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A Comparison of Scleractinian Coral Abundance Between Natural and Artificial Substrata in a High-Latitude Environment Off Broward County, Florida, USA

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A Comparison of Scleractinian Coral Abundance Between Natural and Artificial Substrata in a High-Latitude Environment Off Broward County, Florida, USA

Master's Thesis

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Major Professor

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Submitted to the Faculty of Nova Southeastern University Oceanographic Center in Partial fulfillment of the requirements for the degree of Master of Science with specialty in:

Marine Biology

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Master of Science Thesis

A Comparison of Scleractinian Coral Abundance Between Natural and Artificial Substrata in a High-Latitude Environment Off Broward County, Florida, USA

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Table of Contents

List of Tables and Figures

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1.0 Abstract

The Dania Beach Erojacks Artificial Reef was deployed off the coast of Broward County, Florida on December 31, 1967 as a way to help combat beach erosion. Over the last forty years, the linear pile of concrete hexapods has become an important habitat, for scleractinian corals, octocorals, algae, crustaceans, mollusks, and fish. This study focuses on the density and size of the scleractinian corals found on this artificial reef and how it compares to that of the nearby natural reef. In addition, the impact of two hurricanes on the shallow portion of the artificial reef was documented. In the 2-year study, results indicate that there was higher coral cover on the natural reef (6.45%) compared to 4.27% cover on the artificial reef. Most of the colonies on the natural reef are larger than those found on the artificial reef; 65.6% vs. 29.7% were greater than $25cm^2$. When comparing colony numbers, there are more than three times as many on the artificial reef (3870) compared to the same area of natural reef (1133). This corresponds to colony densities of $5.0/m^2$ on the artificial reef, compared to $1.5/m^2$ on the natural reef. The passage of two hurricanes in close proximity to the artificial reef resulted in no decrease in the number and surface area of corals when pre- and post-hurricane values were compared. Surprisingly, there were significant increases in both coral abundance (GEE Analysis, $p < 0.0001$) and cover (GEE Analysis, $p = 0.0001$), however these changes were attributed to improved proficiency of the researchers in finding corals rather than actual increases in these values.

2.0 Introduction

2.1   *Coral Reefs*

A coral reef is a three-dimensional, tropical, shallow water structure dominated by scleractinian corals (Bellwood 2004), that accretes carbonate (Wainwright 1965). However, the reef ecosystem as a whole contains numerous associated species including, sponges, octocorals, bryozoans, mollusks, crustaceans, fishes, algae, and seagrass. Reaka-Kudla (1996) compared coral reefs to tropical rainforests and concluded that coral reefs are one of the most biologically diverse environments in the world.

Aside from their spectacular diversity, coral reefs serve as great economic resources, providing revenue from tourism, recreational diving, commercial and recreational fishing, as well as, providing food, supporting a supply of marine animals for the aquarium trade, and creating carbonate building materials (Straccione 2002). Both coral reefs and coral communities support a vast array of life and are a major source of revenue in Southeast Florida due to recreational activities of residence and visitors. In 1995, (Scoggins and Pierce), estimated revenue generated by meals, lodging, transportation, equipment rentals, and boat charter associated with diving, snorkeling, and fishing in South Florida can amount to $600 million annually. However, according to John et al. (2001), persons who used the reefs in Broward County spent $1,024,000,000 ($1 billion) on reef-related expenditures. Of this amount $496 million was associated with artificial reef-related expenditures and $529 million was associated with natural reef-related expenditures. Thus, coral health is essential to South Florida's ocean based economy.

2

Coral reefs also serve as the first line of defense against offshore wave assault (particularly those associated with cyclonic storms) and help control shoreline erosion (Edwards and Clark 1992).

In South Florida, actively growing coral reef formation occur South of Miami, along the Florida Keys, to the Dry Tortugas in an area known as the Florida Reef Tract (Marszalek et al. 1977). Reefs can form in this area because seawater temperature is generally above 16˚C, which is conducive for calcium carbonate secretion (Burns 1985). North of Miami, four bathymetric structures exist that run for 170km (SECREMP 2007) from Miami-Dade County, through Broward County, and into Palm Beach County (Figure 1). In 2007, Banks described these structures as: 1. The nearshore reef complex, an area of coquina limestone and carbonate quartz sandstone, interpreted to be deposited between 6500 – 8000 years ago, and is located approximately 500m from shore in 3-4m of water; 2. The inner reef terrace closest to shore is a back reef zone of relatively undeveloped inshore and patch reefs, located 900m offshore in 4-5m of water; 3. The middle reef terrace is an outer reef zone of well-developed reef platform that develops 2-3m of relief and is composed of a broad platform of gorgonians and flat coral colonies in 7-8m of water approximately 1200m offshore; 4. The outer reef terrace is a fore reef zone including deeper areas adjacent to reef habitat that lay in 16-18m of water, approximately 2000m from shore and is the most developed. The reef like ridges north of Miami are relict with no active accretion due to the exceeding low cover of reef building corals (Moyer et al, 2003). Seawater temperature in this area drops below the optimal range for coral growth causing these coral communities to be less diverse and reduced in coral abundance when compared to the reefs to the south (Jaap 1984). One hundred seventeen (117) species of scleractinian corals and gorgonians have been
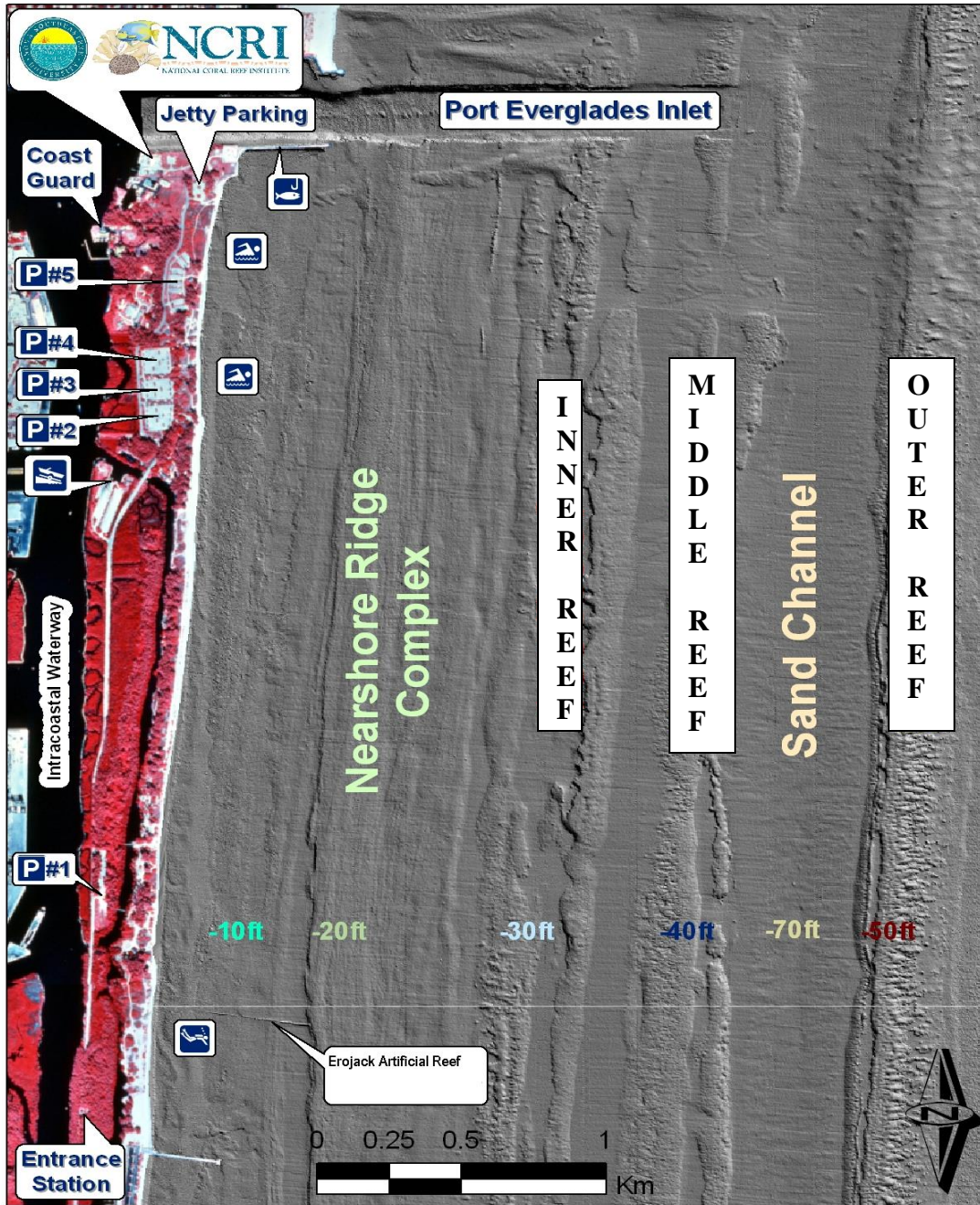
Figure 1: LIDAR Bathymetry Map of Broward County Reef Tract: John U Lloyd State Park and Port Everglades Entrance. Image Courtesy of Brian Walker, NCRI, 2008, per comm.

described in South Florida; however, most of these are only found within the Florida Reef Tract, south of Miami (Jaap et al. 1988). In Broward County, where no active reef accretion occurs, coral communities are comprised of only 36 species (Table 1) of scleractinian corals, with low cover (<6%), and small colony size (<50cm diameter) (Goldberg 1973, University of Florida 2007). According to Moyer et al. (2003) *Montastrea cavernosa* predominates as the major scleractinian coral, is also supported by Loya (1976) who reported that in areas with heavy sedimentation and high turbidity, such as this site, *M. cavernosa* is the most abundant reef building coral. However, my

Acropora cervicornis	*Millepora complanata*[1]
Acropora palmata	*Montastraea annularis*
Agaricia agaricites	*Montastraea faveolata*
Agaricia fragilis	*Montastrea cavernosa*
Agaricia lamarcki	*Mussa angulosa*
Cladocora arbuscula	*Mycetophillia lamarkiana*
Colpophyllia natans	*Mycetophyllia aliciae*
Dendrogyra cylindrus	*Oculina diffusa*
Dichocoenia stokesii	*Oculina robusta*[1]
Dichocoenia stellaris[1]	*Oculina tenella*[1]
Diploria clivosa	*Oculina varicosa*[1]
Diploria labyrinthiformis	*Phyllangia americana*
Diploria strigosa	*Porites astreoides*
Eusmilia fastigiata	*Porites porites*
Favia fragum	*Scolymia cubensis*
Isophyllastrea rigida[1]	*Siderastrea radians*
Isophyllia sinuosa	*Siderastrea siderea*
Leptoseris cucullata	*Solenastrea bournoni*
Madracis decactis	*Solenastrea hyades*[1]
Madracis mirabilis	*Stephanocoenia intersepta*
Meandrina meandrites	*Tubastrea coccinea*
Millepora alcicornis	

Table 1: Broward County Scleractinian Coral Species ([1]Goldberg 1973) (All others Goldberg 1973, Gilliam et al, 2007, Gilliam 2007)

observations indicated that *Diploria clivosa* was the predominant coral on the natural reef. Also noted by Moyer (2004) is that the only missing major reef builder in the area (as compared with the Florida Keys and other Caribbean areas) is *Acropora palmata*.

Today, corals and coral reefs worldwide are in a state of decline (Jameson et al. 1995; Feary et al. 2007). Some of the degradation can be attributed to natural disturbances including disease, changing weather patterns and storms. However, according to Connell et al. (1997), reefs readily reassemble after routine natural disturbances. Therefore, anthropogenic disturbances including coastal development, pollution, ship groundings and overexploitation may be the leading cause of coral reef degradation. Estimates show that nearly 50% of the world's human population lives within 200km of the coast and this proportion is expected to rise (Stegeman and Solow, 2002). As a result, human impacts increasingly threaten productive and diverse coastal ecosystems such as seagrass meadows and coral reefs. One of the greatest threats to these ecosystems comes from "cultural" eutrophication, where nutrient enrichment in coastal waters due to human activities stimulates the growth of algae which overgrows and destroys coral reefs (Mutchler et al. 2007). Throughout the world, management plans involving the use of artificial reefs are being used to replenish losses from both natural and anthropogenic disturbances (Bohnsack and Sutherland 1985; Spieler et al. 2001).

2.2   *Artificial Reefs*

Historically, the primary objective of artificial reef plans has been fishery enhancement. Artificial reefs function ecologically by either aggregating existing scattered individuals, or they allow secondary biomass production through increased survival and growth of new individuals because of shelter, substrate and food resources

provided by the reef (Bohnsack and Sutherland 1985). Using artificial reefs for this purpose dates back to the mid-1800s in the United States (Stone 1972), and it has only been recently that they are being used for other functions. Today, artificial reefs are also used in nature conservation, erosion control, provision of additional habitat, aquaculture, tourism, and coral habitat mitigation, protection, and restoration of damaged reef areas (Bohnsack and Sutherland 1985, Harris 2007).

When artificial reef deployments began in the United States, most were haphazardly located and were constructed of waste materials, including old cars, appliances, aircrafts, boats, tires, culverts, storage tanks, and concrete debris (Figure 2) (Bohnsack and Sutherland 1985). Over time, monitoring programs revealed that many of these items deteriorated rapidly in the marine environment and did little to attract or recruit marine life.

