Coral Recruitment to Various Artificial Substrata, Miami Beach, FL

Nicholas C. Straccione
Nova Southeastern University

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CORAL RECRUITMENT TO VARIOUS ARTIFICIAL SUBSTRATA, MIAMI BEACH, FL

BY

NICHOLAS C. STRACCIONE

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By:

Nicholas C. Straccione

Approved:

Thesis Committee

Major Professor:

Dr. Joshua Feingold

Dr. Richard Spieler

Dr. Robert Pomeroy
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1.0 Abstract

The City of Miami has placed 12 artificial reefs approximately 100m offshore in two parallel transects. The reason for this deployment was to turn a barren seabed into a productive environment for aquatic organisms. The reefs were placed close to the shoreline to allow easy access for snorkellers, divers, and fisherman. Three different types of reef materials were used in constructing the artificial reefs: boulders composed of limestone, concrete shaped as tetrahedrons, and concrete mixed with tire aggregate shaped as tetrahedrons. This study consisted of two separate assessments: 1) a survey from two of each of the different reef types that were assessed bimonthly for one year to observe coral recruitment and 2) a survey of all 12 artificial reefs once at the end of the study to observe coral recruitment. In the year-long study, the results indicated that the number of coral recruits were highest on the boulder reefs (0.05>p>0.025, n=2), a significant difference. However, there was no significant difference in the area of corals on each substrata (0.10>p>0.05, n=2). In the final assessment of all 12 artificial reefs the greatest number of corals and area of corals on average were on the boulder reefs. However, there was no significant difference in either the number of coral recruits (0.50>p>0.25, n=4) or coral area (0.25>p>0.10, n=4). An explanation for this non-significance was the low coral recruitment of boulder reef two (B2). When B2 was treated as an outlier there was significance in both the number and the area of corals (0.025>p>0.01, n=3).
2.0 Introduction:

2.1 Coral Reefs

The importance of coral reef ecosystems may be seen in their numerous ecological, aesthetic, economic and cultural functions (Maragos, et al. 1996). The coral reef’s living organisms generate high structural complexity which support one of the most biologically diverse environments in the world (Reaka-Kudla 1996). Their massive and intricate frameworks provide habitat for other plants and animals. This makes coral communities one of the major sources of income to people who have the privilege of living near them (Jaap and Hallock 1990). The economic benefits of the coral reefs come from tourism, commercial fishing, recreational diving and fishing. Coral reefs are also extremely important in protecting coastlines from shoreline erosion (Margos, et al. 1996). For example, in Broward County the Pleistocene platform covered by a living veneer of organisms functions as a wave resistant structure that reduces beach loss (Hoffmeister 1974).

In the Caribbean, along with many other oceanic reef systems, coral reefs are endangered by overexploitation, chemical and oil pollution, sedimentation, eutrophication, and environmental hazards such as increased ultraviolet light exposure and temperature anomalies (Reaka-Kudla 1996). Examples are many: in Jamaica, it is rare to see a fish greater than 30cm in an hour of diving due to their intense trap fishing (Ferry and Kohler 1987, Sebens 1994). A major oil spill (8,000,000 liters) off the coast of Panama, one of many oil spills that occur worldwide, caused extensive harmful effects on the corals including decreased numbers of corals, coral cover and coral diversity (Guzman et al. 1991). Due to increased anthropogenic eutrophication in certain areas the
abundance of juvenile corals was lower in Barbados as opposed to more oligotrophic reefs (Hunte and Wittenberg 1992). In Bermuda, increases in sedimentation and turbidity due to dredging the ocean floor led to the decreased growth rate and increased mortality of corals (Dodge and Vaisnys 1977). Coral reefs are able to recover from a variety of stress factors, but each of these factors discussed above has negatively affected reefs worldwide. Clearly it is important to identify and manage the effects of natural and anthropogenic stress (Grigg 1995). The United States government has acknowledged the latter by forming the Florida Keys National Marine Sanctuary (FKNMS) and the Protection Act of 1990, amongst others. The main goal of the FKNMS is to competently manage the ecosystem so that natural restoration in the sanctuary occurs and to ensure the long-term ecological and economic viability of the system (Anonymous 1997). Each of these statements discussed above show why artificial reef assessment is important. Many of the detrimental effects occurring on coral reefs are not going to stop, therefore, artificial reef development may be able to assist in coral restoration. Coral reef mitigation is a management effort to enhance or restore damaged coral communities at the site where the injury occurred or to recreate the damaged coral communities at a different location (Hudson et al. 1989 and Jones 1977).

