A Comparison of Fish Communities Over Different Reef Configurations in the Northwestern Gulf of Mexico

by

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A Thesis Presented to the Graduate Faculty of the College of Science, Mathematics and Technology in Partial Fulfillment of the Requirements for the Degree of

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**ABSTRACT**

High fishing pressure and limited natural habitat characterize the otherwise barren northwestern Gulf of Mexico. South Texas lacks extensive research of local natural and artificial reefs, and few studies report fish community and sportfish analysis of different reef densities. To alleviate this lack of data, fish abundances were monitored at different reef configurations in the PS-1047 Reef, 13 km off Port Mansfield, Texas, where 4000 concrete culverts were placed in 2011. Four culvert categories (CC1: 1-30 culverts, CC2: 31-70 culverts, CC3: 71-120 culverts, and CC4: 121-190 culverts in a 30-m radius), natural reefs and bare areas were sampled. Species abundances were assessed with 15-min SCUBA surveys, and total lengths of commercially valuable *Lutjanus campechanus* were measured. In summer 2013, water temperatures were warmer (25.1 ± 0.4°C), and surveys had significantly more adults and more even juvenile populations than in the summer of 2014 (22.8 ± 0.2°C). No fishes were observed at bare areas, whereas sites with structure had 186 ± 28 individuals from 13 ± 1 species. Fish communities did not significantly differ between reefs, yet significantly more adult individuals were seen on natural reefs than CC1, CC2, and CC4. CC3 resembled natural reefs with similarly high species richness and total abundance values. *Lutjanus campechanus* were found at all sites with structure, with an average 41 ± 6 individuals per site, and abundances did not significantly differ among reef categories. CC1 exhibited the largest *Lutjanus campechanus*, 362.9 ± 8.7 mm, whereas all other reef categories exhibited average lengths ranging from 296.5 to 322.8 mm. Longer individuals at CC1 may result from aggressive behaviors exhibited at sites with less suitable habitat. Using a previous study that assessed total length to age ratios in South Texas, the predicted age of *Lutjanus campechanus* was two years old. Findings suggest that culvert reefs are substantial improvements to otherwise bare areas, and reefs with about 100 culverts closely mimic species diversity of nearby natural reefs. Thus, it is recommended that future culvert reefs be deployed with 100 culverts in 100 m increments to cover four times more area than at PS-1047.
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CHAPTER ONE: INTRODUCTION

Historical Use of Artificial Reefs

Significant natural reef cover is diminishing in many parts of the world, including the Middle East, Indian Ocean, Pacific Ocean, Caribbean Sea, and is simply non-existent in others, especially in the northwestern Gulf of Mexico (Molles 1978; Talbot et al. 1978; Rouphael and Inglis 2002; Wilkinson 2004; Berrios et al. 2005; Carpenter et al. 2008; Gallaway et al. 2009; Roff and Mumby 2012). Only 3% of the northwestern Gulf of Mexico has natural reef habitat, with very little reaching over 1 m off the bottom (Gallaway et al. 2009). Due to low habitat coverage, artificial reef deployment continues to be important for fisheries management (Bohnsack and Sutherland 1985; Gallaway et al. 2009).

For several centuries, artificial reefs have been introduced around the globe to aid in conservation efforts (Sheehy 1982; Rouphael and Inglis 2002). For example, Japan and Taiwan use artificial reefs for commercial fishing and aquaculture, whereas Australia and the United States use them primarily for recreational fishing (Sheehy 1982; Bohnsack and Sutherland 1985). Other artificial reef efforts are ongoing to reduce coastal beach erosion, and to reduce fishing pressure and destruction by recreational tourism on coral reefs (Bohnsack and Sutherland 1985; Brickhill et al. 2005).

Before the 1980s, the majority of artificial reef funding came from private organizations, local governments, and private individuals (Sheehy 1982; Bohnsack and Sutherland 1985). The restricted funding resulted in the use of scrap material for artificial reef construction in the US, such as concrete, automobile tires, ships, and oil rigs (Sheehy 1982; Bohnsack and Sutherland 1985; Baine 2001). Although some scrap reefs were
effective, others, such as tire reefs, could easily be destroyed and disintegrated from current, wave action, and tropical storms (Sheehy 1982; Bohnsack and Sutherland 1985; Baine 2001). However, following the US National Fishing Enhancement Act of 1984, the US National Artificial Reef Plan (NARP) of 1985 was initiated to “promote and facilitate responsible and effective efforts to establish artificial reefs in the navigable waters of the United States and waters superjacent to the outer continental shelf” (NARP 2007). Other states used the recommendations from NARP to improve the deployment of artificial reefs (NARP 2007). Since NARP, deployments have gone through rigorous planning and monitoring to improve fish diversity at artificial reefs (Berrios et al. 2005; Lindberg et al. 2006; Al-Horani and Khalaf 2013; Zhang and Zheng 2013).

Following NARP, several artificial reef programs were initiated to increase management and deployment of future artificial reefs in oceanic waters. In 1989, Texas enacted the Artificial Reef Act, and the Texas Parks and Wildlife Department (TPWD) subsequently formed the Texas Artificial Reef Program (Stephan et al. 2013). Three programs were created to recycle different materials into artificial reefs, and aid in structuring and monitoring deployments to meet certain guidelines. These artificial reef programs are Rigs-to-Reef, Ships-to-Reef, and Nearshore Reefing Program. The programs involve recycling unused oil platforms, shipwrecks, and using concrete and steel materials, respectively (Stephan et al. 2013). Such programs are currently still in place, and TPWD continues to deploy reefs.

*Artificial Reef Management and Fisheries*

Ecotourism, recreational diving and fishing are economically important industries that sustain the practicality of artificial reefs globally (Brock 1994; Rouphael and Inglis
Adams et al. (2004) reported that the Gulf of Mexico provides over USD $1.8 billion and 55,000 jobs annually for marine sport-fishing. Reefs produce natural capital that ideally are sustainable and can be accessed easily by fishermen (Adams et al. 2004; Clewell and Aronson 2006). Recreational fishing is an important financial consideration of artificial reef programs. Artificial reefs are responsible for drastic increases in sport fisheries, sometimes increasing the local economy by 10-16% (Bohsnack and Sutherland 1985). Thus, artificial reef deployment is highly influenced by commercial and recreational fishing interests.

Although reefing programs are in place to help manage and plan reef deployments, their benefits can be negated by overfishing. Fishing pressure awareness is starting to grow, because overfishing could very easily deplete fish stocks at a reef to the point of exhaustion (Grigg 1994; Coleman et al. 2000). Grigg (1994) suggests that in a reef fish community, predators are already exploiting fish stock to their maximum yield, and any additional fishing results in additional pressure that cannot be maintained.

Overfishing negatively affects numerous populations of economically important fish species, including groupers and snappers (Bohsnack and Sutherland 1985; Bohnsack 1996; Griffin 1999; Coleman et al. 2000; Gallaway et al. 2009). Thus, to reduce overfishing, proper monitoring and management programs must be utilized to deploy low cost and effective reefs.

Throughout the years, numerous survey techniques have been employed to better monitor reefs and collect fishery-independent data on reef fish community parameters. Remotely Operated Vehicles are frequently used to survey reefs, especially those unreachable by SCUBA divers (Kraus et al. 2006; Stoner et al. 2008; McIntyre et al.
Some new techniques include using hydroacoustic and side scanner sonar to estimate fish biomass in different reefs (Cuevas et al. 2002; Kraus et al. 2006; Boswell et al. 2007; Boswell et al. 2010). Yet visual SCUBA survey methods are among the most popular measures to quantify species diversity and abundance at shallow reefs (Bohnsack and Bannerot 1986; Brock 1994; Berrios et al. 2005; Gratwicke and Speight 2005; Lindberg et al. 2006; Campbell et al. 2011; Williams et al. 2012).