Tires were once thought to be good material for artificial reefs. Rubber is inert in the marine environment, is long lasting, and attracts fish. Deploying tires in the marine environment reduces landfill burden by providing an alternate location for used tire disposal (Parker et al. 1974). However, recent studies show that tires do not make a good artificial reef material. Bundled tires are not stable on the bottom and can be moved and broken apart during storms causing damage to surrounding natural reefs or wash up on shore as had occurred in South Florida (Raymond, 1981). Also, Fitzharding and Bailey-Brock (1989) concluded that, even though they had more space for recruitment, tires attracted the fewest corals of any other material. Cars, planes, small ships, and metal in general do not make suitable artificial reefs as well. This is mainly because they have a short lifespan of only 1-5 years in the marine environment, and in some cases can release toxins (Fitzharding and Bailey-Brock 1989).
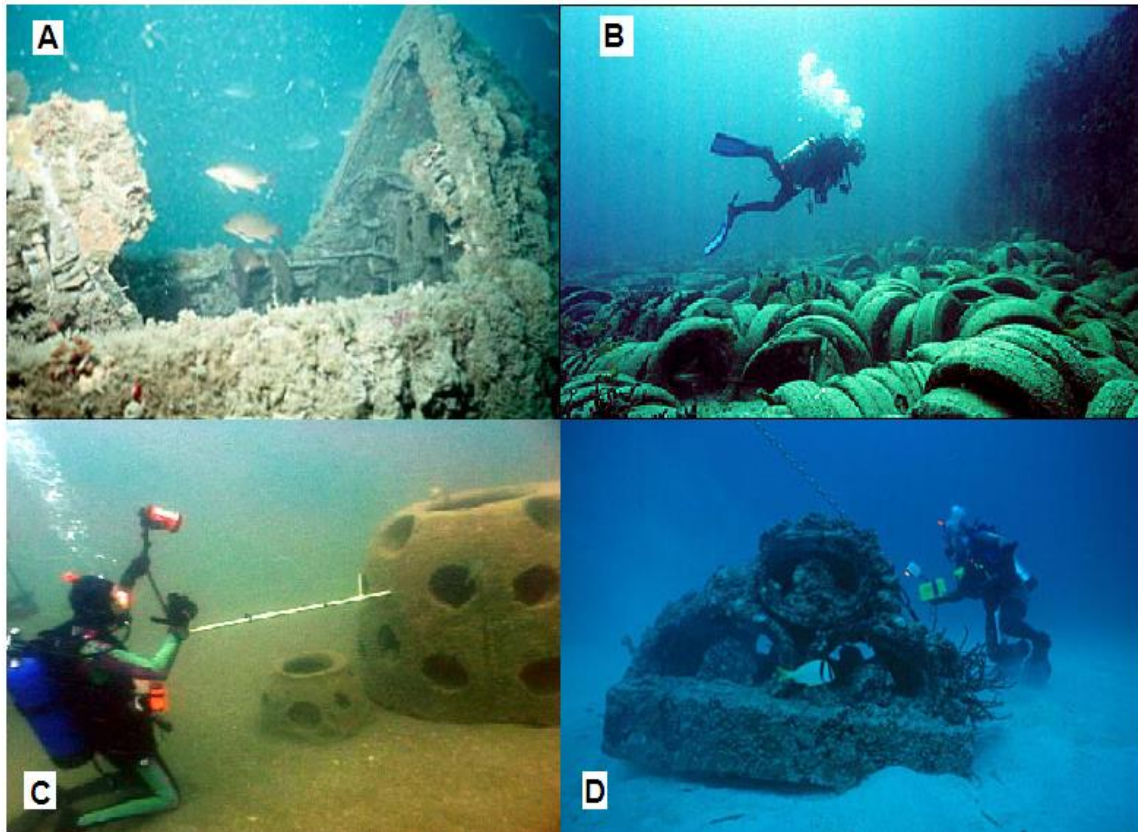
Figure 2: Examples of Broward County Artificial Reefs.
A. Steel Hulled Ship; B. Rubber Tires; C. Pre-cast, Concrete "Reef Balls; D. Concrete Culvert (Images A, C, and D, Intermedia Outdoors, 2008; Image B, Associated Press 2007)

Initially, these materials do attract corals, invertebrates, and fishes, but because of their rate of deterioration, reefs made of light gauge metals are relatively ineffective (Stone 1972). Heavier gauge metals such as those found on large ships have met some success in recruiting corals, yet most are easily overgrown by algae, sponges, and invertebrates (CRC Press 2000). Cement and concrete in either simple boulder forms or specifically designed, pre-cast forms has proven to be the most effective material used for artificial reefs (Fitzharding and Bailey-Brock 1989; Brock and Norris 1989; Edwards and Clark 1992). The rough surface texture of concrete structures provides a suitable area for corals and other invertebrates to colonize. However, concrete has its drawbacks. The cost of

transportation of the material is high, and occasional scouring during storms can occur (Parker et al. 1974). Concrete is still the best option for artificial reefs, and today most are constructed of this material allowing the additional benefit of design flexibility for the purpose of reef enhancement.

2.3   *Broward County Artificial Reefs*

In Broward County, Florida, many artificial reefs have been deployed. Since 1982, the Broward County Department of Planning and Environmental Protection (DPEP) have deployed over 112 artificial reefs offshore of Broward County. These reefs, which are designed to create a new stable substrate were made from a variety of material, including ships, barges, oil rigs, limestone rock, concrete culverts, and engineered concrete artificial reef modules (Figure 2) that were considered environmentally suitable and durable (Broward County Biological Research Division 2007). These materials were deployed at various depths ranging from 4m to 130m where they quickly became habitat for a multitude of marine life.

2.4   Study Area:

The Dania Beach Erojacks Reef is a linear artificial reef composed of thousands of concrete hexapods arranged in a linear fashion perpendicular to the shoreline, located off the coast of John U. Lloyd Beach State Park in Dania Beach, Florida, USA, in 4-7m of water (Figures 1,3,4). It extends perpendicular to the shoreline from its shallowest (3-4m), westernmost end, 100m from shore at 26° 03.786′ N: 80° 06.569′ W to its deepest (5-6m), easternmost end, 500m from shore, at 26° 03.758′ N 80° 06.344′ W. This means the Erojacks Artificial Reef extends from its nearshore origins at the transition from sand to hardbottom out to the Nearshore Ridge Complex at its

offshore terminus. It was deployed on December 31, 1967, making this one of the oldest artificial reefs in Broward County. Each Erojack hexapod module is approximately 1.5m high and has an approximate surface area of $4.4m^2$ on which organism can settle (Figure 3). When piling these Erojacks into the reef form, the width of the reef ranges from 1.5m on the ends to about 7.0m in the middle of the reef where more hexapod modules were deployed (Figure 4). Height of the reef also varied from 1.5m at the ends to nearly 4m in the middle. Given these values the total surface area of all modules composing the Erojacks reef is approximately $4500m^2$.

This study's focus is to determine if there is a difference in species richness, colony number, and colony surface area between corals growing on the Dania Beach Erojack artificial reef and those found on the adjacent ridge complex natural reef. This has important management considerations, especially as artificial reef deployment is used as mitigation for damage to natural reefs. If artificial reefs can never support coral diversity and biomass that is similar to the natural reef, then the differences are important to know.

Since the Erojacks Reef is one of the oldest reefs in the county, it serves as a useful indicator of what could be anticipated over decadal time scales from initial deployment. It is expected that the artificial reef will be more productive (greater number of colonies and greater colony surface area) and diverse (greater number of species) than the surrounding reef due to its greater three-dimensional complexity, lack of competition at the time of deployment, and the availability of substrate for settlement.

Figure 3: Side View of a Hexapod Module and the Erojack Reef in the Background.
Height of individual module is approximately 1.5m.
Photo Courtesy of Dr. Joshua Feingold, NSUOC.

Figure 4: Photograph of the linear path of the Erojacks Reef
Photo Courtesy of Dr. Joshua Feingold, NSUOC.

2.5   *Physical Variables:*

Many physical variables including currents, temperature, salinity, turbidity, light, and physical disturbance may have great impact on the habitat and will affect biological activity on both the natural and artificial substrate.

2.5.1 Currents

Currents can affect reefs in three different ways. Currents can enrich upwelling in coastal areas by adding nutrients to the water column. They can increase turbidity in the nearshore areas by suspending sediments, thus limiting light availability. Finally currents can drastically change nearshore temperatures, thus effecting, species diversity and abundance. According to Chiappone and Sulivan (1994), currents in the Florida Keys at sites with high sedimentation and current velocities <1m/s consist of sparse aggregations of the scleractinian *Siderastrea radians*, and gorgonians *Pterogorgia anceps*, and *Briareum asbestinum*, while sites with low sedimentation and current velocities > 1m/s had a higher species diversity and exhibited a higher cover of scleractinian corals and gorgonians.

At the study site, currents are mainly dominated by the Florida Current, a branch of the Gulf Stream flowing north at approximately 1.3m/s between the Bahamas Banks and Southeast Florida (Banks et al, 2007). On the average, the inner edge of the Florida Current is within 16km of Miami and Ft. Lauderdale, Florida, and at times there is a 2 m/s flow within a several kilometers of the coast (Figure 5). This current is very dynamic and meanders a good deal, generating eddies off of the main body bringing current waters onto the shelf and to the reef environment (Sponaugle et al. 2005). Florida Current perturbations vary from slow-moving mesoscale gyres to faster-moving, sub-mesoscale

spin-off eddies. The Florida Current spin-off eddies have diameters between 5 and 50

km and advection velocities between 0.20 and 0.80 m/s (Lee 1975). These eddies can

affect reef biota through fluctuations in turbidity, temperature, and salinity in the

nearshore environment.

In this study, currents were not examined and surveys were usually not conducted

on days in which currents were too strong to swim against. On days in which local

currents could be overcome, the currents most often flowed to the north, perpendicular to

the Erojacks reef, although southward flowing currents were occasionally encountered.
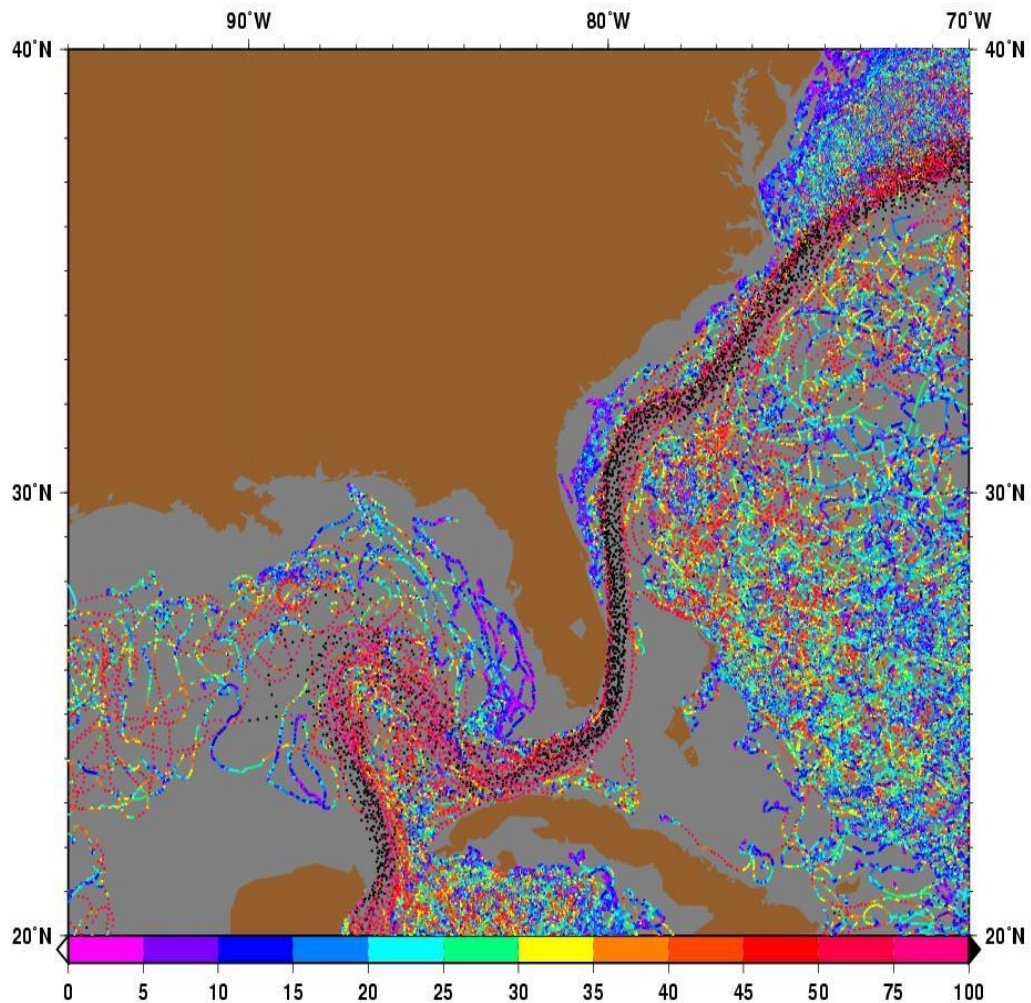
Figure 5: Image of the Gulf Stream and its Proximity to the Florida Coast. Gyory et al. 2001

2.5.2 Temperature:

Coral reefs are especially vulnerable to temperature elevation because coral colonies bleach rapidly and dramatically in response to increased sea surface temperatures. Corals live in environments that are close to their upper thermal threshold (the temperature limit for survival), and even temperature increases of 1 or 2º C above their thermal limit over a sustained period of time (i.e. a month) can cause mass bleaching (Hoegh-Guldberg, 1999).

The nearshore ocean temperatures off Broward County can range from 14˚ C – 38˚ C, with mean values above 18˚ C, the threshold temperature generally accepted for reef development (Jaap 1984). Thermal stress on corals can result in slow or no growth, and loss of the symbiotic zooxanthellae or bleaching. Temperatures were recorded *in situ* at three locations (nearshore, mid-reef, and offshore) along the Erojacks artificial reef and one location in the natural reef community using Onset Computer Stowaway submersible dataloggers.

2.5.3 Salinity and Turbidity:

Both salinity and turbidity can affect coral growth and bleaching. According to Dole and Chambers (1918), heavy precipitation in Miami was almost always followed by a reduction in salinity on the reef in the neighboring areas and has been found to fluctuate between 34.2 and 38.6ppt, which is well within the 27-40ppt (36ppt is ideal) tolerance range for hermatypic corals (Coral Cay, 2007). Buchheim (1998) reported that dilution of reef waters from storm-generated precipitation and runoff in nearshore areas has caused coral bleaching but these bleaching events are rare and confined to relatively small areas. Salinity stress can also affect coral metabolism. Muthiga and Szmant (1987)

suggest that salinity reductions of less than 10ppt from optimal values result in no differences in respiration but there was a significant reduction in photosynthesis, while changes greater than 10ppt show reduction in both respiration and photosynthesis.

Turbidity in the area is also very important as zooxanthellae (coral endosymbiont) require light for photosynthesis. In the western Atlantic, Caribbean and Pacific, dredging associated with the construction of hotels, condominiums, runways, roads, military installations, with beach replenishment has destroyed reefs, seagrass beds, and mangroves. Dredging near coral reefs and accelerated runoff of eroded soils increase turbidity, thereby cutting down light available for photosynthesis, as well as increasing sediment load on corals (Rogers 1990).

Williams et al. (1960) reported Secchi Disc distances between 4.5 to 35m in the Florida Keys. This is a considerable variability and following frequent storms in South Florida the water may become nearly opaque and may take days to clear depending on conditions. Turbidity in the area could also be affected by sediment outflows from Port Everglades located approximately 3km North of the study site (Figure 6). Reduced light will certainly diminish coral growth, and if extended for long periods of time, may kill corals. During the study, turbidity was not measured but visibility was generally low, ranging from 3 to 7m during the survey period.