2.2 Artificial reef substrata and settlement

Over the course of this study three different substrata, limestone boulders, concrete tetrahedrons and concrete tetrahedrons with tire aggregate, were evaluated to see which material supported the greatest amount of coral recruitment in the near shore waters off Miami Beach. Managers of the City of Miami are looking for a suitable
material that they can deploy offshore that will increase benthic and demersal species diversity. These three substrata were surveyed for approximately one and a half years to determine the amount of coral recruitment on each substrate type. In the past, many studies on artificial reef deployment have focused on fish recruitment (Smith et al. 1979, Stone et al. 1979 and Spieler et al. 1994). However, the colonization of the artificial reefs by sessile organisms is also important. According to Fitzhardinge and Bailey-Brock (1989) corals, other invertebrates and algae provide food and shelter for fish and crustaceans. They help to stabilize the reef by cementing elements together and to the substratum. Many fish will aggregate to almost any type of structure or material, but sessile organisms are more selective. Larvae might not settle or successfully metamorphose on a particular material if it lacks correct chemosensory cues for settlement, if it contain toxic chemicals, or if it inhibits metamorphosis and subsequent growth. Sometimes the surface texture and topographic relief may also influence settlement.

When corals attempt to settle on new substrate they are susceptible to predation from fish and/or urchins (Brock 1979), overgrowth and shading by faster growing organisms (Birkeland 1977) and sedimentation (Bak and Engel 1979), all of which may lead to death. The high mortality that occurs between the time of settlement, where the corals cannot be seen by eye, and the visible observation of corals may be related to differences in the settlement rates of coral larvae on different materials (Fitzhardinge and Bailey-Brock 1989). However, the initial phase of settlement can be very difficult to detect in the field because newly settled larvae are small and cryptic. Therefore, most researchers measure recruitment that can be defined as juveniles that have survived for a
period of time after settlement (Connell 1985). Corals that are large enough to see are generally 2mm in diameter or greater (Fitzhardinge 1989).

2.3 Physical variables

Many physical parameters are studied as part of artificial habitat assessments. These parameters can have great impacts on the habitat that will affect the biological activity on the artificial substrate. Water quality measurements are vital to the growth of organisms on or around the reef (Bortone and Kimmel 1991). The specific parameters recorded in this study were: sea state, temperature and visibility. Sea state was obtained from www.marine.weather.com. Temperature, turbidity, and light all contribute to the success of the recruited organisms. Corals require warm ocean temperatures between 20° to 28° C (Anonymous 2000). Temperature was measured by a SeaQuest Suunto dive computer with an accuracy of ± 2° C. High turbidity levels will decrease the growth rate and increase mortality of individual corals (Dodge and Vaisnys 1977). If turbidity levels are high the amount of light that penetrates through the water column will decrease (Bortone and Kimmel 1991). Light is essential for the growth and nutrition of the corals because it is necessary for the symbiotic relationship between the corals and the zooxanthellae (Muscatine 1973). In this study visibility was recorded from an estimation by the SCUBA divers.

2.4 Artificial reef materials

Artificial reef deployment has been thought to be an important approach to enhance biological activity and/or restore reef damage. Artificial reefs can be viewed as
the addition of a structure to a relatively barren seabed that develops into a productive habitat (Brock 1994). Traditionally, most artificial reefs were deployed to aggregate fish into one area. When artificial reefs first started to be implemented in the United States they were made from “materials of opportunity.” The main focus for the reefs was disposal of wastes rather than resource enhancement (Buckley 1982). More recently artificial reef construction materials are geared toward longevity and suitable substrates for marine life. Instead of dumping old cars, refrigerators, tires or other short-lived material, dedicated reef designs and more stable materials are now being used (Teal 1999).