One of the most widely used SCUBA survey techniques is the restricted stationary sampling (SS) method by Bohnsack and Bannerot (1986). To complete an SS survey, divers census exact species abundances in a stationary cylinder for a total of 15 minutes. This allows for maximum yield of data in short time, and limited chances of overlapping counts of species. Although a single technique may not conform to all locations and with all environmental conditions, the general SS survey guidelines can be met or modified to better assess specific reefs. In practice, numerous surveys now incorporate a modified version of SS methodology to collect fish community data (Bohnsack et al 1987; Ault et al 1998; Lindberg et al 2006; Walker et al 2009; Brandt et al 2010; Smith et al 2011; Ayotte et al 2011; Ault et al 2013). Another SCUBA survey often used is the Roving Diver Technique (RDT). The latter method involves the use of survey divers roving freely over reefs to assess diversity (Schmitt and Sullivan 1996; Schmitt et al. 2002). Instead of quantifying exact species counts, abundances are recorded in log_{10} categories. Both the SS method and RDT techniques serve the same purpose, to quantify species abundance, yet experimental design may call for one survey methodology over the other. In either case, monitoring species diversity is necessary to determine if current reefs are effective.
**Lutjanus campechanus** Fisheries in the Gulf of Mexico

Gulf of Mexico fisheries depend on several economically important sport-fishes, such as snappers (Lutjanidae), groupers (Serranidae), dolphinfishes (Coryphaenidae), and mackerels (Scombridae) (Coleman et al. 2000; Carter and Liese 2012). Carter and Liese (2012) found that anglers would value keeping groupers and *L. campechanus* eight times more over releasing them due to maximum bag limitations. In fact, in the Gulf of Mexico, *L. campechanus* fisheries are in the top four most valuable fisheries, both recreationally and commercially (Griffin 1999; Gallaway et al. 2009; Cowan et al. 2010).

Unfortunately, in the late twentieth century, *L. campechanus* have become overexploited, and management practices have been invoked since the 1980s to recover existing populations (Griffin 1999; Gallaway et al. 2009). Currently, Texas state waters allow fishing of *L. campechanus* all year, whereas federal waters only allow a small window of time (a few weeks) starting June 1 of every year. Recent studies reported in the Gulf of Mexico Fishery Management Council (GMFMC, 2013) suggest that *L. campechanus* are recovering since 2009.

*Lutjanus campechanus* are long-lived, schooling, slow growing, and late maturing fishes often found in artificial reefs (Coleman et al. 2000; Wilson and Nieland 2001; Gallaway et al. 2009). Gallaway et al. (2009) reports that *L. campechanus* age structures depend on the location, environment, and strength of cohorts. Understanding *L. campechanus* life history can give insight into movement of populations and expected catch sizes in different areas along the Gulf of Mexico. Throughout their life, *L. campechanus* go through ontogenic stages that follow changing habitat requirements (Wilson and Nieland 2001; Diamond 2003; Gazey et al. 2008; Gallaway et al. 2009).
*Lutjanus campechanus* larvae seek relic shell, or low relief areas (Gallaway et al. 2009). Habitat is a limiting factor for juveniles, and *L. campechanus* will not metamorphose into juveniles if they have not reached adequate habitat (Gallaway et al. 2009). As they continue to grow, *L. campechanus* seek bigger, more complex habitat, such as nearshore small artificial concrete reefs, around one year of age (Gazey et al. 2008; Gallaway et al. 2009). Gallaway et al. (2009) suggest that at age two, *L. campechanus* transition further to deeper reefs with high relief, such as oil platforms, natural rock, and larger artificial reefs. At this age, they report that *L. campechanus* usually range from a starting size of 200 to 375 mm total length (TL), and enter the direct fishing industry. *Lutjanus campechanus* continue to grow fast until age eight. When individuals reach sizes over 700 mm TL, they move to open sand environments (Peabody 2004; Gazey et al. 2008; Gallaway et al. 2009). These ontogenic shifts suggest that habitat use is an important indicator of possible age and size of individuals in local populations of *L. campechanus* depending on different reef characteristics.

**Culvert Reef Density**

Bohnsack and Sutherland (1985) reviewed previous artificial reef literature, and underlined the need to assess the effect of habitat complexity on reef communities. Some studies have analyzed such effects (Luckhurst and Luckhurst 1978; Walsh 1985; Charbonnel 2002a; Lindberg et al 2006; Pais et al 2013). Adding artificial reef complexity increases species richness and available food (Charbonnel 2002b; Lingo and Szedlmayer 2006). What type of complexity is important in consideration of reef planning? Increased reef densities may contain higher species diversity, but more research has to be undertaken to fully analyze the effect on reef fish communities.
One recent study began to tackle patchy distributions of reefs as an indicator of reef fish communities. Lindberg et al. (2006) monitored *Mycteroperca microlepis* populations at the Suwannee Regional Reef System in the Northern Gulf of Mexico. The concrete reefs had either four or 16 concrete cubes of equal sizes, and were placed 25 m and 225 m apart. *Mycteroperca microlepis* grew bigger on smaller reefs, and moved freely over 25 m spaced reefs, whereas no movement was found in 225 m spaced reefs. Lindberg et al. (2006) found that higher residency time and site fidelity were observed in *M. microlepis* aggregating around larger patches with greater spacing. Thus, reef spacing and density may be important for reef planning.

Lukens et al. (2004) proposed guidelines for future artificial reef deployment, and suggested that concrete reefs are highly durable, benign, nontoxic, and long-lasting artificial reefs. The report further describes concrete as being highly conformed to the marine environment due to its calcium carbonate base. High diversity occurs in concrete reefs (Bohnsack and Sutherland 1985; Moffitt et al. 1989; Berrios et al. 2005), and concrete materials can be arranged into different patterns, or simply deployed at random to allow for higher habitat complexity, which increased fish community diversity (Talbot et al. 1978; Bohnsack and Sutherland 1985; Baine 2001; Lukens et al. 2004). Such material is easily accessible and economical, and thus continues to be one of the most important materials used worldwide to act as reef habitat.

*Temperature Variability of South Texas Waters*

Seasonal changes can often affect reef fish communities. The Texas coast line is prone to strong northerly winds that frequent colder months (November to March), which change temperatures drastically (Weber et al. 1990). Colder months tend to reduce
vertebrate and invertebrate species abundances, as well as juvenile recruitment in reefs, and reduce growth of reef fishes (Talbot et al. 1978; Lek et al. 2011; Gillanders et al. 2012; Bijoux et al. 2013; Henriques et al. 2013). If temperature variations are not considered as a factor affecting reef communities, reduced output could be mistaken for low productivity of reefs. Thus, assessment of temperature is important to determine changes in fish communities at artificial reefs.

*Natural Reefs versus Artificial Reefs*

The northwestern Gulf of Mexico lacks much natural reef cover. Sand and clay cover the majority of the continental shelf, and few hard bank reefs exist (Nash et al. 2013). Such banks are relic barrier island reefs and coralgal relic reefs that are deep water octocoral banks, or shallow reefs composed of soft coral and hard rock bottom (Rezak et al. 1983). As a result, artificial reefs continue to be deployed in the area to add suitable habitat in hopes of increasing fish abundance in the Gulf of Mexico.

Bortone and Williams (2011) discusses the limited research in assessing effectiveness of artificial reefs, and Nash et al. (2013) highlights the lack of research along the South Texas coast for assessing fish communities at artificial and natural reefs. Studies that have compared natural and artificial reefs in other areas found that natural reefs generally have higher species abundance and richness than culvert reefs (Talbot et al. 1978; Carr and Hixon 1997; Rooker et al. 1997; Berrios et al. 2005; Perkol-Finkel and Benayahu 2005; Thanner et al. 2006; Perkol-Finkel et al. 2006). Berrios et al. (2005) revealed similar fish community compositions between artificial and natural reefs, but found higher abundances at artificial reefs. Thanner et al. (2006) found that fish communities at natural reefs were less variable than at artificial reefs. Perkol-Finkel et al.
(2005) revealed higher diversity in invertebrate communities at natural reefs than at culvert reefs. Because literature suggests that natural reefs outperform artificial reefs, studies conducted at artificial reefs should be compared to local natural reefs to better assess the effectiveness of the deployed reefs.

**Purpose of the Experiment**

To address limited research of habitat complexity and the increased need for local population analyses of important sport fishes, an experiment was conducted at the PS-1047 Reef, off of Port Mansfield, Texas. The reef is composed of small naturally-occurring reefs as well as over 4,000 concrete culverts, often used in construction, randomly deployed in 2011 around the center of a one km$^2$ area. More reef placement of culverts is predicted in the near future, thus assessing fish communities at the culvert reefs could lead to new guidelines for further and more effective deployment. The experiment was conducted to assess fish community differences between two consecutive summers, between varying culvert reef density categories and nearby natural reefs, and to compare total lengths and abundances of *L. campechanus* across reef categories. Specific hypotheses tested included the following:

1. Reef fish communities at PS-1047 Reef will have higher species richness, evenness, diversity, and abundance with increasing culvert reef density, and be highest at natural reef sites.

2. Observed fish communities will be different among two consecutive summers (due to different temperatures), yet varying site visibility will not affect censuses.