2.5.4 Severe Weather:

Hurricane disturbance to coral reefs has been well documented throughout the Caribbean (Woodly et al, 1981; Blair et al, 1994; Lirman et al, 2001). The physical characteristics of each storm, as well as timing, sequence of disturbance, and disturbance history of an area (Figure 7) has been shown to play a major role in determining damage

Port Everglades

Erojacks
Reef
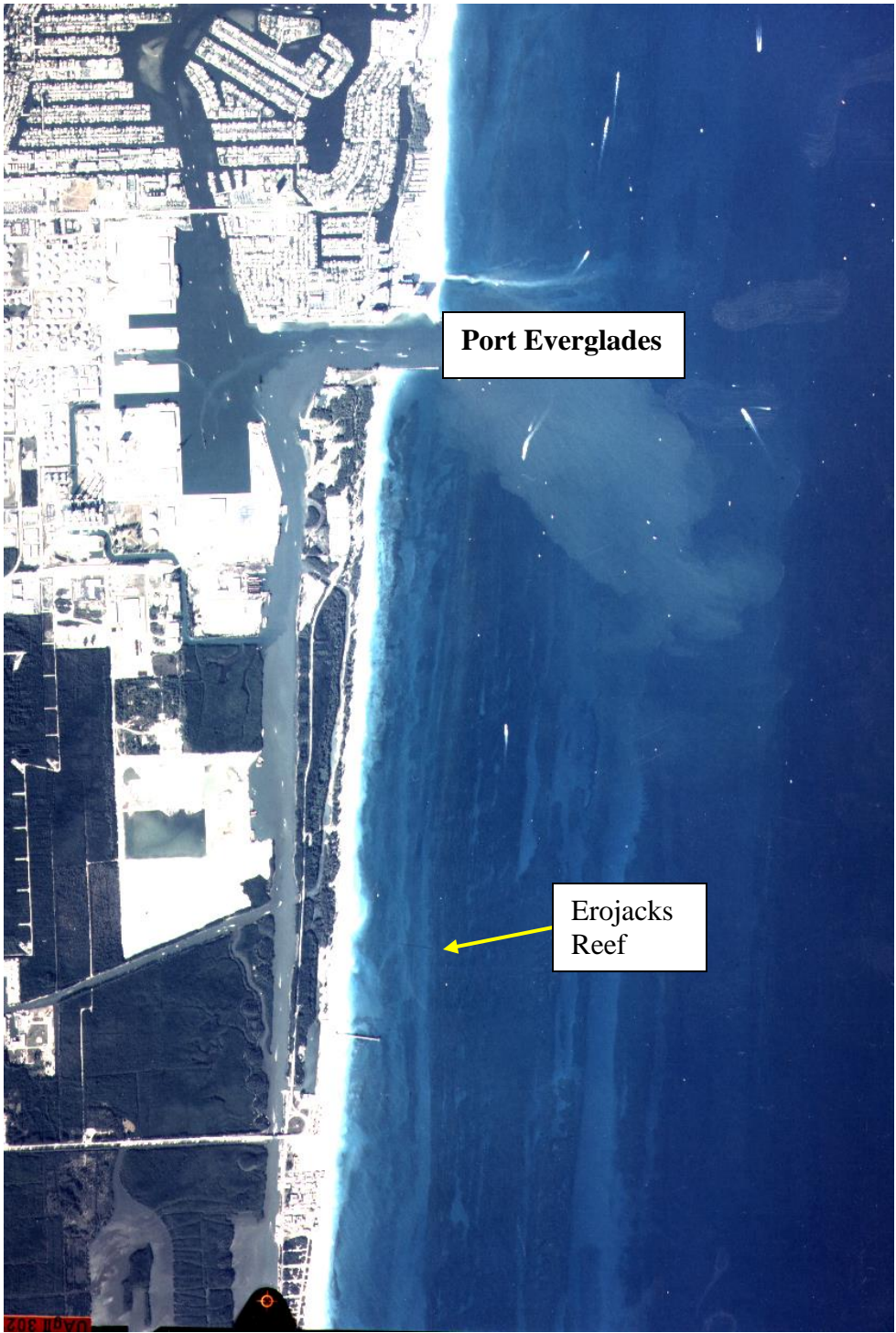
Figure 6: Arial Photograph of Port Everglades and the sediment plume produced by the Port. (Image source unknown)

and recovery patterns of coral reefs (Lirman et al, 2001). Hurricanes can cause physical

destruction through increased turbidity and sedimentation, through lowering of salinity

and increased nutrient concentrations after heavy terrestrial runoff , but direct physical

effects from heavy swells and surge usually are the most damaging (Stoddart, 1970).

These disturbances cause physical destruction of corals and other reef organisms and can

Average Number of Thunderstorm Days Per Year
(See key for explanation)

KEY
Average number of days
with thunderstorms per
year per 10,000 square miles

☐ Fewer than 10   ▧ 30–50   ▧ 70–90
▧ 10–30   ▧ 50–70   ▧ More than 90
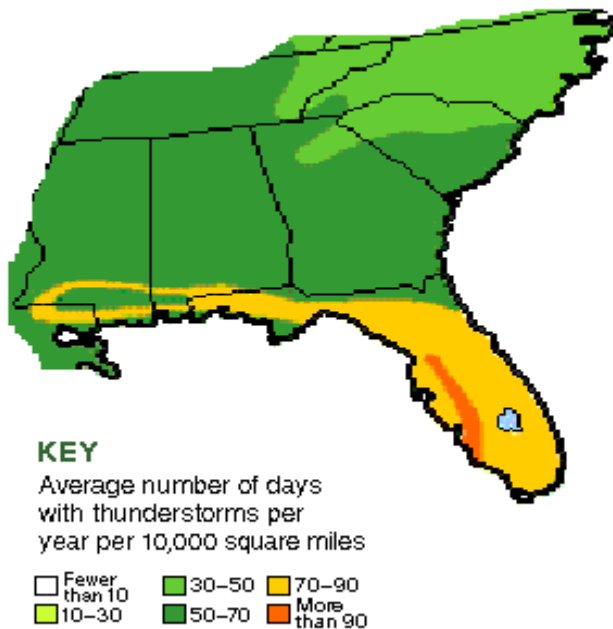
Figure 7: The Severe Weather Pattern of the South East United States (Oklahoma Climatology Survey 1999)

affect the coral community structure in a variety of ways. First, the diversity of a coral

reef system can change due to reduction in species richness or even elimination of a

species in the area (Rogers et al, 1982). Second, competitive interactions between reef

organisms can be altered through removal of the superior competitor or through alteration

of the local environment (Lang 1973). Third, increased destruction of branching species

compared to massive and encrusting forms will reduce the three-dimensional structure of

17

the reef (Rogers et al, 1982). Fourth, fragmentation and overturning of corals, coupled with scouring effects provide new surfaces for colonization by algae, corals, and other invertebrates (Shinn, 1976).

Between August 30 and September 6, 1979, Hurricanes David and Frederic impacted St. Croix, USVI. Hurricane David was the more intense storm with wind gusts up to 86km/hr and wave heights estimated to be 5.8m, while Hurricane Frederic had wind speeds between 64-80km/h and wave heights between 1.5-3.0m (Rogers et al, 1982) This area is dominated by large stands of *Acropora palmata*, as well as *Acropora cervicornis*, and the hydrozoan coral *Millepora complanata*. These branching communities were severely damaged and fragmented due to heavy swells and surge. Surprisingly, after the hurricane the branches which broke off were still alive, the bases of the original colonies were regrowing at their fracture sites, and it was found that nearly 50% of the damaged *A. palmata* had healed within one year of the hurricane (Rogers et al, 1982).   On August 6, 1980, Hurricane Allen passed to the north coast of Jamaica, and severely damaged neighboring reefs. Wind gusts reached 285km/h in the center of the hurricane, and were reported to be 110km/h in Discovery Bay. Wave heights were observed to be over 12m (Woodley et al, 1981). Again, as seen following David and Frederic, large stands of *A. palmata* were leveled, but this time the forereef was also damaged. Damage was not only confined to the shallow reef area but was found to extend to a depth of 50m. Waves and surge accounted for the majority of the damage but scouring sands and dislodged solid objects accounted for more damage than in David or Frederic. According to Woodley et al. (1981), the amount and type of damage inflicted upon the sessile benthic taxa was greatly influenced by their shape, size, and mechanical properties. In some areas, the planar living area of *Acropora* spp was reduced by 99%, while the colony number of the

foliaceous and encrusting coral *Agaricia agaricites* was reduced by only 23%, and the

colony number of the massive coral *Montastrea annularis* was reduced by only 9%. But

due to the variable effects of the disturbance, some of the branching fragments which

broke off remained alive, and the massive corals which sustained damage were healing.

On August 24, 1992, Hurricane Andrew impacted the southeast coast of Florida as a

category 4 hurricane with sustained winds of 234 km/hand gusts up to 282km/h. Impacts

to the natural reefs varied widely among sponge, algal, hard coral and soft coral

communities. However, the inshore reef tract showed the smallest amount of damage

overall, and hard corals were the least affected with a loss of less than 23% (Blair et al,

1994). Impacts to the studied artificial reefs of Blair et al. (1994) also varied widely, and

ranged from no impact, to movement, to partial or total structural modification, but no

pattern of damage relative to location, orientation, or depth of reef material was

discernable. Blair's study looked at a myriad of artificial reefs material including, ships,

tugs, barges, steel tanks, and oil rig platforms but no concrete structures. The alterations

to these structures included movement up to several meters, overturning, bending and

cracking to complete loss of structural integrity. In comparison, the erojack reef is

composed of pre-cast concrete and will be much less susceptible to movement and

degradation caused by violent weather.

The Dania Beach Erojack Reef was deployed on December 30, 1967 as a means

to combat beach erosion. Since that time, nine major hurricanes have passed over the

area, including three during the period of this study. Hurricane Katrina (Figure 8)made

landfall in Southeast Florida along the Miami-Dade and Broward county line between

Hallandale Beach and North Miami Beach (approximately 10km south of the study site),

on August 25, 2005 as a category-1 hurricane (on the five point Saffir-Simpson scale),

19

with wind speeds between 119-153km/hr, and a storm surge generally 1.22-1.52m above

normal (NWSIST, 2005). Fort Lauderdale International Airport, approximately 2.4km

from the study site reported sustained winds of 94km/h with gusts up to 128km/h (Knabb
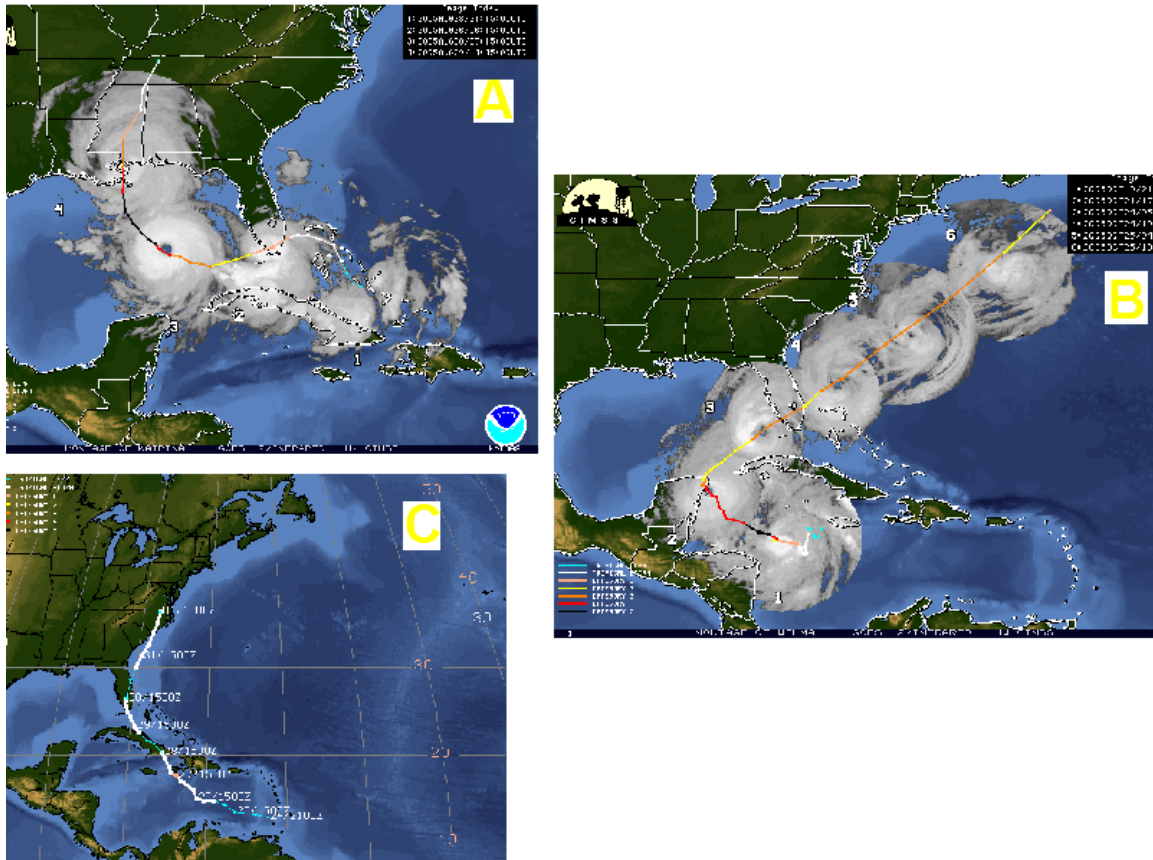
Figure 8: Hurricanes Katrina (A), Wilma (B), Ernesto (C). (National Oceanographic and Atmospheric Association 2006, 2007).

2006). About two months later, Hurricane Wilma (Figure 8) made landfall in

southwestern Florida on October 23, 2005 before cutting a diagonal path across the state

and entering the Atlantic Ocean south and central Palm Beach County. At landfall

Wilma was a category 3 hurricane with sustained winds between 178-209 km/hr, but as

the hurricane crossed Florida it weakened to a category 2 with wind speeds between 154-

177km/hr and storm surge between 1.83-2.44m above normal (NWSIST, 2005). Fort

Lauderdale International Airport approximately 2.4km inland from the study site reported

sustained winds of 114km/h with gusts up to 162km/h (Pasch et al, 2006).   The next

year, Ernesto (Figure 8) made landfall in Miami-Dade on August 29, 2006, as a weak

tropical storm with wind speeds from 62-82km/hr. Sustained winds of 47km/h and gusts

up to 61km/h were reported at Fort Lauderdale International Airport (Knabb 2006).