The materials that are used to construct artificial reefs seem to make a large difference in the amount of coral recruitment. In the past many artificial reefs were constructed of cars, appliances, tires, ships, bridges, piers, aircraft, pipelines, pilings, culverts, storage tanks and concrete debris (Bohnsack and Sutherland 1985). In the State of Florida most of these materials are now banned and strict guidelines are imposed to create artificial reefs with better purposes and acceptable building materials (Horn 1994).

2.4.1 Tires

Artificial reefs constructed from tires were originally thought to be an excellent solution to tire disposal problems. Rubber tires are inert to the marine environment, they appear to last indefinitely and they will attract fish (Tolley 1981). However, in more recent studies tires have proven to be an unsuitable reef building material. Even when tires are bundled a storm can dislodge them from their current position and displace them on beaches or onto adjacent natural reefs creating more damage. Waves, surge and
currents associated with Hurricane David relocated thousands of tires onto the beach in Southeast Florida (McAllister 1981). Other studies have shown tires are not suitable substrata for the settlement of sessile invertebrate species, especially corals. Compared to other materials such as concrete or metal, tires attract the fewest corals, if any at all (Fitzhardinge and Bailey-Brock 1989). Even though tires had more open space available for settlement than other materials fewer corals recruited onto them. This suggests that tires are not the most appropriate material for coral settlement or early survival. A possible explanation could be that bacterial films are known to induce settlement of some marine invertebrates (Hadfield 1986). If these films were not well developed on tires corals may not settle upon them (Fitzhardinge and Bailey-Brock 1989).

2.4.2 Cars, metals and oil rigs

Materials such as cars and other metal appliances were not chosen for this study in the construction of the artificial reefs. They are no longer recommended because they have short-life expectancies, approximately 1-5 years. In some cases there have been detrimental effects on the marine community due to the release of toxins (Fitzhardinge and Bailey-Brock 1989). Initially artificial reefs formed from these items work well for the recruitment of corals and other invertebrates but over long periods of time the structures deteriorate, making them relatively ineffective (McAllister 1981). Only metal structures that can withstand long-term exposure to seawater are recommended for artificial reefs. At some sites the State of Florida has deployed obsolete oil rigs as artificial reefs. However, Blair et al. (1994) stated that the reef sites must be chosen
carefully in deep water to avoid affecting boating traffic with the high relief structures which is not applicable here.

2.4.3 Cement and Concrete

Cement and concrete materials used in the construction of artificial reefs have proven to be the most successful of all artificial reef substrata (Clark and Edwards 1994, Fitzhardinge and Bailey-Brock 1989, Ryder 1981, Brock and Norris 1989). Cement is a powder mix with water whereas concrete has different sizes of rock aggregate added to the mix. These two types of materials can be used to create a habitat that can render protection, food and spawning areas while maintaining their stability over time (Ryder 1981). Cement and concrete can produce a similar texture and are composed of compounds similar to natural coral substrata. Rougher surface texture than that on rubber or metal can also be easily achieved by cement, which is thought to enhance recruitment (Fitzhardinge and Bailey-Brock 1989). In almost every study, cement and concrete structures have proven to surpass other materials for colonization of organisms, especially corals and other invertebrates (Clark and Edwards 1994, Fitzhardinge and Bailey-Brock 1989, Ryder 1981, Brock and Norris 1989). The only problems associated with cement and concrete are the cost in transporting the artificial reef and occasional scouring during storms (Blair et al. 1994 and Ryder 1981). However, scouring of natural substrates has also been known to occur during storms (McAllister 1981).

In Oahu, Hawaii, Fitzhardinge and Bailey-Brock (1989) examined different reef construction materials. Their experiment consisted of placing four different plates composed of car tires, metals, concrete and dead coral on the reef and recording subsequent recruitment. Five species of coral recruited to concrete blocks within three
months of immersion and continued to recruit throughout the study. Metals, such as steel or iron, were not recommended because they deteriorate too quickly and tires did not show any recruitment even after 3 years of immersion. Dead coral plates showed very high recruitment also, but dead coral is not as easily obtained as concrete. They concluded concrete was the preferable material for artificial reef to recruit corals (Fitzhardinge and Bailey-Brock 1989).