3. *Lutjanus campechanus* abundances and lengths will be largest at the densest reefs. Bare areas will contain no *L. campechanus* due to lack of suitable habitat.
CHAPTER TWO: MATERIALS AND METHODS

Site Description

The study was conducted in northwestern Gulf of Mexico at the one km$^2$ PS-1047 Reef (N 26° 31.535’ – W 97° 09.215’, Fig. 1), which lies at a 21 m depth. PS-1047 is part of the Texas Artificial Reef Nearshore Reefing Program, and is located 13 km from Port Mansfield jetties in Texas state waters. TPWD first dropped artificial culvert reef material in 2009, and 4,000 additional culverts (roughly one m by three m) were added in 2011. As of August 21, 2011, 4,922 concrete culverts occupy the sandy mud sea floor. Invertebrates that colonized the culvert reefs include encrusting sponges, soft and solitary corals, algae, ascidians, and bryozoans.

Natural reefs were also surveyed to compare against culvert reefs (Fig. 2). Four naturally-occurring reefs were found at PS-1047. Two other natural reefs were censused outside of the reefing area, but that lay at the same relative depth. Natural reefs studied vary in size from 5 m to over 200 m long, and all are composed of hard clay and sandstone base with solitary soft corals and octocorals, algae, sponges, and polychaete worms. Natural reefs found in this study resemble, in origin, a well-studied nearby reef, Seven and One-Half Fathom Reef, which is a relict coralgal reef (Causey 1969; Tunnell and Chaney 1970; Felder and Chaney 1979; Rezak et al 1983; Nash et al 2013). The reef is from lacustrine origin, and is composed of hard clay and sandstone with sponges, hydroids, ascidians, and polychaete worms (Rezak et al 1983; Nash et al 2013).

Culvert Reef Density

Culverts at PS-1047 were randomly deployed by TPWD. For this study, different culvert reef sites were identified within the one km$^2$ area. All culverts were counted in a
30-m radius, and four culvert categories (CC) were assigned: CC1 (1-30 culverts), CC2 (31-70 culverts), CC3 (71-120 culverts), and CC4 (121-190 culverts). Bare areas, characterized by lacking any structure in a 30-m radius, and naturally-occurring reefs were compared against culvert reefs to assess natural distribution of reef-associated fishes and *L. campechanus* sizes. There was at least 100 m of bare area between each site sampled to reduce possible movement of individuals between sites.

*Selection of Sampling Sites*

Initial reef sites sampled in 2013 were selected based on a low resolution survey collected for TPWD in 2011. Additional sites and naturally-occurring reefs were located in 2014 with Humminbird 1198s SI side scan sonar (455 kHz, Johnson Outdoors Marine Electronics, Inc., Eufaula, Alabama) and towfish (The Tank, First Response Outfitters, Houston, Texas, Fig. 3). To characterize each reef site, still frames from three 200 m transect lines of side scan sonar (40.176 pixels/m) were produced from SonarTRX software (Leraand Engineering, Inc., version 13.1, Honolulu Hawaii). The frames were later imported into image processing software (Image J, National Institute of Health, version 1.48, Bethesda, Maryland) to count culverts, and better describe the culvert categories. Other measures of habitat characteristics calculated from ImageJ included substrate rugosity, percent substrate cover (%), and vertical relief (height, m). Each measure was averaged over the three different transects. To measure substrate rugosity, a line was drawn in the water column, which accounted for the changing relief due to structure, over the 60 m length of each reef site. The length of the line was then divided by 60 m to calculate a substrate rugosity index for each site. Percent substrate cover was calculated by measuring how much of the reef site (in a 30-m radius circle) was covered
by structure. Average and maximum vertical relief were calculated by measuring substrate height every meter along the 60 m length of the reef site.

Single surveys were conducted at 12 sites in June and July of 2013, and then surveys were repeated at the same sites in May to July of 2014. These sites included three replicates each of bare, CC1, CC2, and CC4 sites (Fig. 3). In 2013, finding these sites was only applicable using the low resolution survey for TPWD from 2011, thus only three culvert categories were surveyed in 2013. In 2014, with the assistance of the side scan sonar equipment, an additional 11 sites were located and surveyed from May to July in 2014 without repetition. These sites were selected to increase the coverage of culvert reef densities, and to compare concrete reefs to natural reefs. In the 2014 comparison, a total of 20 sites with structure present were surveyed: four CC1 sites, three CC2 sites, three CC3 sites, four CC4 sites, and six natural reef sites (Fig. 3). The 2014 summer was characterized by fluctuating, and often harsh weather conditions, thus uneven replicates of reef categories were collected.

**Census of Reef Fishes**

Visual SCUBA fish surveys were conducted following the Bohnsack and Bannerot (1986) SS Method with some modifications: A SCUBA diver descended to a survey site, and assessed species richness and abundance of reef-associated fishes in stationary three to five-m cylinders for 5-10 min. The surveyor then searched for cryptic species for 5-10 min around the patch in the 5-m cylinder. Throughout the 15-min long survey, adult and juvenile fishes were recorded separately. Both adults and juveniles were identified with their respective types of coloration and body shape. Horizontal visibility was determined over the reef near the bottom with a Secchi disk (United Scientific Inc.,
Little Canada, Minnesota) and a tape measure (Fig. 4). Water temperature (± 1°C) was recorded on every dive from a dive computer (Oceanic VT3, Oceanic Inc., San Leandro, California).

*Lutjanus campechanus* Total Lengths

Alongside the surveys, *L. campechanus* lengths were documented using parallel lasers, each 0.3 m apart, mounted on aluminum flat bar (3.9 x 70.0 x 0.3 cm) with a high definition camera attached (GoPro HD Hero 3+, GoPro Inc, San Mateo, California, Fig. 5). While the fish counts were conducted, a second diver aimed the lasers at the broad side of *L. campechanus* to record as many as possible. To reduce the chances of sampling the same individual, the diver stayed at relatively the same location in the water.

Individual *L. campechanus* total lengths were collected from scaled videos and manual measurements using a ruler in Adobe Premier Pro software (Adobe Inc., version 7.2, San Jose, California). In some cases, video attenuation did not allow for an accurate estimate of *L. campechanus* size, and these recordings were excluded. An average of 78 ± 8 *L. campechanus* fishes were measured in each reef category. Ages were estimated from total length measurements using the Von Bertalanffy Growth Model derived by Syc (2011):

\[
TL_t = 936.37 \left(1 - e^{-0.205(t+0.142)}\right)
\]

where TL was the total length of fish, and t was the age at total length.

Statistical Analyses

Reef sites surveyed in both years were compared to determine if fish communities were different between the years in two-way permutational analyses of variance (PERMANOVA). Three analyses were conducted to compare species abundances of (1) the whole fish community, (2) juvenile, and (3) adult populations. Species abundances
for each analysis were compared against initial reef categories and sampling year in a two-way PERMANOVA using the Bray-Curtis similarity index (Clarke and Warwick 2001). To reduce the effect of dominant species, abundances were square-root transformed (Molles 1978; Gratwicke and Speight 2005; Lindberg et al. 2006; Lingo and Szedlmayer 2006; Harborne et al. 2012). Water temperature and reef visibility were assessed as covariates alongside reef category and sampling year in PERMANOVA analyses with covariates. Multi-dimensional scaling (MDS) plots and Principal Components Analysis (PCA) were used to analyze different clusters of samples based on environmental variables. To assess significant clustering of samples based on species abundances, regardless of other factors, Hierarchical Cluster (CLUSTER) analysis, along with the Similarity Profiles (SIMPROF) routine, was conducted. Similarity Percentages (SIMPER) routine was run to determine what species contributed to similarities and dissimilarities between different sites, reef categories, and years.

All sites surveyed in 2014 were compared in one-way PERMANOVAs to assess differences among reef categories (CC1, CC2, CC3, CC4 and natural sites), following the same resemblance matrix and transformation as mentioned above. To test effects of reef category, species abundances of (1) the whole fish community, (2) juvenile, and (3) adult populations were assessed. Bare areas were not included in the 2014 analysis because these were already assessed in the year to year analysis. Similarly to the comparison between the years, MDS plots were analyzed, CLUSTER analyze with SIMPROF were conducted, and SIMPER was run to assess species abundances, significant clustering, and characteristic species, respectively. PCA analysis was conducted to assess how sample sites differentiated among substrate rugosity, average height, maximum height, and
percent cover. To see what species were correlated with the latter variables, Pearson correlations were calculated, and species with at least 10 total individuals and at least 20% correlation were included. All multivariate analyses were performed using PRIMER-E v6 package.

The diversity routine in PRIMER-E generated species richness (number of species censused per site), total abundances (number of individuals regardless of specie), species evenness (Pielou’s evenness, how evenly distributed individuals are amongst species), and species diversity (using Shannon-Weaver Index) for each survey sample (Clarke and Warwick 2001). To compare species indices of (1) all fish, (2) juvenile, and (3) adult populations between the two consecutive years and between initial culvert categories, two-way analyses of variance (ANOVA) were conducted. To compare species indices of samples among reef categories taken only in 2014, one-way ANOVAs were conducted. *Lutjanus campechanus* abundances and lengths were both compared among reef category in 2014 using one-way ANOVAs.