Several cities in the South Florida Metropolitan Area, which includes Palm Beach, Fort

Lauderdale, and Miami suffered damage from all three of these storms as a result of the

intense winds.

2.6   Hypotheses

Artificial reefs are used to mitigate damage to natural reefs by providing suitable

habitat for marine organisms. However, little information exists about whether this result

is achieved. Since the Erojacks reef is the county's oldest know purposefully deployed

artificial reef, it is more likely to have reached a state of biological equilibrium than other

more recently deployed structures. This study examines species richness, and density

values for live tissue surface area and numbers of scleractinian corals between the Dania

Beach Erojack artificial reef and the natural reef that lies adjacent to the eastern-most end

of the Erojacks. It is expected that the artificial reef will be higher in all respects

compared to the surrounding natural reef due to its 3-dimensional complexity. Results

from this study will provide managers with information on the effectiveness of artificial

reefs as a tool to mitigate damage to natural reefs and enhance nearshore resources. Also,

the impact of two hurricanes upon the artificial reef will be assessed by comparing pre-

and post-hurricane data on its shallowest portion. It is expected that the hurricanes will

have damaged some of the corals living on the reef, thus reducing colony size and/or abundance.

3.0   Materials and Methods

Sampling of both the artificial Erojack reef and the natural reef offshore Dania Beach, Florida, was performed using SCUBA techniques over the course of two years (2005-2007). During the study, temperature was recorded *in situ* using Onset submersible dataloggers, but salinity, turbidity, and currents were not examined.

3.1   Erojacks sampling:

The Dania Beach Erojack Reef is composed of thousands of concrete hexapods with an approximate surface area of $4500m^2$. Because there are physical differences from shallow to deeper water, surveys were split into three distinct areas, nearshore (3-5m in depth), mid-depth (5-6m in depth) and offshore (6-7m in depth), allowing me to see if there were any differences among segments. The nearshore segment of the reef was from 0-125m as measured from the western-most (shoreward) edge towards the east (offshore). The mid-depth segment was from 125-250m, and the offshore segment was from 250-380m. In each segment, randomly located, 2m wide belt transects perpendicular to the main axis of the artificial reef were stretched across the pile of hexapods from north to south (belts varied in area based on the width of the Erojacks Reef). Thirty belt transects were performed in the nearshore and middepth segments, and 29 were performed in the offshore segment for a total of 89 belts (Figure 9). The 2m width was used because point-intersept transects or narrower belts did not intercept sufficient numbers of corals. And, when attempting to use larger widths (i.e. 3m and 5m),

repetitive counts of some colonies occurred and often corals were being missed due to the complexity of the reef. Within each belt, each scleractinian coral was measured for surface area (live tissue's measures, length x width) and species, also an approximate surface area of the reef itself within the belt was calculated by projecting its dimensions as a half cylinder. This underestimated the actual surface area of the reef modules. A more detailed area calculation was too cumbersome to implement for data collection because of the intricate and elaborate 3-D structure of the Erojacks Reef.
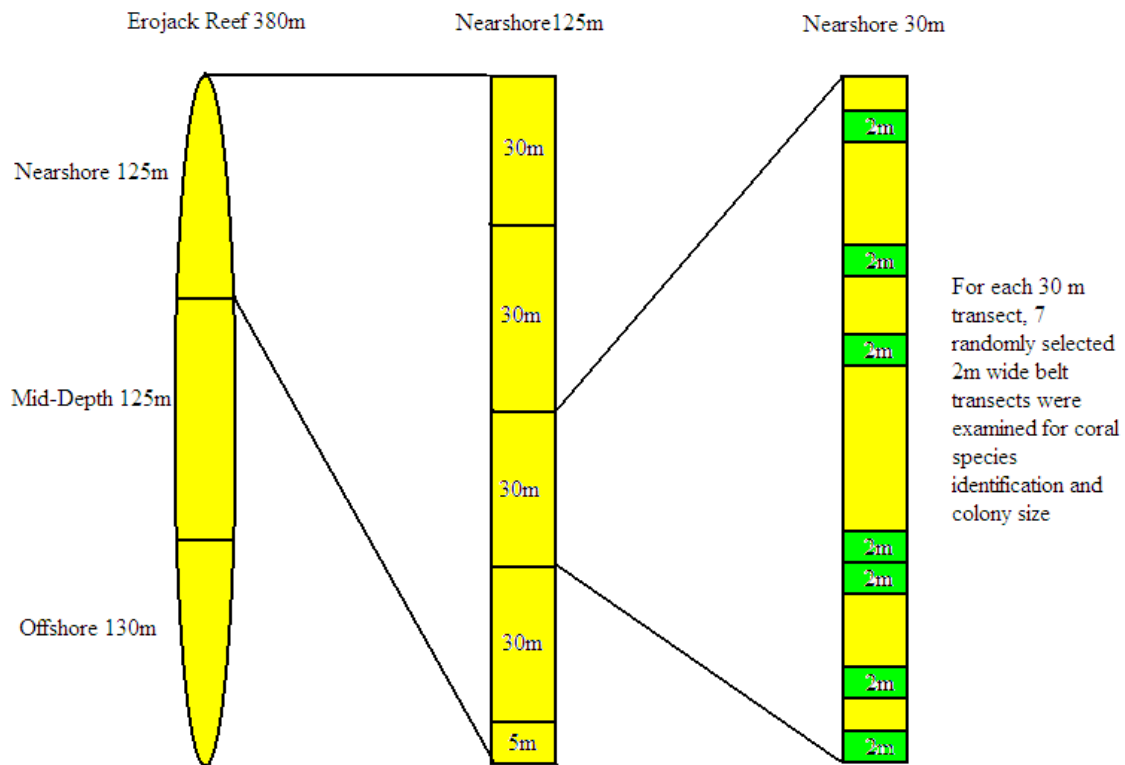
Figure 9: Erojacks Sampling Method. Sampling was continuous from nearshore to offshore, thus 4.17, 30m transects were used for the nearshore and middepth sections, and 4.3 were used for the offshore section resulting in 30 transects in the nearshore, 30 in the mid-depth, and 29 in the offshore segments).

3.2   *Natural Reef Sampling:*

In order to sample the natural reef, and cover the same area as that on the Erojacks, four 100m transects were used. Two ran from an area slightly seaward and north of the Erojack reef to the north, and two ran from an area slightly seaward and south of the Erojack reef to the south along the main axis of the natural reef. Within each transect, randomly located 2m wide belt transects were used to sample coral cover. The number (89) and total surface area of these belt transect were the same as those on the artificial reef. Again, within each belt, each scleractinian coral encountered was recorded for species and surface area by measuring the live tissue's maximum length and width.

4.0   Results:

4.1   *Hurricane Impacts:*

Before the arrival of the first hurricane that impacted the study site (Katrina, Aug. 2005), 90m of the nearshore portion of artificial reef had been surveyed. Approximately 3 weeks following the two hurricanes in 2005 (Katrina & Wilma), this segment was resurveyed to determine if there were effects from the storms. Prior to the hurricanes, 771 coral colonies were observed with a mean coral surface area of 1792 cm^2, while after the hurricanes there were 818 individuals with a mean coral surface area of 1805 cm^2 (Figures 10). Density of corals increased from 5.69 corals/m^2 before the hurricanes to 6.09 corals/m^2 after the hurricanes (Figure 11). Also, total surface of live coral colonies and number were also compared (Figure 12,13). Here we see 771 colonies accounting for 3.76 m^2 of living tissue Pre-Hurricane and 818 colonies accounting for 3.79m^2 of live tissue Post-Hurricane. Density values were then calculated for the amount of live
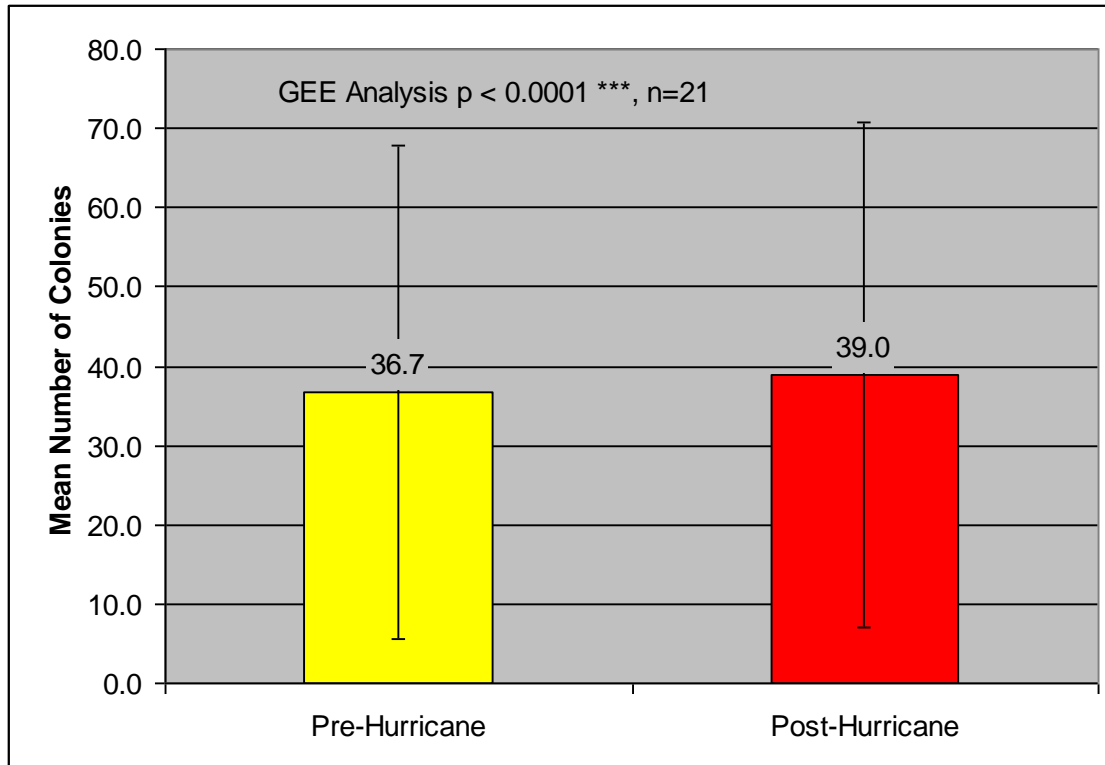
Figure 10: Mean Number of Corals Present per Belt Pre-and Post-Hurricanes Katrina and Wilma (2005)
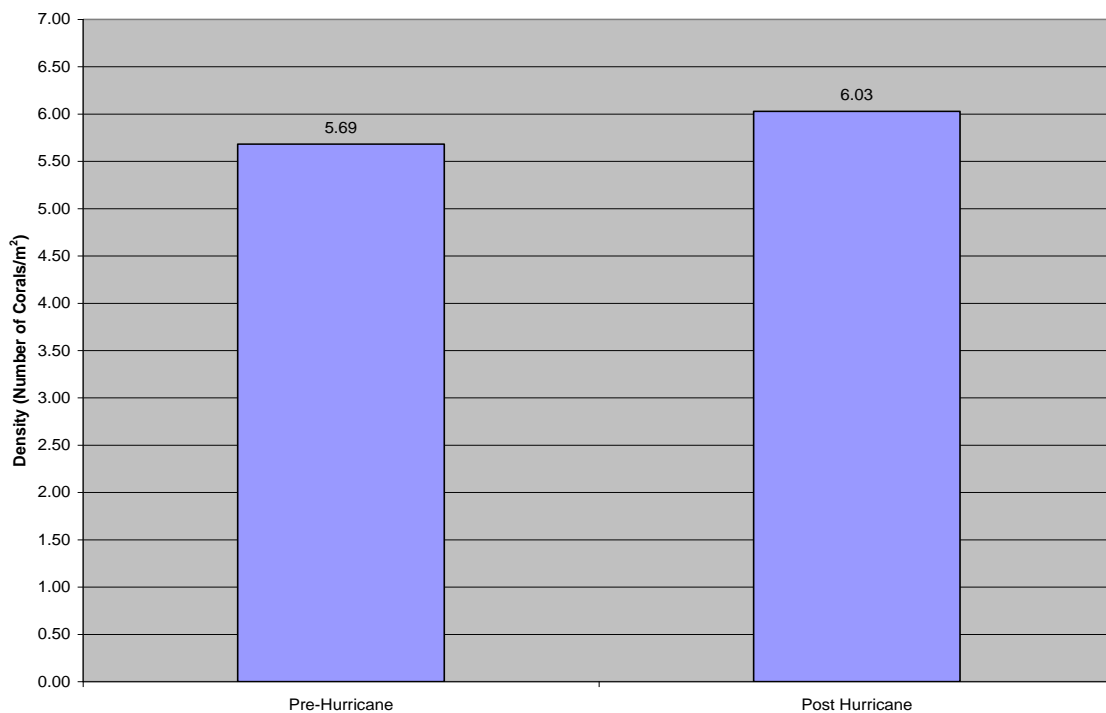
Figure 11: Density of Corals (# of corals/m^2) pre- and post-huricanes.
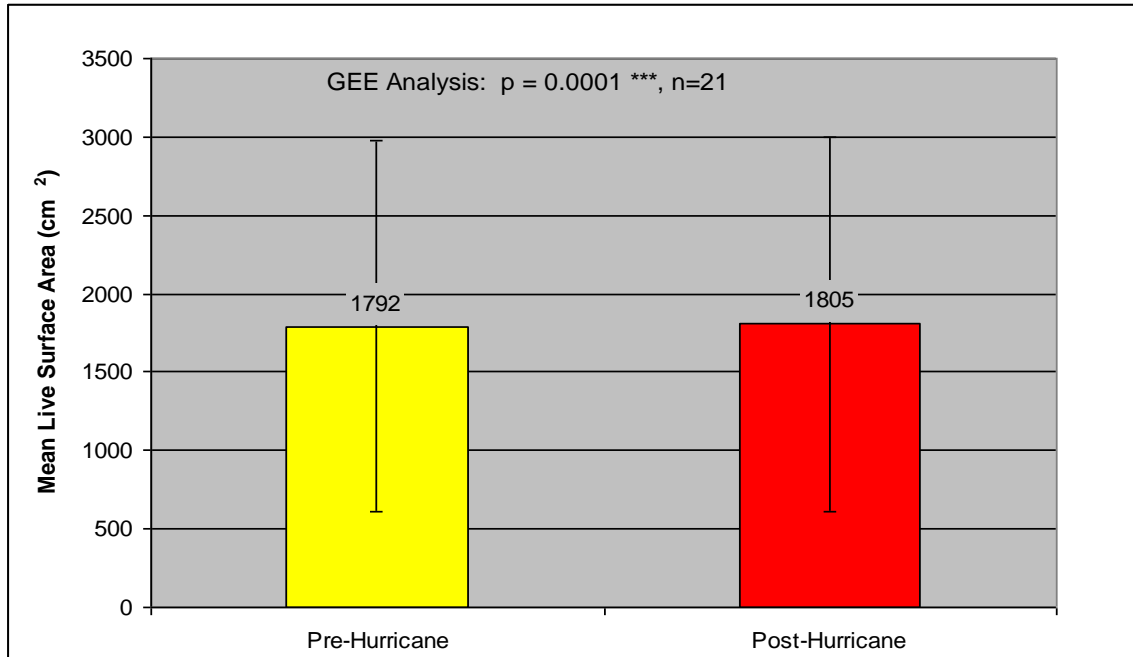
Figure 12: Mean Live Coral Surface Area (cm^2) of Corals per Belt Pre-and Post-Hurricanes Katrina and Wilma (2005)
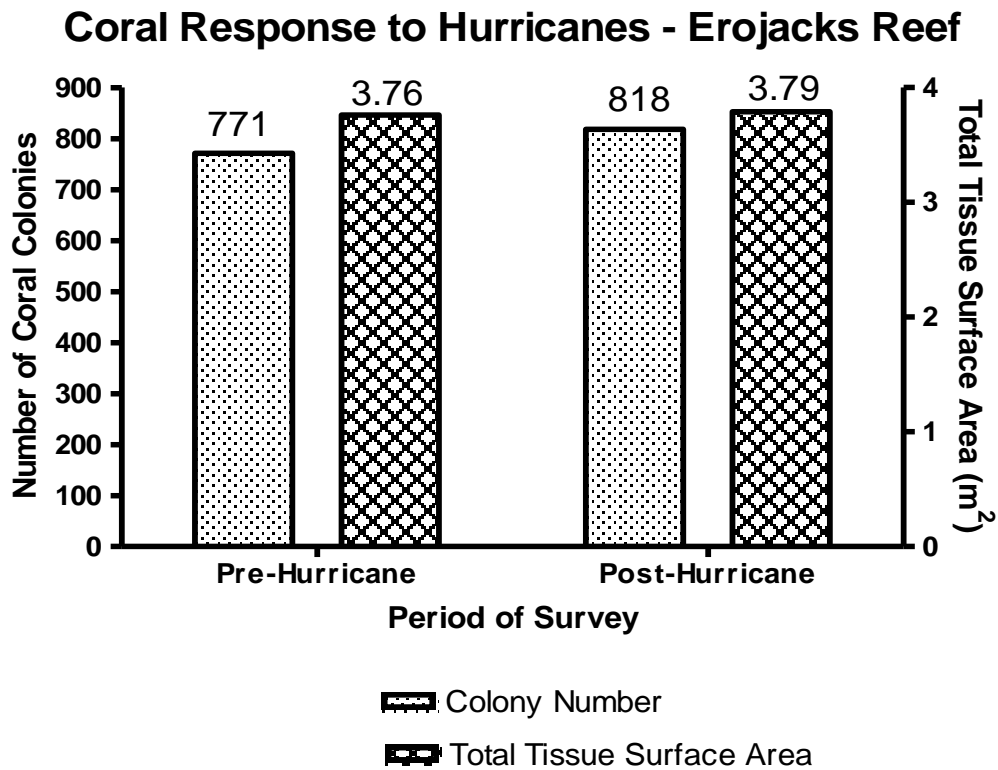
Figure 13. Comparison of the Total Number of Coral Colonies and Total Live Coral Tissue Surface Area(m^2) Pre- and Post Hurricanes For the Entire 90m Section.

