the four smallest size classes (0-2 cm, >2-5 cm, >5-10 cm, >10-20cm), indicating that the reef modules are capable of hosting a more diverse community of juvenile and small fishes than the control sites. Larger size classes (>20-30 cm, >30-50 cm, >50 cm) tended to be transient in their choice of habitat, with the exception of moray eels (Muraenidae). Individuals in these size classes were mostly seen swimming through the survey area or following divers, and were rarely associated with reef modules.

4.2 Haemulidae and Lutjanidae Module Use

In terms of species-specific use of the modules, most grunts appeared to prefer using the outer ledges of the modules for protection, although some larger members were occasionally observed inside the modules. This may be due to the interior of the module providing refuge for juvenile piscivores (i.e., snappers). In previous studies utilizing similarly designed modules that were caged to exclude predators, large numbers of grunts were observed seeking refuge inside the modules (Gilliam, 1999; Jordan et al., 2012).

In this study, the interior spaces and ledges were heavily utilized by small snapper individuals (Figure 16). These fishes exited the module for short distances but retreated back inside when threatened by larger fish. The interaction between the two species and the design of the artificial reef module may provide some further support for the decrease in abundance over time due to density dependence as both predators and prey were utilizing the same space.

Figure 16. (Left) Artificial reef module with three Lane Snappers. (Right) A Lane Snapper entering the interior of the reef module.

4.3 Observed Fish Species Site Use

Although the majority of the fishes observed were from families Haemulidae and Lutjanidae, there were several other families worthy of discussion. Damselfishes (Pomacentridae) (5.3% of the total) were almost completely dominated by Sergeant Majors (*A. saxatilis*) (97% of all damselfish recorded), and were found in greater numbers on artificial reef sites. Porgies (Sparidae) (4.2% of total) were also found in slightly higher numbers on the modules, and primarily represented by Spottail Pinfish (*Diplodus holbrookii*) and Seabream (*Archosargus rhomboidalis*). It is not uncommon to find large Sheepshead (*A. probatocephalus*), the largest and most commercially important member of this family, in the boat basin. It does occur in this dataset, but only in very small numbers (3 total). Jacks (Carangidae) (2.3% of total) were also recorded, primarily Lookdowns (*Selene vomer*) and Crevalle Jacks (*Caranx hippos*), although their presence at artificial reef or control sites is believed to be entirely coincidental.

Not all families had higher occurrences on the artificial reef sites. Interestingly, mojarras (Gerreidae) (8.9% of the total) were found in slightly higher numbers on control sites, although they were all newly settled juveniles (0-2 cm size class) and this family is well adapted to living on seemingly barren fields of sediment and feeding on benthic invertebrates. Also, it is interesting that out of the 7 goby species recorded (Gobiidae) (1.3% of the total), 5 species were found in greater numbers on control sites. Perhaps this is a result of having a large number of piscivores in residence on the artificial reef modules. Pufferfishes (Tetraodontidae) (1.3% of total) were frequently encountered throughout the boat basin, but did not show affinity towards one type of site versus another.

There was a distinct lack of herbivorous fishes in this dataset, with parrotfishes and surgeonfishes (Scaridae and Acanthuridae, respectively) making up <3% of the total when combined. In addition, essentially every member of these two families that was observed was a large adult (>20cm) that was just transiting through rapidly.

In April 2015 and March 2016, a Green Moray (*Gymnothorax funebris*) was in residence inside of an artificial reef module, using at least one interior cavity level of the module. In addition, a Spotted Moray (*Gymnothorax moringa*) individual was surveyed in January 2016 inside of an artificial reef module. The colonization of an artificial reef module by large piscivores such as *G. funebris* and *G. moringa* illustrates how the modules, intended to act as a refuge from predation, may end up attracting predator species, especially when there are limited alternatives for refuge.

4.4 Module Condition

The artificial reef modules proved to be structurally sound; none were damaged during the study period and they acquired a diverse fouling community, including macroalgae, sponges, bivalves, small crustaceans and at least one scleractinian coral recruit. The high turbidity within the boat basin led to silt settling on the surfaces of the artificial reef modules but not to the extent that significant refuge space was lost or access to the interior of the modules was compromised. The substrate of the basin was extremely silty in some areas and four modules showed partial to total burial of the bottom tier. However, no modules tipped over or sank beyond the bottom tier.

5.0 Conclusions

We have reached a level of understanding where artificial habitat can start to be designed to be species-specific and size-class-specific; however, much more research is required before we can do so with certainty (Spieler et al., 2001; Pioch et al., 2011a). The reef modules used in this study were dramatically more effective in acquiring an associated aggregation of fishes than the marina wall (control sites). However, it would be premature to assume that the basic design I employed is appropriate for all situations. For example, initially high numbers of newly settled grunts were found directly after deployment of the reefs, however, this number quickly tapered off over time. Within several months the interior cavities of the reefs were preferred by individuals in the >5-10 cm and >10-20 cm size classes, and were mainly avoided by individuals in the 0-2 cm and >2-5 cm size classes. While the habitat was good for juvenile predators such as snappers (Lutjanidae) it appeared to be less effective for some settling forage species (i.e., grunts, Haemulidae). Thus, I believe future reefs, with the aim of mitigating onshore nursery areas, should incorporate better habitat for settling species and/or some form of predator exclusion such as caging (see Gilliam, 1999; Jordan et al., 2012). Small rubble cemented to the top of the module or in some interior spaces or the use of partial caging could increase available preferred habitat for smaller size classes. This, in turn, would presumably provide additional foraging opportunities and increase the numbers of juvenile piscivores.