In all univariate analyses, pairwise comparisons between groups were assessed using Tukey’s Post Hoc Comparisons (Sokal and Rohlf 2012). Assumptions, including normality, outliers and homoscedasticity, were tested for each ANOVA using Shapiro-Wilk’s Test of Normality (P > 0.05), boxplots, and Levene’s Test of Homogeneity (P > 0.05), respectively (Sokal and Rohlf 2012). Transformations were done to meet assumptions. In one-way ANOVAs, if assumptions of homogeneity were violated, Welch’s Robust Test of Equality of Means and the paired Games-Howell Post Hoc Comparisons were reported instead. All univariate analyses were performed using SPSS IBM Statistics v20 package.
CHAPTER THREE: RESULTS

Across all samples, there were 59 species censused across 27 families (Table 1). Out of all species observed, only 13 species were seen as both juveniles and as adults, specifically *Anisostremus virginicus*, *Chaetodon ocellatus*, *Chaetodon sedentarius*, *Epinephelus adscensionis*, *Haemulon aurolineatum*, *Halichoeres bivittatus*, *Halichoeres burekae*, *Holacanthus bermudensis*, *Lutjanus campechanus*, *Pareques umbrosus*, *Seriola dumerili*, *Stegastes variabilis*, and *Sphyraena picudilla*. No adults were observed for 5 species, specifically *Lactophrys trigonus*, *Ocyurus chrysurus*, *Pomacanthus arcuatus*, *Pomacanthus paru*, and *Stegastes leucostictus*. Thus, the remaining 41 species were only observed as adults. Throughout the course of the study, only one or two individuals were observed for 20 species. These rare fish species included *Aluterus scriptus*, *Bodianus rufus*, *Canthigaster rostrata*, *Coryphopterus punctipectophorus*, *Dasyatis americana*, *Diplodus holbrooki*, *Elagatis bipinnulata*, *Gymnothorax moringa*, *Gymnothorax vicinus*, *Haemulon plumierii*, *Holocentrus adscensionis*, *Lactophrys trigonus*, *Lopholatilus chamaeleonticeps*, *O. chrysurus*, *Paralichthys albigutta*, *Paralichthys lethostigma*, *Pomacanthus arcuatus*, *Pomacanthus paru*, *Ptereleotris calliura*, and *Sphyraena barracuda* (Table 1).

**Bare Areas and Culvert Reefs Sampled Over Two Consecutive Summers**

Bare areas were significantly lacking reef-associated fishes when comparing them to other reefs sampled (Fig. 6, PERMANOVA: pseudo-F(1,3,19) = 15.519, p = 0.0001). Bare areas were significantly different from reefs at a 7.3% similarity (SIMPROF: π = 10.35, P = 0.01). When comparing culvert categories, no significant differences were found between overall community compositions, regardless of year (Fig. 6, pseudo-
F(1,3,19) = 0.844, P = 0.622) or between the consecutive summers (Fig. 6, pseudo-
F(1,3,19) = 1.196, P = 0.271). Water temperatures ranged from 21 to 27°C, and
significantly affected adult communities (pseudo-F(1,3,18) = 2.173, P = 0.0246), but did
not affect juvenile communities (pseudo-F(1,3,18) = 1.283, P = 0.279), or the community
as a whole (pseudo-F(1,3,18) = 1.987, p = 0.063). Water temperatures were higher
overall in 2013 (25.1 ± 0.4°C) than in 2014 (22.8 ± 0.2°C, Fig. 7), and species evenness
of juveniles was significantly higher in 2013 than in 2014 (Table 2, ANOVA: F(1,2,12) =
6.584, P = 0.025). Total square-root transformed abundances of adults were significantly
higher in 2013 (Table 2, F(1,2,12) = 6.191, P = 0.029). Bottom visibility ranged from
0.61 to 4.88 m throughout the surveys collected, but was not a significant predictor of
differences between surveys regardless of the year (Fig. 7, pseudo-F(1,2,18) = 0.951, P =
0.50).

Juvenile communities were 78.3% dissimilar (SIMPER) between the two years.
SIMPER suggested that *Haemulon aurolineatum*, *Halichoeres bivittatus* and *P. umbrosus*
juveniles were generally observed in higher abundance in 2014 than in 2013, and *Seriola
dumerili* were only seen in 2014. On the other hand, slightly more *Stegastes variabilis*
juveniles were censused in 2013. Additionally, SIMPER revealed that adult communities
were 55.2% dissimilar between 2013 and 2014. The top three species that contributed the
most to differences in adult communities were *Caranx crysos*, *Chaetodipterus faber*, and
*Lutjanus griseus*. Less individuals of the latter species were observed in 2014 than in
2013. Overall, the most abundant species, regardless of reef or sampling year, were
*Balistes capriscus*, *H. aurolineatum*, *L. campechanus*, *Parablennius marmoreus*,
*Pareques umbrosus*, and *Serranus subligarius*. 
In 2014, *Balistes capriscus, Haemulon aurolineatum, Halichoeres bivittatus, L. campechanus, P. marmoreus*, and *S. subligarius* were the most abundant species censused over all reef categories and communities. Fish communities, including all adults and juveniles, did not significantly differ between reef categories in 2014 (Fig. 8, pseudo-F(4,15) = 1.516, *P* = 0.0759). Sites in each reef category ranged from being 40.2% similar to 62.4% similar, with CC3 (71-120 culverts) and natural sites being 57.0% similar. CLUSTER analysis produced two significant clusters of samples (Fig. 8, SIMPROF: *π* = 4.18, *P* = 0.01). SIMPER indicated that one cluster contained all natural and CC3 sites, two CC1 (1-30 culverts), one CC2 (31-120 culverts), and two CC4 (121-190 culverts) sites, and represented samples that were 61.3% similar. The other cluster included two CC1, CC2 and CC4 sites, and represented samples that were 44.0% similar. SIMPER revealed that species that contributed to the dissimilarity between the two clusters included *Archosargus probatocephalus, B. capriscus, E. adscensionis, Haemulon aurolineatum, Halichoeres bivittatus, L. campechanus, L. griseus, Parablennius marmoreus, Pareques umbrosus, Seriola dumerili*, and *Stegastes variabilis*. All the latter species, except for *A. probatocephalus*, exhibited higher abundances in the 61.3% similar cluster, whereas *A. probatocephalus* was observed in higher abundances in the 44% similar cluster. *Epinephelus adscensionis* was only observed in the former cluster. Total abundance of all fishes, including adults and juveniles, significantly varied between reef category (Welch statistic = 11.899, DF1 = 4, DF2 = 6.166, *P* = 0.005). Significantly higher total abundances of fishes were observed at CC3, on average 282 ± 7 individuals, than at CC4, 120 ± 26 individuals (Fig. 9A, Games-Howell: *P* = 0.026). Species richness,
evenness, and diversity were not significantly different between reef categories, although CC3 and natural sites consistently had the highest species indices (Table 3 & 4).

Juvenile communities did not significantly differ among reef categories (Fig. 10, pseudo-F(4,15) = 1.072, P = 0.391). CLUSTER analysis suggested two significant clusters with samples that were at least 20.3% similar (Fig. 10, SIMPROF: π = 6.88, P = 0.01). The two clusters exhibit similar site groupings to the clusters found in the whole community analysis, except for two of the natural sites (Fig. 10). No significant differences were seen between juvenile species indices and reef categories, but CC3 and natural sites had the highest values for all species indices (Fig. 9B, Table 3 & 4).

Adult communities differed significantly between natural sites and CC1, CC2, and CC4, whereas CC3 and natural sites had significantly similar adult communities (Fig. 11, pseudo-F(4,15) = 2.095, P = 0.0009). SIMPER revealed that species contributing to the dissimilarity between culvert and natural sites included B. capriseus, E. adescensionis, H. aurolineatum, Parablennius marmoreus, and Sphoeroides spengleri. The latter species were observed more often over natural sites, whereas A. protabocephalus, Mycteroperca phenax, and Pareques umbrosus were seen more often within culvert sites. Log-transformed adult abundances were significantly higher at sites than at CC2 sites (Fig. 9C, Tukey’s P = 0.048). Other species indices did not significantly differ among reef categories (Table 3 & 4).