26

Density (Live Tissue/m2)
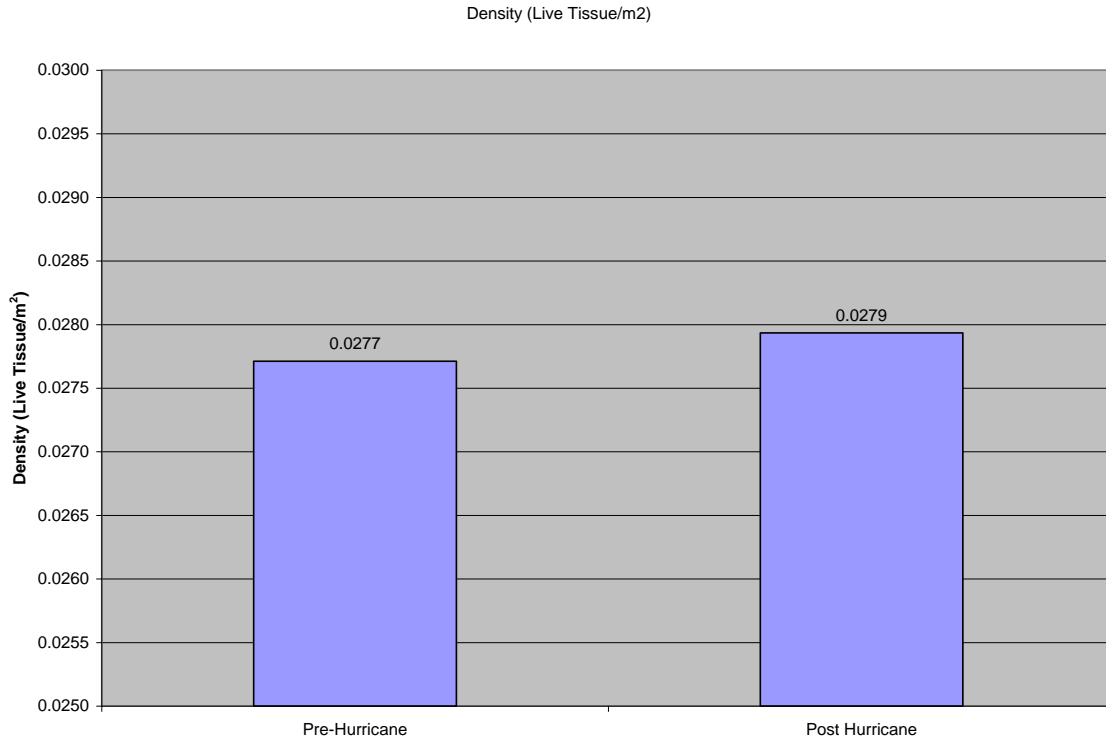
Figure 14: Live coral tissue surface area/m^2

tissue/m^2. Here we find 0.0277 of live tissue/m^2 before the hurricanes and 0.0279 of live

tissue/m^2 after the hurricanes (Figure 14).

The pre- and post-hurricane coral cover data was analyzed using a GEE Analysis

and we find a significant increase in both coral abundance (p < 0.0001, n=21) and live

tissue cover (p = 0.0001, n = 21).   Since the GEE Analysis is a relatively new technique,

the following will help explain its application (Suciu pers. comm.).

Coral abundance represents count data, they have a Poisson distribution, with two

repeated measurements: pre- and post- hurricanes on same location. Consequently, we

used a Poisson regression for repeated measurements. The data of pre- and post-

measurements are correlated, which implies the use of the generalized estimating

equation methodology (GEE), which is the only methodology that can be used for repeated correlated count data (Liang and Zeger, 1986; Stokes et al, 2000).

The surface area represents interval measurements, thus continuous scale repeated measurements that are also correlated: pre- and post- hurricanes on the same corals. For this type of data we used a multiple linear regression for repeated measurement. Since the data are correlated we used the generalized estimating equation methodology (GEE). The normality assumptions for the GEE methodology are relaxed, the parameter estimates being very robust based on the convergence of the GEE algorithm and its exchangeable covariance matrix.

With regard to pre and post hurricane abundances the model has 2 dependent variables (Pre and Post Hurricane) and 2 independent variables (presence of the hurricane and the location of the measurement: the belts). Using the above GEE regression we found a significant difference between coral abundance, pre- and post- hurricane season $(p < 0.0001)$ as well as a significant difference between the belts, pre- and post- hurricane season, concerning the coral abundance count $(p = 0.003)$.

Next we used the GEE regression for the surface area measurements. Here we find a significant difference in coral surface area $(p = 0.0001)$ pre- versus post- hurricane and a significant difference in surface area $(p = 0.0035)$ among belts as well.

4.2   Temperature Variation

Temperature is an important factor in determining the local distribution of scleractinian corals (Japp et al, 2008). In order to document possible differences in environmental conditions between different segments of the artificial reef and the natural reef, *in situ* submersible data loggers were deployed from July 2005 through February

2007. Data were collected on an hourly basis. The results show how the temperature fluctuated in the four sections (nearshore, mid-depth, offshore, and natural reef). In general, temperatures in all areas generally ranged between 15° C to 35° C, with lowest values in February and highest values in August. Temperatures varied up to 2° C per day (Figures 15, 16, 17, and 18). In the nearshore and mid-shore segments, omissions in the data sets were caused by loss of the data logger and subsequent redeployment at a later time. Natural reef temperature data collection did not begin until December 2005 because of logger malfunction. Several quick drops in temperature can be attributed to the passing of the three hurricanes over the course of the study. Katrina on August 25, 2005, Wilma on October 23, 2005, and Ernesto on August 29, 2006. Hurricane Katrina (Figure 16) produced a drop of 1.6° in 48 hours from 30.9°C at 00:00 (midnight) on August 25 to 28.5°C at 00:00 on August 27. Wilma (Figure 17) decreased the ocean temperature 3.9° in 48 hours from 28.3°C at 00:00 on October 23 to 24.4°C by 00:00 on October 26. Finally, Ernesto (Figure 18) produced a temperature decline 1.5° in 48 hours from 30.5°C at 00:00 on August 29 to 29.0°C by 00:00 August 31. The large spikes, anomalies, and outliers were not correlated with any significant weather events or change in ocean condition and may have been caused by malfunction or loss of the equipment. The natural reef and nearshore artificial reef segment records show the least amount of data variability and have the most continuous records of *in situ* water temperature in the shallow waters (1.5-7m depth) off of John U. Lloyd State Park in Dania Beach, Florida.

Seawater Temperatures July 2005 - February 2007
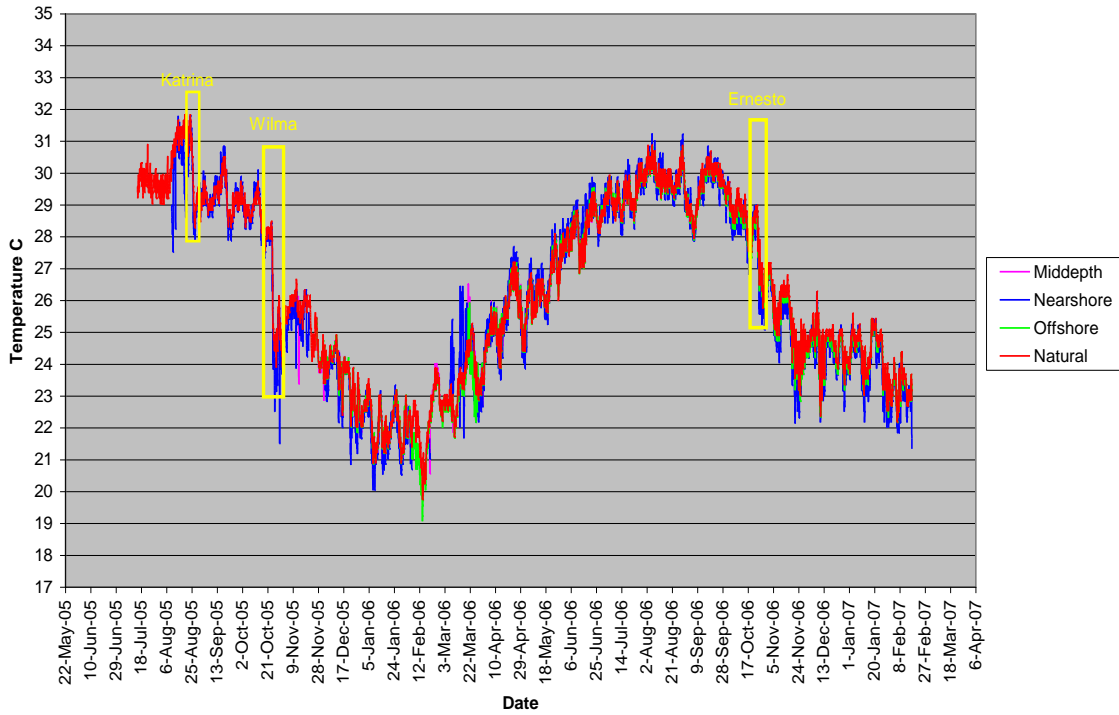
Figure 15: Seawater Temperatures July 2005 – February 2007