Artificial reef research has long been beset by the question of attraction vs. production, e.g., do artificial reefs increase the *de novo* production of fishes or simply attract and aggregate fishes already in the area (Pickering & Whitmarsh, 1997). It is a difficult question to address in a natural setting due to a host of confounding factors. My study, likewise, did not address the question due to time and funding constraints. However, this type of project would be ideal to study attraction vs. production due to the small site size, relative ease of surveying, and the ability to conduct surveys thoroughly before and after module deployment. In addition, the enclosed nature of the survey area reduces potential movement of juvenile fish.

Human populations on coastlines will continue to increase, with concomitant coastal construction projects and the associated negative ecological impacts. While these construction projects are inherently harmful to the environment, improved construction techniques may minimize some negative impacts. Ideally, in the future all coastal infrastructure will be built with some form of 'green construction' technique included in the original design phase, which will benefit both humans and marine organisms (Pioch et al., 2011a).

This research does not suggest the use of artificial habitats to excuse further coastal construction, dredging, or other destructive anthropogenic processes. However, with juvenile fish habitats constantly being degraded or lost, our research highlights a technique for reducing such negative impacts. While impacts to coastal ecosystems should ideally be avoided, unavoidable impacts should be minimized. Artificial structures do not wholly compensate for the habitat lost during coastal construction projects; however, simple but effective methods, such as those studied here, could be used to mitigate new coastal construction and also placed in pre-existing coastal infrastructures as a type of retroactive mitigation.

Appendix 1. Table of all recorded survey events.

Survey	Date	Time Start	Time End	Visibility (m)	Survey Method
1	March 4, 2015	1:30 PM	2:30 PM	2	Modified Point Count
2	April 22, 2015	1:00 PM	2:00 PM	2	Modified Point Count
3	June 1, 2015	10:00 AM	11:00 PM	2	Modified Point Count
4	July 14, 2015	12:45 AM	1:50 PM	2	Modified Point Count
5	August 25, 2015	12:50 AM	1:50 PM	2	Modified Point Count
6	September 25, 2015	12:30 PM	1:30 PM	2	Modified Point Count
7	October 22, 2015	12:50 PM	1:50 PM	2	Modified Point Count
8	November 5, 2015	12:30 PM	1:30 PM	2.5	Modified Point Count
9	December 2, 2015	1:00 PM	2:00 PM	2	Modified Point Count
10	January 19, 2016	1:00 PM	2:00 PM	2.5	Modified Point Count
11	February 12, 2016	1:00 PM	2:00 PM	2.5	Modified Point Count
12	March 28, 2016	12:00 PM	1:00 PM	2	Modified Point Count
13	May 2, 2016**	12:00 PM	1:00 PM	2	Modified Point Count
14	May 26, 2016	11:30 PM	12:30 PM	2	Modified Point Count

The count done on May 2nd, 2016, will count as the April 2016 count. Frequent storm events and elevated turbidity levels prevented surveys during April 2016.

Appendix 2. Project Data

Appendix 2.1. Mean fish abundance and species richness by treatment for artificial reef (AR) and control sites with standard error margins (SEM).

Treatment	Abundance	Abundance SEM	Abundance p=	Species Richness	Species Richness SEM	Species Richness p=
AR	9.607	1.561	p<0.001	1.108	0.184	p<0.001
Control	4.017	0.801		0.389	0.130	

Appendix 2.2. Abundance and species richness by month for artificial reef (AR) and control sites (ANOVA, SNK, $p<0.05$) with standard error margins (SEM).

Month	Count Number	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM	Abundance p=	AR Species Richness	AR Species Richness SEM	Control Species Richness	Control Species Richness SEM	Species Richness p=
March	1	40.625	10.126	8.667	1.795	<0.001	6.375	1.015	2.875	0.349	0.011
April	2	12.542	5.302	3.833	4.858	0.036	2.917	0.526	1.333	0.490	0.040
June	3	4.875	14.663	1.500	8.476	0.031	2.208	0.596	0.708	0.410	0.051
July	4	7.417	1.530	7.875	1.882	0.964	3.167	0.486	2.375	0.540	0.288
August	5	13.542	2.792	11.375	2.266	0.422	5.042	0.446	3.333	0.297	0.004
September	6	7.583	1.738	3.333	0.705	0.025	3.583	0.543	2.125	0.500	0.061
October	7	6.333	1.189	2.833	0.920	0.025	3.417	0.733	1.750	0.592	0.091
November	8	12.125	2.453	5.792	1.242	0.014	5.333	0.462	3.125	0.581	0.007
December	9	5.958	1.617	1.833	0.405	0.022	3.250	0.673	1.542	0.366	0.036
January	10	7.583	1.361	2.750	0.664	0.004	4.000	0.587	1.958	0.419	0.010
February	11	6.917	1.030	2.333	0.400	0.001	3.875	0.512	1.667	0.291	0.001
March	12	3.333	1.280	1.708	0.899	0.312	2.000	0.674	0.750	0.334	0.111
April	13	3.000	0.919	1.875	0.791	0.220	1.667	0.284	0.875	0.186	0.029
May	14	2.667	0.794	0.542	0.168	0.018	1.667	0.419	0.458	0.144	0.012