Natural and CC3 sites had higher species evenness, and species diversity indices than other reef categories (Table 3). A total of 11 species were only observed at natural reefs, and they included: Ariopsis felis, Chromis scotti, G. moringa, G. vicinus, Halichoeres burekai, Haemulon plumierii, Lutjanus synagris, Orthopristis chrysoptera,
*Ptereleotris calliura, Stegastes leucostictus,* and *Selene vomer.* A total of 18 species were observed only at culvert reefs, and they included: *Aluterus scriptus, B. rufus, Caranx hippos, Canthigaster rostrata, Dasyatis americana, Diplodus holbrookii, Decapterus macarellus, E. bipinnulata, Holocentrus adscensionis, Lactophrys trigonus,* *Mycteroperca interstitialis, M. phenax, Ocyurus chrysurus, Paralichthys albigutta,* *Pomacanthus arcuatus, Paralichthys lethostigma, Pomacanthus paru,* and *Seriola rivoliana.*

PCA analysis produced four PC axes to explain variation in substrate rugosity, average height, maximum height, and percent substrate cover over at sites sampled. Two PCs explained 91.6% of variation between the variables tested (Fig. 12), and these were interpreted for further analysis. Substrate rugosity, average and maximum height were positively correlated with PC1, while percent cover was positively correlated with PC2 (Fig. 12A). Substrate rugosity ranged from 1.001 to 1.288, average height from 0 m to 1.49 m, maximum height from 0 m to 2.95 m, percent cover from 0.76% to 100%.

Natural sites were the least rugose sites with the least average and maximum height. Natural sites had the biggest range of percent cover, and were strongly correlated with PC1 and PC2. Increasing culvert categories were positively correlated with PC2 (Fig. 12A). A total of 14 species that were found at both culvert and natural sites were correlated with the two PC axes. No overall trends were seen between species analyzed and specific PC axes, yet each species favored their own combinations of PC axes. *Archosargus probatocephalus, Anisotremus virginicus, M. microlepis, Pareques umbrosus,* and *R. maculatus* were positively correlated with PC1, and *Parablennius mamoreus* and *Sphoeroides spengleri* were negatively correlated with PC1 (Fig. 12B).
Haemulon aurolineatum, Halichoeres bivittatus, L. griseus, and Stegastes variabilis were positively correlated with PC2. Seriola dumerili was positively correlated with PC1 and PC2, while B. capriscus, E. adscensionis, and Serranus subligarius were negatively correlated with PC1 but positively correlated with the PC2 axis (Fig. 12B).

*Lutjanus campechanus* Population and Size Analysis

*Lutjanus campechanus* abundances did not significantly differ between any reef categories (Fig. 13, F(4,11) = 1.721, P = 0.205). A total of 732 *L. campechanus* were observed at the PS-1047 Reef and neighboring natural reefs. No juveniles were observed at culvert sites, but some juveniles were seen at natural sites. Each site had on average of 41 ± 6 *L. campechanus*.

Total lengths of *L. campechanus* ranged from 127.0 to 710.0 mm, with an mean of 321.0 ± 3.1 mm. Inverse-transformed *L. campechanus* total lengths were significantly different between certain reef categories, including different culvert categories and naturally occurring reefs (Welch statistic = 16.733, DF1 = 4, DF2 = 11, P < 0.0005). Significant differences were seen among reef categories without transforming the data, however a transformation was necessary to assess the significant difference with pairwise comparisons. Reefs that had less than 31 culverts exhibited significantly larger *L. campechanus* than all other reef categories (Fig. 14, Games-Howell P ≤ 0.002). CC2 exhibited significantly smaller *L. campechanus* than CC4 and natural reefs (Games-Howell P = 0.006, P = 0.023, respectively). All other reefs categories did not significantly differ from one another (Fig. 14). Using the Syc (2011) Von Bertalanffy growth curve equation coefficients, *L. campechanus* age estimates in the present study ranged from 0.57 to 6.79 years old, with an average age of 1.95 ± 0.03 years. However, when
comparing the latter growth model to five other growth models with data from the present study (Fig. 15), average age estimates of *L. campechanus* in the present study varied by 0.19 years (Szedlmayer and Shipp 1994; Patterson et al 2001; Wilson and Nieland 2001; Fischer et al 2004; Saari 2011).
CHAPTER FOUR: DISCUSSION

Bare Areas

As expected, bare areas lacked reef fishes. Suitable habitat is necessary for foraging, shelter, predation, reproduction, and gardening for reef fishes (Lobel 1980; Holbrook et al 2000). Bare areas provide no such habitat, and settling juveniles, as well as recruiting adults, can detect differences in suitable habitat using mechanosensory, auditory, olfactory and visual cues (Gutiérrez 1998; Leis 2002; Wright et al 2005; Dixson et al 2011). Gratwicke and Speight (2005) compared varying concrete reef configurations to account for reef height and complexity, and to assess the use of additional reef habitat in seagrass beds. Seagrass beds without additional habitat had significantly fewer fishes than seagrass beds with concrete habitat. Berrios et al. (2005) also tested the effectiveness of artificial reefs with control sites at seagrass beds, and found an average of 4 individuals per control sites versus an average of 861 individuals per reef sites. Thus, adding suitable structure to otherwise limited habitat areas drastically increases species diversity.

Whereas no fishes were seen at bare areas in the current study, a total of 27 families of fish were surveyed at culvert and natural reefs, with an average of 13 ± 1 species and 186 ± 28 individuals per reef, and a relatively even community (0.68 ± 0.01). Thus, culvert reefs and naturally-occurring reefs are a substantial improvement to otherwise barren seafloor in the northwestern Gulf of Mexico. Surveys conducted at bare areas in a concurrent study in 2014 at PS-1047 found a few individuals of Centropristic philadelphica, Diplectrum bivittatum, and Ophichthus gomesii. However, none of these species were seen at any sites with structure in this study.
**Water Temperature and Year Differences**

Year to year variation did not show a clear pattern with regard to the whole fish community over culvert reefs. On the other hand, the abundance of adults alone were affected. Samples from 2013 had higher temperatures and higher abundances of *Caranx crysos, Chaetodipterus faber, and Lutjanus griseus* compared to 2014. All three species are warm water subtropical reef fish, and several individuals may have died or moved to deeper waters during the cold winter, because deeper waters vary less in temperature (McKenney et al 1958; Bortone and Williams 1986; Ditty et al 1994). For example, reported temperature ranges for *L. griseus* is from 18.9°C to 27.8°C (Bortone and Williams 1986). The winter from 2013 to 2014 was colder than average for South Texas, as well as the US and several other countries, and sea waters stayed colder for longer in 2014 than in 2013. Some of the warm water subtropical individuals may never have returned to PS-1047 after the winter. Similarly, Henriques et al. (2013) suggests that natural variability may not impact fish guilds, whereas species abundances are impacted.

Juveniles censused in 2014 had less even populations than in 2013. Although differences in temperature did not affect changes in juvenile species present, less even populations in 2014 may suggest the presence of stronger cohorts of some juvenile species than others. Changes in water temperature affect reproduction, growth rates of larvae and juveniles, ontogenic shifts, and survivability of larvae (Jokiel and Coles 1990; Green and Fisher 2004; Sponaugle et al 2006). Colder water temperatures in 2014 may have shifted spawning season to later months. Consequently, this could have prevented the influx of some species, and allowed other juvenile species to settle in bigger numbers.
Perhaps, differences in abundances among the two years may be a result of different overall temperatures.

_Culvert Reef Complexity and Natural Reef Comparisons_

Species at PS-1047 occurred at culvert reef sites with relatively similar abundances, regardless of drastic differences in the number of culverts present. The lack of difference may be due to the lack of complexity in the reef. Culverts found at PS-1047 are not all the same exact shape and size, however the vast majority are one m by three m. Walsh (1985) tested the effects of different shaped culvert blocks, with similar sizes, resting on top of each other, and found no significant differences among reef characteristics with regard to colonization rate, species richness, or diversity. By adding similarly sized concrete reefs, the shape or amount of material may not be driving differences in species yield.

Although some species were solely found on culvert reefs or solely on natural reefs, the overall fish communities did not vary significantly between natural and culvert reefs. The highest species richness and diversity was recorded at natural reefs, however the third culvert category (CC3: 71-120 culverts) had similarly high species index values (Table 3). This suggests that CC3 may be similar in composition to natural reefs, and may have the optimal density of culverts to mimic natural habitat characteristics. Findings from this study revealed that the total number of individuals was the major driver of differences between reef categories. Although the pattern of juveniles settlement is unclear, the adult population seems to be driven by the presence of different reef configurations, with highest diversity seen at CC3 and natural sites. Similarities and
differences between natural and artificial reefs have been debated for a few decades, but no clear patterns have surfaced.