Hurricane Katrina Temperatures 2005
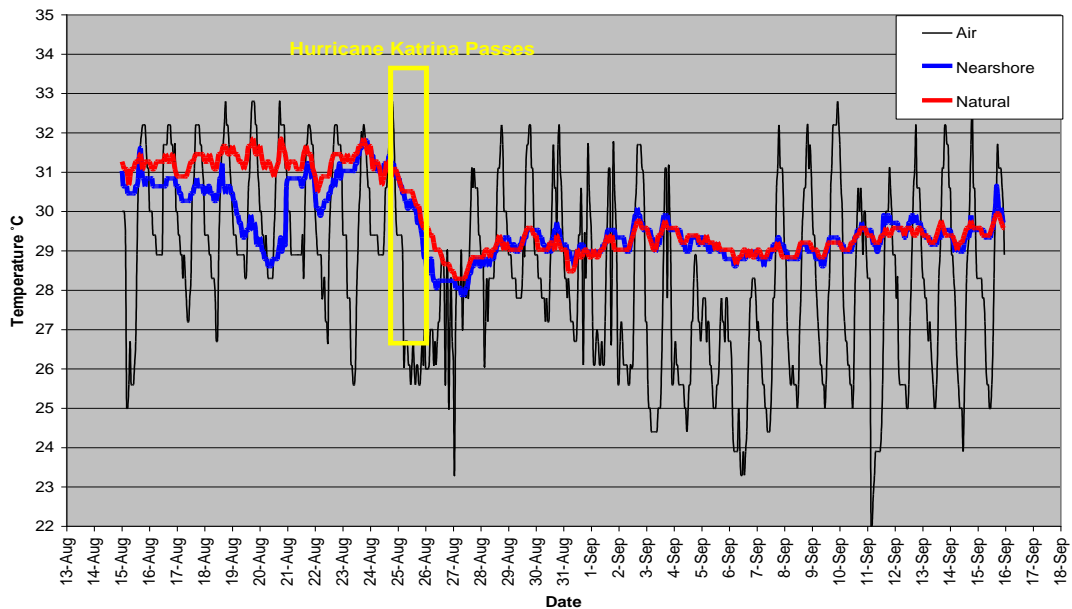
Figure 16: Air and Sea Temperatures: Hurricane Katrina, August 25, 2005
Air temperatures courtesy of the Fort Lauderdale International Airport
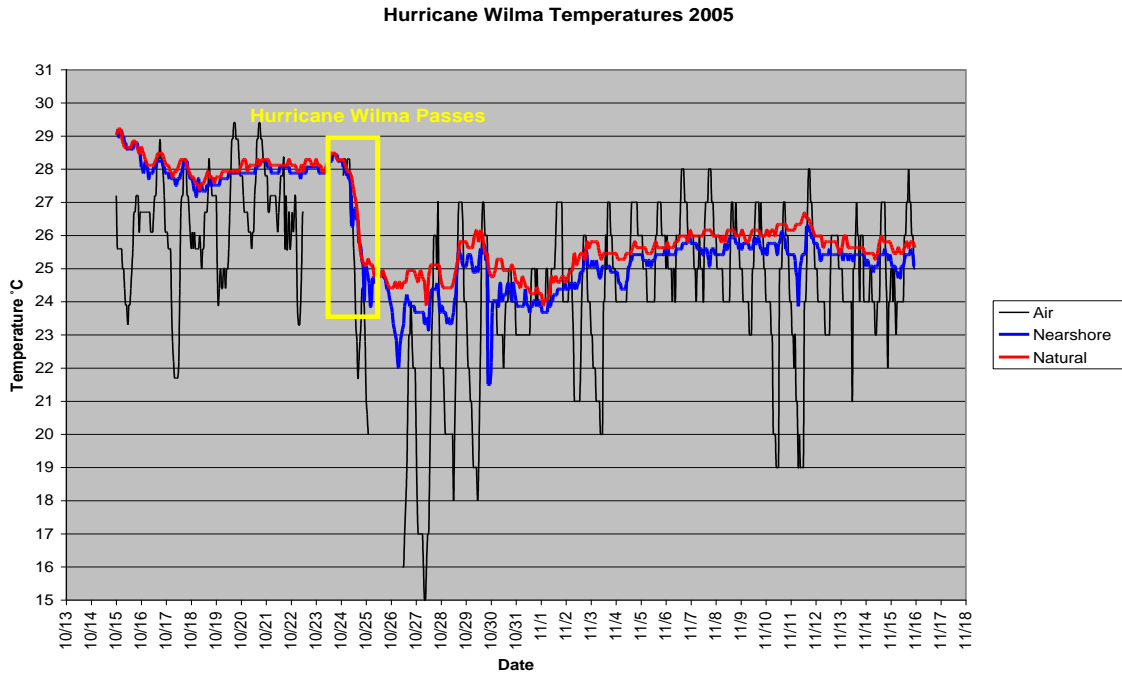
Figure 17: Air and Sea Temperatures: Hurricane Wilma: October 23, 2005
Air temperatures courtesy of the Fort Lauderdale International Airport
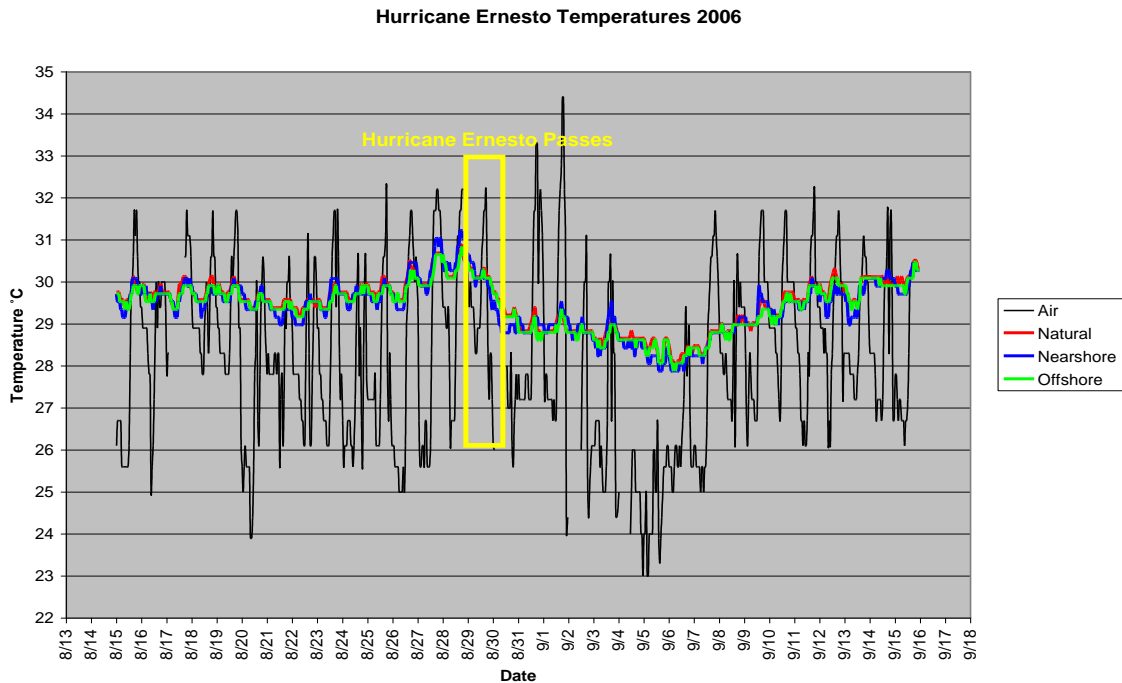
Figure 18: Air and Sea Temperatures: Hurricane Ernesto, August 29, 2006
Air temperatures courtesy of the Fort Lauderdale International Airport

4.3   Live Tissue Surface Area Per Segment

At the conclusion of the study, the total live tissue surface area of corals found in each particular segment was examined. The natural reef had the highest live tissue density with $0.065/m^2$, followed by the offshore artificial reef segment with $0.059/m^2$, then the mid-depth artificial with $0.040/m^2$, and finally the nearshore artificial with $0.034m^2$ (Table 2, Figure 19)

These values were then compared with the total available surface on both reef types to determine a percent cover for each segment. Again, the natural reef had the highest percent cover with 6.5%. The values then diminished as one moved toward shore along the artificial reef, from 5.9% for the offshore segment, 3.9% for the mid-depth segment, and 3.4% for the nearshore segment (Table 2).

Next, in order to compare coral cover for the four segments the nonparametric Kruskal-Wallis single factor analysis of variance was employed. This test is appropriate when comparing more than two independent samples of equal or unequal size when all the requirements for parametric testing are not met (Ambrose et al. 2002). This test will allow us to assess if there is any difference in coral surface area among the segments and natural reef. The Kruskal-Wallis test H value was 29.28 which is larger than the χ^2 value of 7.815 where $\alpha = 0.05$ and $v = 3$. Therefore the null hypothesis, stating that the mean coral surface areas among each sampled area do not differ significantly from one another, was rejected.

Density (Live Tissue/m2)
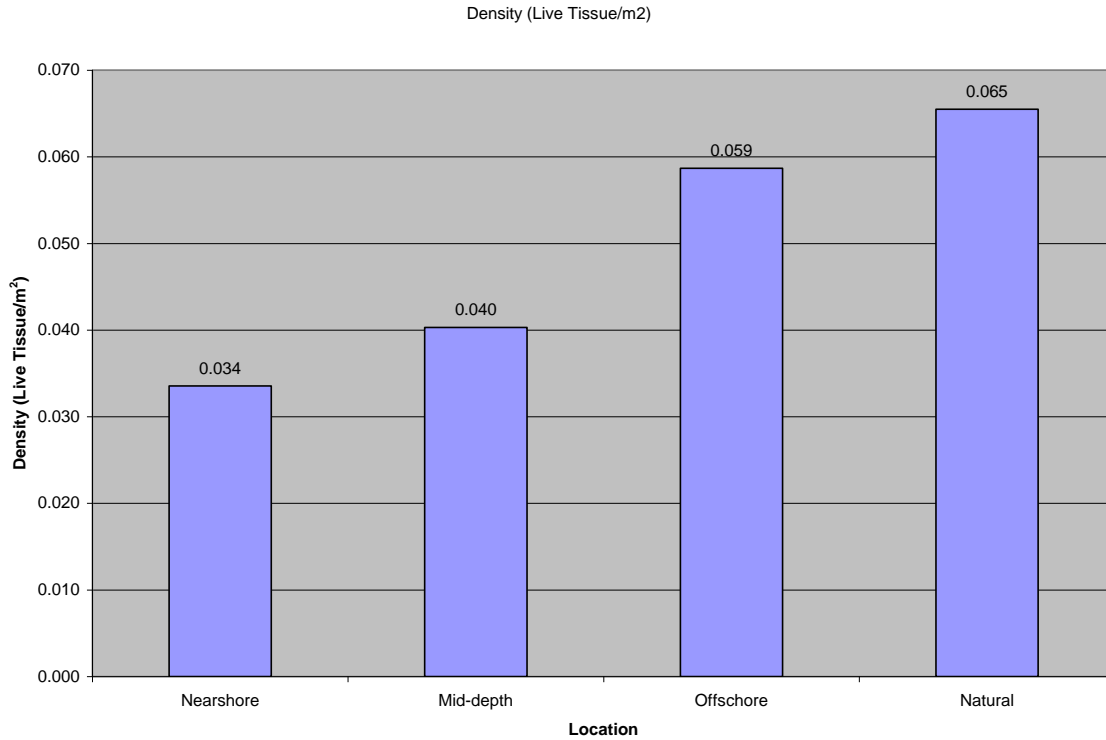
Figure 19: Live tissue surface area/m^2 on both the natural and artificial reef segments.

Once it was determined that significant differences did occur among the four areas, the Newman-Keuls Test (Table 3) was used to determine where differences occurred among segments. When q is larger than $q_{(0.05, 115, p)}$, the null hypothesis is rejected and thus results show that: $\mu1 = \mu2 \neq \mu3 = \mu4$, or that the Natural reef and Offshore artificial reef segments differ significantly from the Nearshore Artificial and Midshore Artificial reef segments in terms of coral surface area. Finally, the percentage of individual corals >25cm^2 on the natural reef was 65.6% followed by the offshore segment with 35.1%, the mid-depth with 29.8%, and the nearshore with 24.3% (Table 4).

	Nearshore (0-125m)	Middepth (125-250m)	Offshore (250-380m)	Total Artificial Reef (0-380m)	Natural Reef
Number of Colonies/m^2	5.77	4.45	4.99	5.00	1.46
Live Tissue cover/m^2	0.034	0.040	0.059	0.046	0.065
Percent Cover (%)	3.4	3.9	5.9	4.6	6.5
Depth Range (m)	3-5	5-6	6-7	3-7	4-5

Table 2: Coral Data per Segment

Comparison	Difference	SE	q	p	p-value	$q_{0.05,115,p}$	Conclusion
4 vs 1	4218.26	651.35	6.476	4	p < 0.001	3.68	Reject H$_o$: μ4 = μ1
4 vs 2	2791.76	651.35	4.286	3	p < 0.01	3.35	Reject H$_o$: μ4 = μ2
4 vs 3	137.05	656.91	0.209	2	p > 0.50	2.78	Accept H$_o$: μ4 = μ3
3 vs 2	2654.71	656.91	4.041	2	p > 0.025	2.78	Reject H$_o$: μ3 = μ2
3 vs 1	4081.21	656.91	6.213	3	p < 0.001	3.35	Reject H$_o$: μ3 = μ1
2 vs 1	1426.50	651.35	2.190	2	p > 0.10	2.78	Accept H$_o$: μ2 = μ1

Table 3: Newman-Keuls Comparison of Surface Areas. Ranked means: μ1 = Nearshore, μ2 = Mid-depth, μ3 = Natural, and μ4 = Offshore.

Nearshore	Middepth	Offshore	Natural Reef
(0-125m)	(125-250m)	(250-380m)	
24.3%	29.8%	35.1%	65.6%

Table 4: Percent of corals greater than 25cm^2 by segment

4.4 *Coral Density per Segment*

The density of corals for each artificial reef segment and natural reef was then examined. In contrast to the percent cover, the natural reef segment had only 1.46 corals/m^2, followed by the mid-depth artificial reef segment with 4.45 corals/m^2, then the offshore segment with 4.99 corals/m^2, and finally the nearshore segment with 5.77 corals/m^2 (Table 5, Figure 20).

	Nearshore	Middepth	Offshore	Natural Reef
	(0-125m)	(125-250m)	(250-380m)	
Number of Corals/m^2	5.77	4.45	4.99	1.46

Table 5: Coral Abundance per Reef Segment
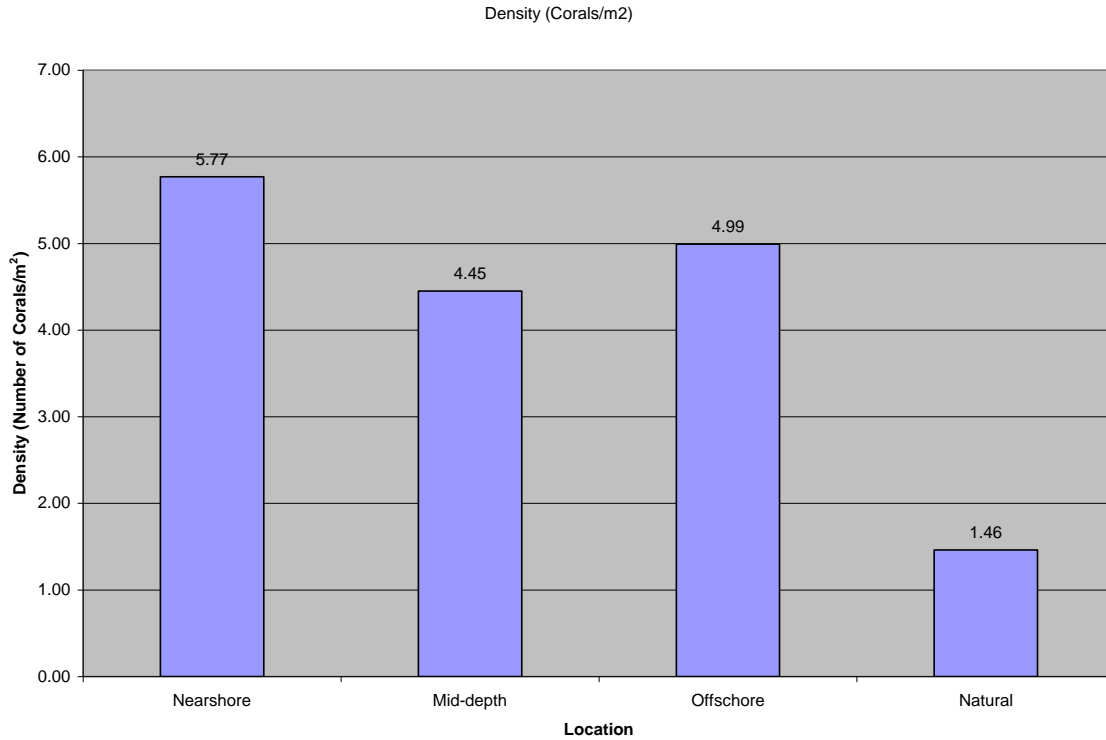
Figure 20: Number of coral colonies /m^2 on the artificial and natural reef segments.