Appendix 2.3. Mean Abundance and species richness by size class for artificial reef (AR) and control sites (ANOVA, SNK, $p<0.05$) with standard error margins (SEM).

Size Class (cm)	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM	Abundance p=	AR Species Richness	AR Species Richness SEM	Control Species Richness	Control Species Richness SEM	Species Richness p=
0-2	3.173	0.989	0.914	0.458	0.051	0.196	0.031	0.119	0.024	0.047
>2-5	3.196	0.812	2.021	0.522	0.052	0.887	0.088	0.661	0.069	0.045
>5-10	2.208	0.229	1.208	0.133	0.001	1.369	0.118	0.815	0.083	<0.001
>10-20	1.152	0.133	0.726	0.088	0.012	0.896	0.102	0.545	0.057	0.003
>20-30	0.446	0.105	0.390	0.099	0.364	0.241	0.034	0.182	0.031	0.190
>30-50	0.176	0.052	0.054	0.015	0.043	0.071	0.017	0.060	0.016	0.601
50+	0.015	0.009	0.003	0.003	0.221	0.015	0.009	0.003	0.003	0.205

Appendix 2.4. Mean abundance of grunts *(*Haemulidae*)* by size class for artificial reef (AR) and control sites (ANOVA, SNK, p<0.05) with standard error margins (SEM).

Size Class (cm)	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM	Abundance p=
0-2	1.280	1.280	0.375	0.375	0.335
>2-5	2.018	2.018	0.333	0.333	0.00
>5-10	1.244	1.244	0.500	0.500	0.00
>10-20	0.524	0.524	0.164	0.164	0.00
>20-30	0.039	0.039	0.030	0.030	0.373
>30-50	0.000	-	0.000	-	-
50+	0.000	-	0.000	-	-

Appendix 2.5. Mean abundance of grunts (Family Haemulidae) by month for artificial reef (AR) and control sites with standard error margins (SEM).

Month	Count Number	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM
March	1	33.083	10.562	4.542	1.416
April	2	7.083	3.171	2.375	1.339
June	3	2.000	0.625	0.500	0.289
July	4	3.042	0.966	3.167	1.072
August	5	4.333	1.140	2.083	0.795
September	6	1.917	0.536	0.333	0.207
October	7	2.167	0.806	0.750	0.509
November	8	4.625	1.757	1.292	0.527
December	9	2.667	1.077	0.708	0.217
January	10	2.250	0.559	0.792	0.257
February	11	3.625	0.833	0.625	0.255
March	12	1.583	0.746	1.125	0.697
April	13	1.792	0.811	1.167	0.777
May	14	1.292	0.419	0.167	0.094

Appendix 2.6. Mean abundance of snapper (Lutjanidae) by size class for artificial reef (AR) and control sites (ANOVA, SNK, $p<0.05$) with standard error margins (SEM).

Size Class (cm)	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM	Abundance p=
0-2	0.012	0.007	0.009	0.007	0.789
>2-5	0.342	0.047	0.028	0.028	<0.001
>5-10	1.030	0.109	0.640	0.042	<0.001
>10-20	0.646	0.077	0.445	0.040	<0.001
>20-30	0.196	0.047	0.170	0.046	0.229
>30-50	0.042	0.018	0.024	0.004	0.049
50+	0.00	-	0.00	-	-

Appendix 2.7. Mean abundance of snapper (Family Lutjanidae) by month for artificial reef (AR) and control sites with standard error margins (SEM).

Month	Count Number	AR Abundance	AR Abundance SEM	Control Abundance	Control Abundance SEM
March	1	0.500	0.289	0.833	0.297
April	2	0.500	0.195	0.583	0.336
June	3	0.667	0.355	0.083	0.083
July	4	1.250	0.993	0.917	0.358
August	5	0.750	0.351	0.167	0.167
September	6	1.167	0.787	1.000	0.522
October	7	1.917	0.633	0.667	0.188
November	8	1.167	0.534	1.250	0.494
December	9	2.750	0.579	1.250	0.351
January	10	2.083	0.701	1.417	0.398
February	11	2.833	0.548	1.167	0.207
March	12	1.000	0.389	0.917	0.398
April	13	1.167	0.474	1.833	0.796
May	14	0.833	0.458	0.750	0.411

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