Carr and Hixon (1997) compared small artificial reefs with coral patch reefs in the Bahamas, and found higher species richness and abundance at coral patches, but the overall composition of fish communities at both was similar. Coral patch reefs were more structurally complex than their artificial reef counterparts, specifically with variability in hole sizes and edible benthos associated with coral, and the added vertical relief in artificial reefs did not compensate for differences in complexity. Carr and Hixon (1997) suggested that artificial reefs should be structurally complex and similar to natural reefs to better mitigate losses of coral cover.

Talbot et al. (1978) observed lower species diversity at concrete artificial reefs than at natural reefs, and suggested that artificial reefs had smaller carrying capacities. This study found that reefs lacking holes had only slightly lower species diversity, suggesting that other factors affected species diversity, such as season and currents. Unfortunately, weather conditions hindered such comparisons in the present study. Walker et al. (2009) studied natural reefs in Southeastern Florida, and found similar species richness (12-21), abundance (56-211), and substrate rugosity (1.14-1.30) ranges as the present study. Walker et al. (2009) also revealed that topographic complexity and species richness were positively correlated to a certain extent in offshore habitats, whereas the relationship was not as strong in shallow areas. Thanner et al. (2006) suggested that artificial reef complexity should be similar to natural reefs to result in similar fish community compositions, since higher species abundances were seen at natural reefs.
Such findings reveal that stronger resemblance in topographic complexity would allow for artificial reefs to hold more similar fish communities to naturally-occurring reefs in the vicinity. What topographic characteristics should be considered to make artificial reefs more similar to natural reefs? Molles (1978) found that interspace size diversity in artificial reefs was not a significant driver of species richness, but reef height was positively correlated with species richness and diversity. Gratwicke and Speight (2005) found reef height to have no effect on fish communities at concrete block reefs. The present study found *E. adscensionis*, a relatively understudied species, to be correlated with high percent cover, and to be more often present at natural reefs than culvert reefs. One study found *E. adscensionis* to have a complex hierarchical social system with dominant and very territorial individuals in each group (Kline et al 2011). A strong positive correlation of this species with percent cover may indeed suggest that more reef space and higher complexity allows for less competition and more individuals. Thus, more complexity on artificial reefs may result in suitable habitat for more species than less complex environments.

Charbonnel (2002) added small artificial reef material to large artificial reef units already established. The study found that the added complexity doubled species richness, and increased density and biomass 10 fold and 40 fold, respectively. A large portion of new species arrivals in the latter study came from increased presence of sparids and other commercially important species. Lingo and Szedlmayer (2006) similarly found that added complexity, such as fused stacks of concrete blocks, significantly increased species diversity at artificial reefs. Arney (2014) deployed small caged 0.3 m³ artificial coral head units alongside bare areas and culvert reefs at PS-1047, and collected juveniles up to
90 days after deployment. Arney (2014) found juveniles previously unrecorded at these culvert reefs, including *Brotula barbata, Histrio histrio, Hypleurochilus gematus, Opsanus beta,* and *Yrophycis floridana,* and two commercially important species *Hyporthodus flavolimbatus* and *Hyporthodus nigritus.* Gratwicke and Speight (2005) revealed that increasing small crevices and increasing percent hard substrate positively correlated with higher fish abundances at artificial reefs. Such studies suggest that adding complexity to culvert reefs may be a better alternative than simply adding more culverts of the same size to increase overall diversity.

*Lutjanus campechanus* Population Dynamics

In recent years, populations of *L. campechanus* have started to recover due to increased management practices and new habitat (GMFMC 2013). Research of in situ population stocks at artificial reefs continues to be important in order to fully understand how *L. campechanus* are using added habitat. Varying densities of culvert reefs in this study did not show significant differences in *L. campechanus.* Big schools of *L. campechanus* were found at every site censused. However, trends suggested that intermediate-sized culvert sites with 71-120 culverts and natural sites yielded the highest abundances out of all other reef categories. Very little research is done studying the effect of habitat density on abundance of *L. campechanus,* however *L. campechanus* are schooling fish that move to different habitats following ontogenic shifts (Diamond 2003; Gazey et al 2008). Perhaps a lack of difference in abundance is due to their schooling behaviors, and when one is present then many are as well.

Juvenile *L. campechanus* were only seen at natural reefs, not at culvert reefs. Natural reefs have more complex habitats, with varying burrow sizes, and may indeed
resemble nursery grounds for *L. campechanus* where larvae first settle and grow into juveniles. Once juveniles metamorphose into adults, *L. campechanus* move to environment with bigger structure, such as the culvert reef at PS-1047 (Gazey et al. 2008; Gallaway et al. 2009; Arney 2014). In a concurrent study, Arney (2014) found that juvenile *L. campechanus* only settled around the small enclosed artificial coral structures in bare areas far from culvert reefs. Gallaway et al. (1999) studied factors affecting the presence of juvenile *L. campechanus*, and suggested that an inverse relationship was found between oil platform density and abundance of juveniles. Presence of juveniles at natural reefs and at small solitary structures is supported by literature suggesting larvae settlement and movement to low relief rubble reefs.

Saari (2011) suggested that *L. campechanus* grow slower at natural banks than at artificial reefs. Overall, the populations assessed from Saari (2011) and other *L. campechanus* age assessment experiments were older than those in the present study (Fig. 17; Szedlmayer and Shipp 1994; Patterson et al. 2001; Wilson and Nieland 2001; Fischer et al. 2004; Syc 2011). The latter studies (except for Syc 2011) assessed *L. campechanus* ages from otolith samples collected from recreational and commercial fisheries. Such estimates may not suffice for representative population analysis. Syc (2011) collected *L. campechanus* from hook and line to catch bigger individuals, and from fish traps to collect smaller individuals. The present study found younger cohorts of *in situ* *L. campechanus*, with an average age of 1.95 ± 0.03 years. These age estimates should be verified with otolith samples taken directly from PS-1047 populations, but such a small average age at PS-1047 suggests that many *L. campechanus* at this site are not yet
mature. Thus, PS-1047 is a shallow reef where juvenile *L. campechanus* grow and become reproductively mature before the individuals move to deeper and bigger reefs.

In the present study, total lengths of *L. campechanus* were highest at the lowest culvert density. Lindberg et al. (2006) studied the distribution and size of gag grouper (*M. microlepis*) at two concrete densities. The study revealed that larger individuals were found at the least dense sites. Lindberg et al. (2006) suggested that gag grouper behaviors caused differences in sizes of individuals between reefs. Bigger populations may be more aggressive to their counterparts, and a strong initial cohort of recruits at small reefs would not allow for more space to be occupied by later cohorts. Perhaps *L. campechanus* remain longer at lower density reefs, potentially driving away smaller individuals.

In either case, literature suggests that *L. campechanus* will move further offshore to deeper artificial reefs, such as oil platforms, and will stratify by size (Pruett et al 2005; Gallaway et al 2009; Saari 2011). Gallaway et al. (2009) suggests that fish over the age of 8 or 10 may in fact not need to rely on structured habitat, because predation is rather inexistent at that size. *S. barracuda* were only observed twice in June 2013, and a few *Carcharhinus leucas* and *Sphygma mokarran* were seen on a different study in 2013 at PS-1047. *Stenella attenuata* were also seen on several occasions swimming at the surface in pods at PS-1047. Such species are predators of *L. campechanus*, but their limited occurrence suggests natural predation may not be a key factor drastically affecting populations at PS-1047. However, older fish were not observed at PS-1047.

Other important sportfish observed during this study include *Mycteroperca microlepis*, *Mycteroperca phenax*, *L. griseus* and *Seriola dumerili*. Less than 30 individuals of *M. microlepis* and *M. phenax* were observed each during the study.
*Mycteropecra microlepis* and *M. phenax* were found at sites with more rugosity and vertical relief, but *M. phenax* were only seen at culvert sites. *Lutjanus griseus* were more often observed in schools over natural reefs than culvert reefs, and populations were strongly correlated with percent cover, with 225 individuals observed in total. Only two *S. dumerili* adults were observed, however 293 juveniles were seen swimming in schools over reefs with more rugosity, percent cover and vertical relief, regardless whether the reef was natural or artificial. The latter species was the only one observed as juveniles at all reefs surveyed in this study. Further population analysis could confirm that added rugosity, percent cover, and vertical relief may allow for stronger cohorts of these at concrete reefs.
CHAPTER FIVE: CONCLUSIONS

As expected, natural sites had the highest diversity of all reef categories, however CC3, and not CC4, had the second highest diversity values. Reef fish communities were different between the two summers, perhaps due to the differences in water temperature. As hypothesized, site visibility did not affect surveys. No L. campechanus were observed at bare areas, yet, contrary to expectation, there were no significant differences in abundance between reef categories. The lowest culvert categories had the largest L. campechanus, but CC3 and natural sites had the second largest individuals.