Here again the Kruskal Wallis test was first used to assess if there were any

significant differences in coral abundance among the segments and the natural reef. The

Kruskal-Wallis H value was 46.41 which is much larger than the χ^2 value of 7.815 where

$\alpha = 0.05$ and $v = 3$. Therefore the null hypothesis stating that the mean number of corals

among each sample area do not differ significantly from one another, was rejected.

Once we determined a significant difference in mean coral abundance to exist

among the four areas, the Newman-Keuls Test (Table 6) was again used to determine

between which segments these differences occurred.

Comparison	Difference	SE	q	p	p-value	$q_{0.05,115,p}$	Conclusion
Off vs Near	38.71	4.084	9.478452	4	$p < 0.001$	3.68	Reject H_o: $\mu4 = \mu1$
4 vs 2	19.24	4.084	4.711068	3	$p < 0.005$	3.35	Reject H_o: $\mu4 = \mu2$
4 vs 3	15.17	4.084	3.714496	2	$p < 0.005$	2.78	Reject H_o: $\mu4 = \mu3$
3 vs 2	4.07	4.049	1.005186	2	$p > 0.20$	2.78	Accept H_o: $\mu3 = \mu2$
3 vs 1	23.54	4.049	5.813781	3	$p < 0.001$	3.35	Reject H_o: $\mu3 = \mu1$
2 vs 1	19.47	4.049	4.808595	2	$p < 0.001$	2.78	Reject H_o: $\mu2 = \mu1$

Table 6: Newman-Keuls Comparison of Coral Abundance. Ranked means: $\mu1 =$ Natural reef, $\mu2 =$ Nearshore, $\mu3 =$ Mid-Depth, and $\mu4 =$ Offshore.

When q is larger than q(0.05, 115, p), the null hypothesis is rejected and thus the results show that $\mu2 = \mu3 \neq \mu4 \neq \mu1$, or that the nearshore (35.9) is equal to the mid-depth (40.0) but not equal to the offshore (55.1), and not equal to the natural reef (16.4) in terms of coral abundance.

4.5   Overall: Natural Versus Artificial

Finally, the density of corals and their surface areas on the entire sampled area on the artificial reef was compared to the sampled area on the natural reef. Here, the percent cover of scleractinian corals on the artificial reef was 4.5% and the cover on the natural reef was 6.5%. Next, in comparing the actual number of corals, the artificial reef had 3875 individual coral colonies or 4.9 corals/m^2 and the natural reef had 1133 individual coral colonies or 1.4 corals/m^2 (Table 7).

Based on the SNK results (Table 3), there are greatest similarities in coral live tissue surface area between the nearshore and mid-depth artificial reef segments, and between the offshore artificial reef segment and the natural reef. There are significant

Location	Number of Corals/m^2	Coral Surface Area (m^2)	Substrate Surface Area (m^2)	Percent Cover (All Corals)	Percent Corals Larger Than 25cm^2
Nearshore	5.8	6.3	186.9	3.4	24.3
Mid-depth	4.3	10.6	247.6	3.9	29.8
Offshore	5.0	18.3	351.8	5.6	35.1
Total Erojacks	5.0	35.2	786.3	4.3	29.7
Natural	1.4	50.7	786.3	6.5	65.6

Table 7: Overall Coral Abundance and Surface Area

differences between the following pairs of comparisons; nearshore artificial reef segment and natural reef, nearshore and offshore artificial reef segments, mid-depth and offshore artificial reef segments, and mid-depth artificial reef segment and natural reef.

Based on the SNK results (Table 6), the greatest similarity in coral abundance is between the nearshore and mid-depth artificial reef segments. There are significant differences in all other comparisons.

Finally we looked at the average size of the corals (Table 8) between all three segments of the artificial reef (Figure 21) and overall between the Erojacks artificial reef and natural reef (Figure 22) by species. Here we find a general trend that as on progresses from the nearshore artificial reef to the natural reef, most of the coral species increase in size.

Species	Nearshore	Mid-depth	Offshore	Total Artificial	Natural
Siderastrea radians	2.63	2.01	2.52	2.40	4.58
Siderastrea sideria	3.84	15.43	54.35	15.31	15.77
Oculina diffusa	118.80	176.14	215.15	177.91	0.00
Millepora aclicornis	270.16	333.48	441.19	363.28	111.39
Porites astreoides	89.77	0.02	210.65	95.34	172.90
Diploria clivosa	344.17	409.18	590.99	450.08	2353.05
Agaricia agaricities	51.72	44.03	38.96	39.78	45.53
Dichocenia stokesi	231.86	94.55	230.67	185.63	185.79
Phyllangia americana	0.00	10.22	0.58	3.53	0.00
Montastrea cavernosa	0.00	225.01	325.53	315.77	1180.89
Diploria stirgosa	278.70	1530.07	633.85	676.61	2751.54
Diploria labyrinthaformis	785.48	676.51	699.49	710.95	2227.50
Montastrea annularis	0.00	0.00	154.43	154.43	100.41
Stephanocoenia intersepta	119.96	421.08	568.85	257.28	118.58
Solenastrea bournoni	0.00	294.37	531.49	426.11	1359.73
Meandrina meandrites	0.00	0.00	135.97	135.97	981.80
Colpophilia natans	0.00	407.55	485.70	459.65	502.07
Eusmilia fastigiana	60.92	0.00	0.00	60.92	0.00
Porites porites	0.00	1.00	0.00	1.00	69.99
Acropora cervicornis	0.00	0.00	0.00	0.00	308.46

Table 8: Average Live Tissue Surface Area (cm^2) by Coral Species
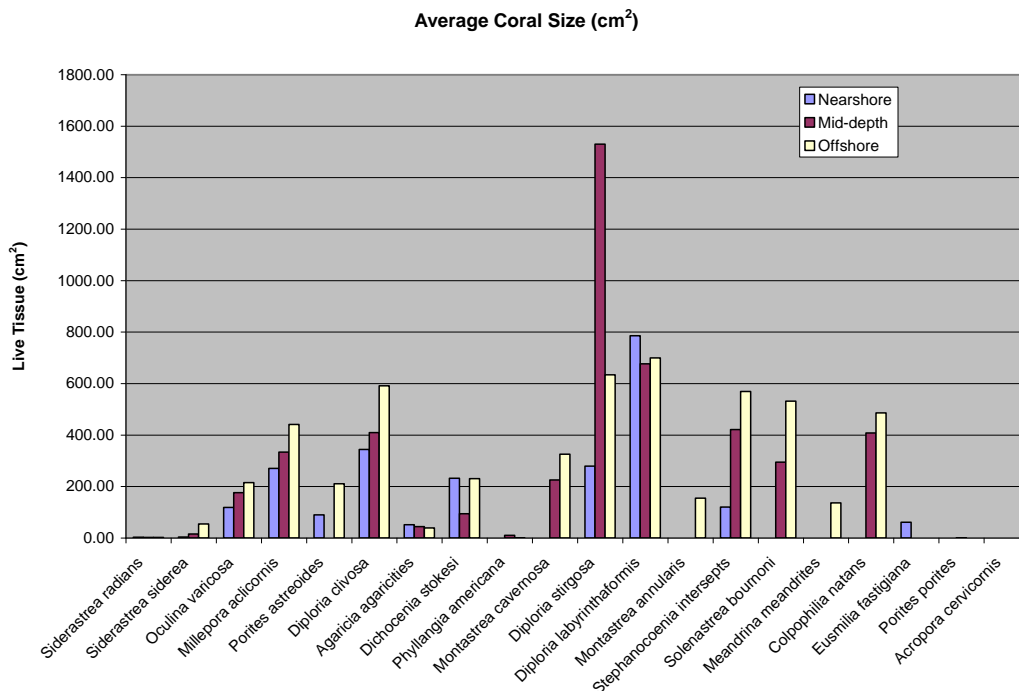
Figure 21: Average Live Tissue Surface Area (cm^2) on Each Segment of the Artificial
Reef by Species.
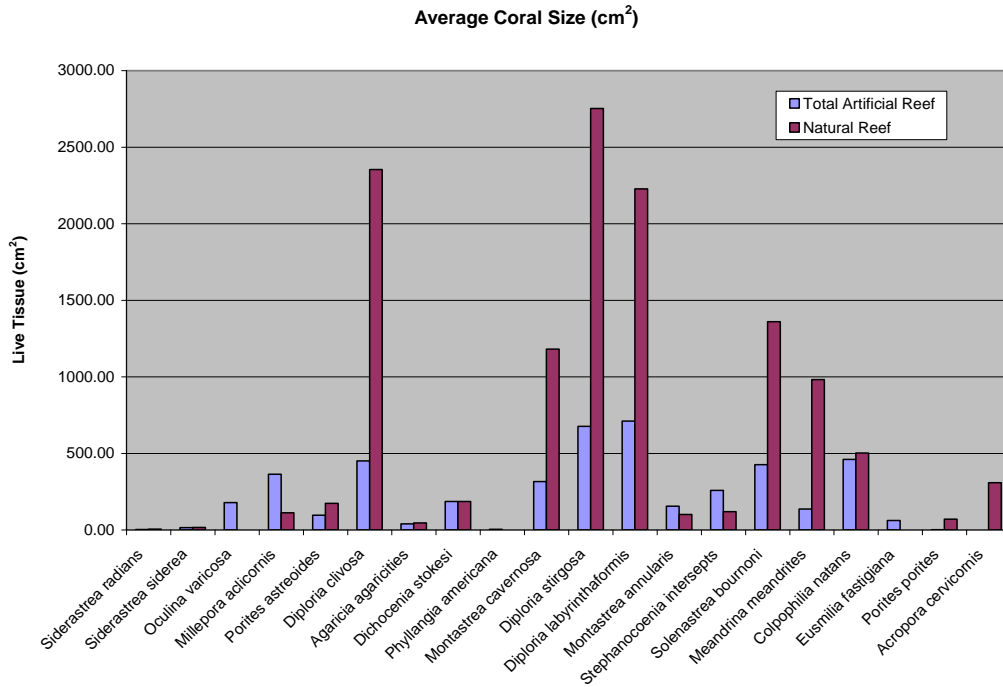
Figure 22: Average Coral Size (cm^2) on both the Natural and Artificial Reef by Species.

4.6   Shannon-Weiner Diversity Index and Eveness

The Shannon-Weiner index was used to determine the diversity and eveness of the scleractinian corals on both the artificial and natural reef. We can use these values to see how much the artificial reef resembles the natural reef in terms on the coral community. This is important to determine if artificial reefs can support the same corals as the natural reef and see if they are useful tools for mitigation. On the artificial reef, Shannon-Weiner calculation gives an H value of 1.799 and an E_H value of 0.089, while on the natural reef the H value is 2.198 and E_H is 0.129 (Table 8).

Species Artificial	Frequency Artificial	Species Natural	Frequency Natural
Agaricia agaricites	106	*Agaricia agaricites*	3
Colpophylia natans	3	*Acropora cervicornis*	120
Dichocoenia stokesi	81	*Colpopyilia natans*	2
Diploria clivosa	106	*Dichoecenia stokesi*	88
Diploria labyrinthiformis	22	*Diploria clivosa*	101
Diploria strigosa	37	*Diploria labyrinthiformis*	1
Eusmilia fastigiata	2	*Diploria strigosa*	21
Meandrina meandrites	5	*Meandrina meandrites*	3
Millepora alcicornis	358	*Millepora alcicornis*	93
Montastrea annularis	13	*Montastrea annularis*	19
Montastrea cavernosa	56	*Montastrea cavernosa*	40
Oculina diffusa	376	*Porites astreoides*	245
Phyllangia americana	72	*Porites porites*	8
Porites astreoides	127	*Siderastrea radians*	63
Porites porites	1	*Siderastrea sideria*	279
Siderastrea radians	1712	*Solenastrea bournoni*	29
Siderastrea sideria	774	*Stephanocoenia intersepts*	18
Solenastrea bournoni	9		
Stephanocoenia intersepta	12		
N = 19 species		N = 17 species	
H=1.799		**H=2.198**	
E_H=0.089		**E_H=0.129**	

Table 8: Species Richness and Shannon-Weiner Diversity.

5.0   Discussion:

Artificial reefs have been deployed world-wide over the last 150 years for a
variety of purposes, for example enhancing fisheries, combating beach erosion,
preserving habitat, and mitigation of natural reef damage. Benefits are somewhat
equivocal. In studies by Fitzharding and Bailey-Brock (1989), natural substrata is much
more favorable for scleractinian corals and invertebrates than artificial substrata, while
Carr and Hixion (1997) have shown artificial reefs to be more favorable for coral

recruitment and growth, and according to Walton (1979) substrata complexity is an important factor in artificial reef success.

Previous studies have shown that recruitment differs greatly between natural and artificial reef substrata. A study by Perkol-Finkel and Benayahu (2007) investigated the recruitment processes to experimental settlement plates attached to artificial and natural reefs and revealed the factors that shape community structure at the two reef types. Their results showed that over time (18 months) the artificial reef resembled the natural reef community in terms of number and diversity of scleractinian corals. Another study by Fukunaga and Bailey-Brock in 2007 showed that an artificial reef in Hawaii, displayed lower abundance of infaunal organisms including polychates, nematodes, and scleractinian corals, but the artificial reef did not differ significantly from two surrounding natural reef sites. In this study, we find the Dania Beach Erojack Reef as a whole is statistically different in both coral abundance and coral surface area. Also comparisons between segments of the artificial reef and natural reef also show statistical differences between and among segments. This information provides useful information to mitigation, to assess how well an artificial reef of this age has done to replace natural habitat.