The project’s findings suggest an intermediate density of culverts (71-120 culverts) could be deployed in the future to reach high species richness and diversity. Culvert reefs at this density hold similar species abundances as natural reefs in the area. Concrete culverts are nontoxic, and are very similar to the rock characteristics on the natural coralgal reefs studied. Thus, culvert reefs are considered effective structures to add suitable habitat for reef associated fishes, especially commercially important fishes. Anglers typically desire bigger fishes, and determining ideal patch reef sizes to maximize habitat for other sport fishes, such as groupers, may also be important for fisheries management.

Suggestions for further culvert reef deployment, based on the results of this study, are as follows: reefs composed of roughly 100 culverts in a 30 m area could be deployed with a minimum of 100 m distance among reefs. Small microhabitat concrete material could also be randomly distributed over these reef sites to add complexity, and hopefully carry higher diversity. Thus, 4,000 culverts, such as those that compose PS-1047, could
be used to deploy 40 reefs in a four km$^2$ grid, thus quadrupling the area covered at PS-1047

Walsh (1985) studied the effect of small scale isolation around artificial reefs, and found higher species richness and diversity in reefs that were more isolated than others, with single reefs found in up to 370 m$^2$ sand areas. Molles (1978) revealed that reef isolation was negatively correlated with species richness for resident species, however no correlation was found when transient species were included in the analysis. Lindberg et al. (2006) revealed that bigger concrete reefs separated by 225 m, compared to 25 m and 75 m, exhibited higher residency of *M. microlepis*. On the other hand, smaller reefs exhibited the least residency of *M. microlepis* at the most isolated reefs. Shipley and Cowan Jr. (2010) found that ideal distances between reefs should be between 500 m and 950 m to result in the optimal *L. campechanus* populations. If deployment of artificial reefs is solely based on the possible outcome of sport fish populations, perhaps reefs should be more isolated than 100 m (Shipley and Cowan Jr 2001; Lindberg et al 2006). Yet if overall species diversity is sought after, then small culvert reefs isolated from one another by 100 m may yield the highest total species biodiversity, and be most cost-effective.

*Suggestions for Future Research*

The current study could be continued over several years to better assess the impact of varying temperatures. To better characterize reefs studied and small scale factors affecting fish communities, invertebrate community analysis and more detailed rugosity measures should be collected. Benthic communities will only mimic natural distributions at artificial reefs if these reefs are similar in structural complexity to their natural
counterparts. However, measurements of substrate rugosity in this study were very small over natural reefs. The latter measurements did not account for more detailed topographic characteristics, including microhabitat associated with algal and invertebrate growth on the rock. Invertebrate surveys alongside fish surveys could also be collected to help determine if presence of certain invertebrates affected the presence of fish species, and to better assess topographic complexity. Pais et al. (2013) suggested that substrate rugosity measures, taken with the chain-link method proposed by Luckhurst and Luckhurst (1978), be combined with the number of corrugations at reef sites, as well as maximum vertical relief. More comprehensive measures, such as the latter, may provide better measures of natural and culvert reef complexity. Thus, more predictive fish community analyses may result in additional improvements of artificial reef composition and in the development of richer reef habitats.
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Fig. 1 Culvert and natural reefs at PS-1047 Reef, located 13 km from Port Mansfield, Texas (N 26° 31.535' – W 97° 09.215'). Image modified from Google Earth.
Fig. 2 Examples of culvert reefs (on the top) and natural reefs (on the bottom) at PS-1047 Reef, off the coast of Port Mansfield, Texas (N 26° 31.535’ – W 97° 09.215’).
Fig. 3 Humminbird 1198 side imaging was used to quantify topographic characteristics of each reef site surveyed at PS-1047 Reef, off Port Mansfield, Texas. Reef sites fit into six reef categories, each with or without structure in a 30-m radius: (a) CC1: 1-30 culverts, (b) CC2: 31-70 culverts, (c) CC3: 71-120 culverts, (d) CC4: 121-190 culverts, (e) bare areas, and (f) naturally-occurring reefs.
Fig. 4 Water visibility recorded by a diver using a secchi disk and measuring tape at each survey at PS-1047 Reef, Texas.
Three lasers were mounted, each 0.3 m apart, on an aluminum flat bar (3.9 x 70 x 0.3 cm), with a GoPro HD Hero 3+, to record total lengths of *Lutjanus campechanus* underwater by SCUBA divers at PS-1047 Reef, Texas.

**Fig. 5**
Table 1 Presence/absence of species from summers 2013 and 2014 at PS-1047 Reef, off Port Mansfield, Texas. Gray blocks indicate presence of the species.

<table>
<thead>
<tr>
<th>Family</th>
<th>Fish Species</th>
<th>Common names</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
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<tr>
<td>Apogonidae</td>
<td>Apogon maculatus</td>
<td>Flamefish</td>
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<td>Ariidae</td>
<td>Anoplos felis</td>
<td>Hardhead Sea Catfish</td>
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<td>Balistidae</td>
<td>Balistes capriscus</td>
<td>Gray Triggerfish</td>
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<td>Blenniidae</td>
<td>Hypsoblennius inermar</td>
<td>Tesselated Blenny</td>
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<td></td>
<td>Parablennius marmoreus</td>
<td>Seaweed Blenny</td>
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<td>Carangidae</td>
<td>Caranx cryos</td>
<td>Blue Runner</td>
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<td></td>
<td>Caranx hippos</td>
<td>Common Crevalle Jack</td>
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<td>Chaetodontidae</td>
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<td>Spotfin Butterflyfish</td>
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<td>Chaetodon sedentarius</td>
<td>Reef Butterflyfish</td>
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<td>Orthopristis chrysoptera</td>
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<td>Halichoeres burekiae</td>
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<td>Sphoeroides spengleri</td>
<td>Bandtail Puffer</td>
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48
Fig. 6 Fish community composition in relation to density categories of culvert reef habitat and bare sites over two consecutive “summers” (June to July 2013 & May to July 2014) at the PS-1047 Reef, off the South Texas coast. Lines attached to squares indicate samples that fall on top of one another on the plot. Dashed ovals indicate an overlay of Hierarchical Cluster Analysis that defined two clusters of samples as being significantly different from one another and being 7.3% similar. Low stress of 0.05 indicates that the 2D representation of a multi-dimensional scaling plot was appropriate.
Fig. 7 Principal component analysis (PCA) of water temperature (°C) and site visibility (m) over varying culvert density categories and over two consecutive “summers” (June to July 2013 & May to July 2014) at PS-1047 Reef off the South Texas coast. Vectors point in the direction of increasing values. Distance relative to the outer circle provides indication of how much variation is explained by each vector.
Table 2 Species richness, abundance, evenness and diversity indices of culvert reefs censused in summers 2013 and 2014 at the PS-1047 Reef, off Port Mansfield, Texas. Significant differences between the two years are indicated by an asterisk (*).

<table>
<thead>
<tr>
<th>Species Index</th>
<th>All Individuals</th>
<th>Juveniles</th>
<th>Adults</th>
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<tbody>
<tr>
<td><strong>2013</strong></td>
<td></td>
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<tr>
<td>Species Richness</td>
<td>13 ± 4</td>
<td>2 ± 0.2</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Total Abundance</td>
<td>142 ± 68</td>
<td>17 ± 11</td>
<td>125 ± 26 *</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.65 ± 0.14</td>
<td>0.72 ± 0.09 *</td>
<td>0.67 ± 0.04</td>
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<tr>
<td>Shannon-Weaver Index</td>
<td>1.66 ± 0.45</td>
<td>0.61 ± 0.10</td>
<td>1.55 ± 0.13</td>
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<tr>
<td><strong>2014</strong></td>
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</tr>
<tr>
<td>Species Richness</td>
<td>11 ± 1</td>
<td>3 ± 1</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>Total Abundance</td>
<td>121 ± 27</td>
<td>62 ± 24</td>
<td>59 ± 10</td>
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<tr>
<td>Species Evenness</td>
<td>0.65 ± 0.02</td>
<td>0.33 ± 0.12</td>
<td>0.68 ± 0.03</td>
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<tr>
<td>Shannon-Weaver Index</td>
<td>1.54 ± 0.10</td>
<td>0.51 ± 0.16</td>
<td>1.43 ± 0.12</td>
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<td><strong>Total</strong></td>
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<tr>
<td>Species Richness</td>
<td>12 ± 1</td>
<td>3 ± 0.4</td>
<td>9 ± 1</td>
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<tr>
<td>Total Abundance</td>
<td>131 ± 17</td>
<td>39 ± 14</td>
<td>92 ± 16</td>
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<tr>
<td>Species Evenness</td>
<td>0.65 ± 0.03</td>
<td>0.52 ± 0.09</td>
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<tr>
<td>Shannon-Weaver Index</td>
<td>1.60 ± 0.09</td>
<td>0.56 ± 0.09</td>
<td>1.49 ± 0.09</td>
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</table>
Fig. 8 Fish community composition in varying density categories of culvert and natural reefs in the summer of 2014 at the PS-1047 Reef off the South Texas coast. Number “1:” 1-30, “2:” 31-70, “3:” 71-120, “4:” 121-190 culverts, respectively, “N:” natural reefs inside the PS-1047 reeﬁng area, and “No:” natural reefs outside the reeﬁng area. Ovals indicate an overlay of Hierarchical Cluster Analysis that deﬁned two clusters of samples as being signiﬁcantly different from one another and clusters that are at least 44% similar. Low stress of 0.13 indicates that the 2D representation of a multi-dimensional scaling plot was appropriate.
Fig 9 Total abundance of (a) all individuals, (b) only juvenile individuals and (c) only adult individuals censused among reef types at the PS-1047 Reef, off the South Texas Coast. Note change in scale along the vertical axis. “CC1:” 1-30, “CC2:” 31-70, “CC3:” 71-120, “CC4:” 121-190 culverts, respectively, and “natural:” naturally-occurring reefs. Asterisks(*) correspond to samples that are significantly different (P > 0.05).
Table 3 Species richness, abundance, evenness, and diversity indices of culvert and natural reefs censused in the summer of 2014 at the PS-1047 Reef, off Port Mansfield, Texas.