5.1 *Changes Following Hurricanes*

Immediately following hurricanes Katrina and Wilma in 2005, the shallowest portion of artificial reef (which was already surveyed for scleractinian corals) was resurveyed to determine if there were changes associated with the natural disturbances. GEE regression shows a significant difference between coral abundance, pre- and post-hurricanes ($p < 0.0001$), a significant difference between belts ($p = 0.003$), a significant

difference in coral surface area (p = 0.0001), and a significant difference in surface area among the belts (p = 0.0035).   It was found that there was a significant increase in coral cover and coral number after the hurricanes. No comparisons with the natural reef both pre- and post-hurricanes were made.

The majority (78.3%) of the corals were less than $25cm^2$ in size, and did not have much vertical relief or branching. Therefore, increased wave energy during the hurricane merely flowed by the coral without dislodging them. This could be attributed to several factors. First, hurricane Wilma passed from west to east across the reef area and was a very rapidly moving system. This limited the duration of exposure to the disturbance. Plus the disturbance was not particularly intense. As a Category 2 storm Wilma possessed sustained winds of approximately 114kph as measured at the Fort Lauderdale International Airport, 2.4km to the west of the study site. Also, the Erojacks reef is in very shallow water and is susceptible to scouring during storms but it is protected by the middle and inner reef terraces, as well as the nearshore ridge complex, which may have reduced wave intensity.   The increase in number, live tissue surface area, and densities may be attributed to some scouring effects in that the increased wave action and scouring removed some algal cover or sediment, thus exposing more coral colonies or a larger portion of an individual colony, making it easier to see. Fragmentation of coral colonies may also contribute to the increased number and density of corals post-hurricane, although this was not noted in the field   Another possible reason for the increases in coral cover and abundance may have nothing to do with the hurricane, but more to do with the increased proficiency of the observers, particularly since the corals in this shallowest segment were small and inconspicuous. Here, simply by reevaluating an area

which was already surveyed allowed for the expression of better technique in locating, identifying, and measuring the corals.

5.2   Temperature

Scleractinian corals function best in a certain range of temperatures, generally between 18˚ and 32˚C (Leichter 1999). Water temperature for the nearshore segment ranged from 19.7˚ C to 31.9˚ C, mid-depth ranged from 19.1˚ C to 31.4˚ C, offshore from 19.1˚ C to 30.8˚ C, and the natural reef temperature ranged from 19.8˚ C to 31.2˚ C. Leichter's results and those from this study (Figure 13) confirm that temperatures in the study area remain in the coral's optimal range throughout the year, thus promoting coral survival, growth and reproduction.

Temperature was recorded during each of the three passing Hurricanes; Katrina, Wilma, and Ernesto. The passing of each hurricane produced a reduction in sea surface temperature. During Katrina, seawater temperatures fell from 30.9˚C to 28.5˚C, Wilma produced a decline from 28.3˚C to 24.4˚C, and Ernesto produced a decline from 30.5˚C to 29.0˚C, over 48 hour period, however, these temperatures still remain within the limits of coral tolerance.

5.3   Artificial versus Natural Reef

In this study, coral cover, coral colony number, colony size, and coral densities for three distinct segments of a pre-cast concrete artificial reef were compared among themselves and to the surrounding natural reef. Statistical analyses (Kruskal-Wallis and Newman-Keuls) of the surface area data shows that coral cover in the natural reef and offshore artificial reef segment are not significantly different from one another nor are there significant differences between coral cover in the mid-depth artificial reef segment

and nearshore artificial reef segment. There was a significant difference between the natural reef and offshore artificial reef segment compared to the mid-depth and nearshore artificial reef segments. Next, the Kruskal-Wallis test and the Newman-Keuls (Table 6) was used to compare the numbers of individual corals on each segment. Here we find the nearshore and mid-depth segments are not significantly different but the offshore artificial reef segment and natural reef segments are significantly different from one another as well as the nearshore and mid-depth artificial reef segments. We also find that when observing densities, the number of corals/m^2 increases as one moves from the natural reef to the nearshore segment of the artificial reef, however, the live coral tissue surface area/m^2 decreases from natural to nearshore segment.

This could be caused by several factors. First, larvae may be preferentially settling near the natural reef due to better environmental conditions (less temperature variability, more water flow and lower nutrients) because the offshore reef is the closest to the natural reef and since most corals reproduce through the release of egg and sperm or larvae into the water column, and the subsequent settlement may have allowed the offshore segment to recruit first and more often than the other segments. Soong (1993) reported that *Diploria clivosa*, *Siderastrea sideria*, and *Diploria strigosa* all broadcast gametes during a very short spawning season, and that dispersal is limited by local currents. Nearshore eddies spinning off of the Florida Current could allow for the recruitment of the Erojack offshore segment, and on subsequent spawning events, natural reef and the newly recruited offshore segment could allow for the progression of coral recruitment along the artificial reef toward the shore. Alternatively, reproduction on the natural reef may disperse directly to the shallower artificial reef segments, but with less abundance of recruits due to their greater distance from the source.

45

This same idea can also be applied to the percentages of corals on each segment that are larger than 25cm^2 because even under the best conditions coral growth is only about 4cm per year depending on species (Hallock 1997). In a study by Hubbard and Scaturo (1985) *Diploria clivosa* and *Siderastrea sideria* (the major species found in our study) in the Caribbean grow at a much slower rate of approximately 0.7 to 0.9 cm/year. The corals located nearest to shore may have recruited less frequently and later than those of the mid-shore segment, and even later than the offshore, allowing the offshore corals a longer growing period. This is consistent with why the percent of corals larger than 25cm^2 on the natural reef (65.6%) almost doubles that of the offshore artificial reef (35.1%) counterpart.

The size of the corals on the artificial reef may also be limited by not only age but by the size and shape of substrate. The natural reef presents a vast flat surface for coral colony growth, while the erojack's complex 3-D structure has surfaces only 8-11cm wide on each leg. On the natural reef, a coral has no physical limit to its ability to spread laterally (Figure 21). Coral colonies on the natural reef have less vertical relief than those of comparable width from the Erojacks Reef. Larger corals on the erojacks reef are typically bulbous in shape since they grow around the faces of the leg (Figure 21). The species composition of the natural and artificial reefs also may account for the differences in coral colony size between the artificial and natural reefs. Some species (e.g. *Diploria clivosa*) attain large size and are found more frequently on the natural reef, compared to a common coral on the artificial reef (*S. siderea*) that is smaller. On the natural reef, 101 *D. clivosa* colonies account for 23.77m^2 of live coral cover, while 279 *S. siderea* colonies only account for 0.44m^2. In contrast, on the Erojacks Reef, 106 *D.*

clivosa colonies account for 4.77m^2 of live coral cover, while 774 *S. siderea* colonies account for 1.18m^2.
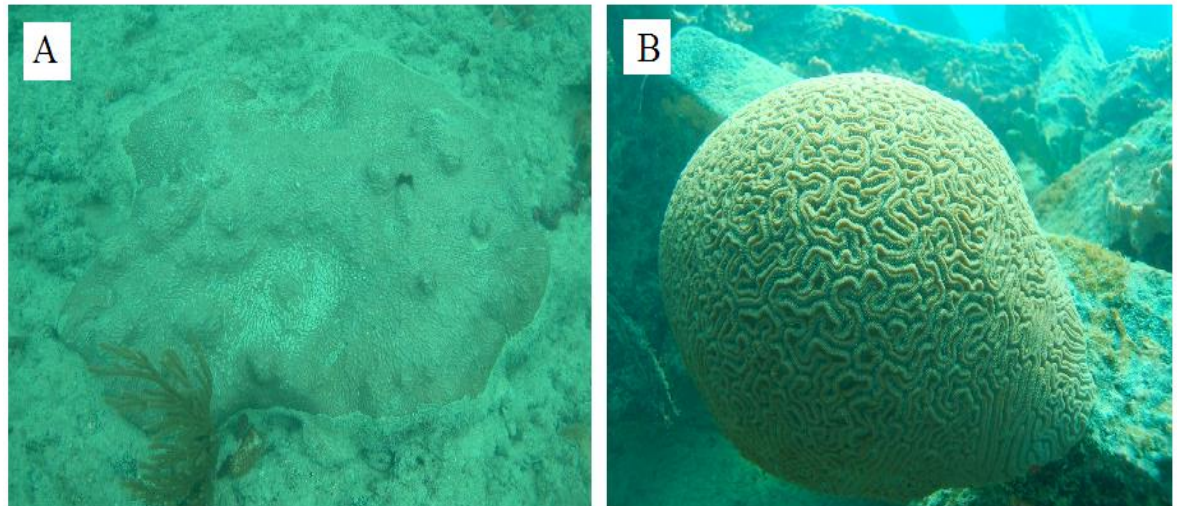
Figure 23: Growth forms of corals. A: *D. clivosa* colony on the natural reef.
     B: *D. labyrinthiformis* colony on the Erojack Reef.

When comparing the number of corals on each segment to one another, significant differences occur between the natural reef, the offshore segment and the midepth segment (Table 6), yet the middepth and nearshore segments are not significantly different (Table 6). The density (number of corals/m^2) increases from natural to nearshore. This could have occurred for several reasons. First, the competition for space on both the natural and artificial reef is intense, and nearly every square centimeter is covered by some type of benthic organism, including algaes, sponges, *Palythoa*, gorgonians, and hard and soft corals. Perhaps, spawning events over the last 40 years since the deployment of the erojacks have lead to each segment reaching its carrying capacity. The carrying capacity is the population size at which population growth change equals zero. Population size is constrained by food availability, competition with other species, lack of suitable habitat, and interactions with predators

and diseases. It is possible that as the artificial reef aged, the carrying capacity has been reached on the offshore segment and new coral recruits have progressively moved to the middepth and nearshore segments in search of suitable substrate.

Next, the shape of an individual erojack is a hexapod, which has a surface area of about $4.4m^2$. Of this area, some will be shaded by the rest of the hexapod so much as to not allow light to reach certain parts. More of this remaining suitable area is lost by piling the erojacks on top of one another. The points where two erojacks meet has also been eliminated from settlement by corals. Finally, after all the jacks have been piled into there current location, much of the interior of the reef may not receive enough light for coral growth, thus eliminating more available area for settlement. Based on hindsight, it is estimated that less than 50% of the Erojack reef is actually suitable for coral recruitment and growth based on these three-dimensional complexity issues. However, as one moves from the offshore segment to the nearshore, the erojacks occasionally become less densely aggregated allowing for some differences in coral abundance between segments because of more available substrate.

When comparing the entire artificial reef with the natural reef, the natural reef had a higher percent cover, however the numbers of individual corals was more than 3 times greater on the artificial reef. Here again, its longer history and larger space available for recruitment and growth has allowed for the larger corals to form and persist on the natural reef. Once a coral colonizes a space it can expand over a larger area, whereas this expansion space is limited on the Erojacks. The nearshore reef complex is approximately 6500 years old (Banks et al, 2007) therefore, time may also be a factor in why the natural reef had significantly fewer, but larger coral colonies. There has been more time for predation, competition, and physical disturbance to have had an effect on the natural reef

48

corals. The lack of time for development then suggests why the artificial reef has more, smaller, coral colonies. The artificial reef was bare concrete at the time of deployment, providing suitable, uninhabited, substrate for coral recruitment where none had existed before. After a suitable "incubation period" to allow biofilms to form on the new substrate corals can then recruit, making the artificial reef was a great place for corals to settle and grow, with little competition for space at the time of deployment (Webster et al, 2004). Over time, competition will become more apparent with more corals recruiting as well as other benthic species, including *Palythoa*, sponges, and soft corals.

On each segment as well as the natural reef, an average size of each coral species was calculated. Here we find that the majority of the corals found in the area, increase is size from the nearshore artificial reef segment, to the mid-depth, offshore, and natural reef. When one compares the total artificial reef with the natural reef, only *Millepora alcicornis, Montastrea annularis, and Stephanocoenia intersepta*, decreased in size on the natural reef.

 Here it is believed that the length of time for recruitment and growth are involved. As previously stated, the natural reef is approximately 6500 – 8000 years old (Banks 2008) and the Erojacks Reef is a mere 40 years old. As the Erojacks Reef was colonized, the offshore recruited first, followed by the mid-depth and nearshore segments. Subsequent spawning events on the offshore reef may have allowed for the natural progress of new recruits toward the shore over a longer period of time due to inability to find suitable substrate, or from increased competition, thus diminishing the time for growth within a segment.

Finally, the Shannon-Weiner diversity index showed that both the diversity and eveness of the corals on the natural and artificial reef are very similar. Moyer et al.

49

(2003), report 23 species of scleractinian corals, with *M. cavernosa* being the dominant species in Broward county. In our study we found 19 species of coral on the artificial reef and 17 on the natural reef. *Porites astreoides* (279 colonies) and *S. siderea* (245 colonies) being the most abundant on the natural reef while *S. radians* (1712 colonies) and *S. siderea* (774 colonies) are the most abundant on the artificial reef. The natural reef does have both a slightly higher H and EH values meaning that the diversity is somewhat higher on the natural reef and that these species are more evenly distributed within the community. This shows that forty years after deployment, the Dania Beach Erojacks Reef does not yet resemble the surrounding natural reef, although the artificial reef and possibly other artificial reefs in Broward County can serve as mitigation sites with coral diversity and biomass that is not too different than the natural reef.

6.0   Conclusion

Based on the results of the study, an artificial reef that was submerged 40 years ago shows no statistical difference in the number of coral colonies when compared to the surrounding natural reef, and that the size of the corals on the two shallowest segments of the artificial reef were significantly smaller than those on the deepest artificial reef segment and natural reef. Significantly larger corals were found on the natural reef as compared to a combination of all three artificial reef segments in the study. The limitations in the length of time for corals to recruit and grow, as well as the limitations in the width of available substrata, results in lower diversity and evenness on the artificial reef compared to the natural reef. Differences in environmental factors including differences in temperature, currents, turbidity, and salinity may also play a role in the species composition, size, and abundances between and among each surveyed segment.

Finally, the passage of two hurricanes did not have a negative impact on the small corals located on the shallow (3-4m) portion of the artificial reef.

Here we show that even after 40 years of submergence, the artificial reef still does not resemble the natural reef (in terms of scleractinian coral abundance and density) providing evidence that artificial reefs like the Erojacks Reef may not be the best solution for mitigation of damaged coral colonies in Broward County, Florida.

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