<table>
<thead>
<tr>
<th>Species Index</th>
<th>All Individuals</th>
<th>Juveniles</th>
<th>Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CC1 (1-30 culverts)</strong></td>
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</tr>
<tr>
<td>Species Richness</td>
<td>11 ± 3</td>
<td>3 ± 1</td>
<td>8 ± 1</td>
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<tr>
<td>Total Abundance</td>
<td>121 ± 56</td>
<td>66 ± 38</td>
<td>56 ± 20</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.68 ± 0.04</td>
<td>0.25 ± 0.14</td>
<td>0.68 ± 0.04</td>
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<td>Shannon-Weaver Index</td>
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<td>0.42 ± 0.24</td>
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<td><strong>CC2 (31-70 culverts)</strong></td>
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<td></td>
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<td>Species Richness</td>
<td>10 ± 1</td>
<td>3 ± 2</td>
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<td>Total Abundance</td>
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<td>Species Evenness</td>
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<td>0.41 ± 0.41</td>
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<td><strong>CC3 (71-120 culverts)</strong></td>
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<td>Species Richness</td>
<td>13 ± 1</td>
<td>5 ± 1</td>
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<td>Total Abundance</td>
<td>282 ± 7</td>
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<td>Species Evenness</td>
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<td><strong>CC4 (121-190 culverts)</strong></td>
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<td>Species Richness</td>
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<td>Total Abundance</td>
<td>120 ± 26</td>
<td>52 ± 35</td>
<td>69 ± 11</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.64 ± 0.04</td>
<td>0.48 ± 0.19</td>
<td>0.72 ± 0.07</td>
</tr>
<tr>
<td>Shannon-Weaver Index</td>
<td>1.64 ± 0.20</td>
<td>0.62 ± 0.25</td>
<td>1.76 ± 0.27</td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species Richness</td>
<td>17 ± 2</td>
<td>5 ± 1</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>Total Abundance</td>
<td>276 ± 53</td>
<td>94 ± 28</td>
<td>200 ± 56</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.69 ± 0.02</td>
<td>0.67 ± 0.07</td>
<td>0.67 ± 0.01</td>
</tr>
<tr>
<td>Shannon-Weaver Index</td>
<td>1.92 ± 0.13</td>
<td>0.95 ± 0.18</td>
<td>1.71 ± 0.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species Richness</td>
<td>13 ± 1</td>
<td>4 ± 1</td>
<td>11 ± 1</td>
</tr>
<tr>
<td>Total Abundance</td>
<td>186 ± 28</td>
<td>75 ± 15</td>
<td>110 ± 22</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.68 ± 0.01</td>
<td>0.46 ± 0.07</td>
<td>0.69 ± 0.02</td>
</tr>
<tr>
<td>Shannon-Weaver Index</td>
<td>1.73 ± 0.07</td>
<td>0.68 ± 0.10</td>
<td>1.59 ± 0.08</td>
</tr>
</tbody>
</table>
Table 4 Significances from one-way ANOVAs to compare species indices between reef types (four different culvert categories ranging from 1 to 190 culverts and natural reefs) censused in the summer of 2014 at the PS-1047 Reef, off Port Mansfield, Texas. Asterisks (*) indicate significant values (P < 0.05).

<table>
<thead>
<tr>
<th>Species Index</th>
<th>All Individuals</th>
<th></th>
<th>Juveniles</th>
<th></th>
<th>Adults</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-stat</td>
<td>P-value</td>
<td>F-stat</td>
<td>P-value</td>
<td>F-stat</td>
<td>P-value</td>
</tr>
<tr>
<td>Species Richness</td>
<td>1.628</td>
<td>0.219</td>
<td>0.715</td>
<td>0.594</td>
<td>1.678</td>
<td>0.207</td>
</tr>
<tr>
<td>Total Abundance</td>
<td>11.899</td>
<td>0.005 *</td>
<td>1.966</td>
<td>0.152</td>
<td>6.928</td>
<td>0.022 *</td>
</tr>
<tr>
<td>Species Evenness</td>
<td>0.608</td>
<td>0.663</td>
<td>1.981</td>
<td>0.149</td>
<td>4.992</td>
<td>0.800</td>
</tr>
<tr>
<td>Shannon-Weaver Index</td>
<td>1.400</td>
<td>0.282</td>
<td>1.109</td>
<td>0.388</td>
<td>0.968</td>
<td>0.454</td>
</tr>
</tbody>
</table>
Fig. 10 Community composition of juvenile fishes in varying density categories of culvert and natural reefs in the summer of 2014 at the PS-1047 Reef off the South Texas coast. Number “1;” 1-30, “2;” 31-70, “3;” 71-120, “4;” 121-190 culverts, respectively, “N;” natural reefs inside the PS-1047 reefing area, and “N_o;” natural reefs outside the reefing area. Lines attached to numbers indicate samples that fall on top of one another on the plot. Dashed ovals indicate an overlay of Hierarchical Cluster Analysis that defined two clusters of samples as being significantly different from one another, and clusters that were at least 20.3% similar. Low stress of 0.07 indicates that the 2D representation of a multi-dimensional scaling plot was appropriate.
**Fig. 11** Community composition of adult fishes in varying density categories of culvert and natural reef habitat in 2014 at the PS-1047 Reef off the South Texas coast. Number “1:” 1-30, “2:” 31-70, “3:” 71-120, “4:” 121-190 culverts, respectively, “N:” natural reefs inside the PS-1047 reefing area, and “N_o:” natural reefs outside the reefing area. Relatively low stress of 0.18 indicates that the 2D representation of a multi-dimensional scaling plot was appropriate.
Fig. 12 Principal component analysis (PCA) of (a) percent substrate cover, substrate rugosity, average height, and maximum height and (b) correlated species found over differing reef types at PS-1047 Reef off the South Texas coast. Species shown had over 9 individuals censused, occurred over both culvert and natural reefs, and had a Pearson correlation coefficient of over 0.2 with PC1 and/or PC2. Number “1:” 1-30, “2:” 31-70, “3:” 71-120, “4:” 121-190 culverts, respectively, and “N:” natural reefs. Vectors point in the direction of increasing values. Distance relative to the outer circle provides indication of how much variation is explained by each vector.
Fig. 13 Lutjanus campechanus abundances over varying reef types in 2014 at the PS-1047 Reef, off the South Texas coast. L. campechanus were not observed at any bare sites. “CC1:” 1-30, “CC2:” 31-70, “CC3:” 71-120, “CC4:” 121-190 culverts, respectively, and “natural:” naturally-occurring reefs. Error bars represent standard error (± 1).
Fig. 14 Frequency distributions of *Lutjanus campechanus* total lengths among reef categories in 2014 at PS-1047 Reef, off Port Mansfield, Texas. “CC1:” 1-30, “CC2:” 31-70, “CC3:” 71-120, “CC4:” 121-190 culverts, respectively, and “natural:” naturally-occurring reefs. Non-matching lower case letters indicate reef categories that are significantly different from one another (P > 0.05). Curves represent overall pattern of each frequency distribution.
Fig. 15 Comparison of Von Bertalanffy Growth Models for *Lutjanus campechanus* in the Gulf of Mexico. Length at age data from the present study, at PS-1047 Reef off Port Mansfield, Texas, was calculated from the Syc (2011) growth model, and the range is indicated by the solid oval.