Corals and other sessile organisms also successfully recruited to artificial surfaces formed of concrete cubical reefs (Brock and Norris 1989, Clark and Edwards 1994). The hollow cubical structures have an open framework which increases surface area and microhabitats which could in turn improve diversity of the biotic assemblages of the reef. With increased surface area there is more substrate for recruitment which can lead to increases in species diversity and richness. In the Maldives, near the center of the Indian Ocean, corals colonized the artificial reef design within 6.5 months. After about two years several hundred juvenile corals inhabited the hard substrate. These cubical structures also helped to stabilize the reef upon which they were laid. This study illustrates how artificial reefs of the right design and correct material, concrete, can simulate a coral reef community by increasing structural complexity (Clark and Edwards 1994).

Concrete tetrahedrons and concrete tetrahedrons with tire aggregate mixed inside are also promising designs for artificial reef construction. In an experiment conducted in Ft. Lauderdale, Florida Spieler et al. (1994) surveyed two tetrahedron reef designs for 28 months. A total of 86 species of fishes were found at both of these sites. However, only four coral species were observed over the study period.
2.4.4 Boulders

Carbonate boulders are quarried from natural materials, but are classified as artificial reefs because they are placed on the seafloor by man. There has been speculation that boulders are an excellent substratum for recruitment of corals. They have similar components to natural coral substrata (CaCO₃) and the irregular surfaces of boulders could promote the settlement of coral larvae (Carelton and Sammarco 1987). In Southern California, in 1980, an artificial reef made of quarry stone was deployed and monitored for five years. The benthic community went through several stages of development and at the end of this time the turf community was compared with the natural reefs and older artificial reefs in the area. The results showed that the quarry stone material developed an epibenthic assemblage similar to more mature artificial reefs in less time (Palmer-Zwahlen and Aseltine 1994). A possible explanation for this idea is that the quarried stones have edges that are not smooth. Complexity at several spatial scales is important for artificial reef success (Walton 1979 and Smith et al. 1979) which may encompass design, spatial arrangement, number of chambers and openings and the amount of interstitial space (Bohnsack and Sutherland 1985). In general, uneven surfaces with cracks, crevices and holes increase benthic diversity and biomass (Kensler and Crisp 1965).

These and other studies have determined that concrete and quarry stone are suitable materials for artificial reef construction. Therefore two types of reef material made from concrete (concrete tetrahedrons and concrete tetrahedrons with tire aggregate) were compared to another reef type made from lime-rock quarry stone in Miami Beach.
2.5 Hypothesis

Based on previous research (Palmer-Zwahlen and Aseltine 1994, Cummings 1994 and Fitzhardinge and Bailey Brock 1989) I expected that the boulder reefs would be a better substratum for coral recruitment. For each of my measured variables (number of corals / m$^2$, area of coral / m$^2$ and average area of coral in mm$^2$) I predicted that corals would preferentially settle upon the boulder artificial reefs over the two types of tetrahedron reefs. I also suspected that the concrete tetrahedrons would have more coral recruits than the concrete tetrahedrons with the tire aggregate because of the presence of rubber in the latter structure.
3.0 Material and Methods:

3.1 12 Artificial Reefs

Twelve artificial reefs, constructed of three different materials and two different module shapes, were deployed off the coast of the City of Miami (Figure 1) in June 1998. These included: boulders made of quarried limestone (Figure 2), tetrahedrons made of concrete with gravel aggregate (Figure 3), and tetrahedron made of concrete with gravel and tire aggregate mixed inside (Figure 4).

The reefs were initially deployed on June 18, 1998 in approximately seven meters of water at 12 predetermined sites (Figures 5 and 6). Six reefs are arranged along each of two transects oriented parallel to shore. Each reef is separated from its nearest neighbor by approximately 100m. Four limestone reefs were each constructed with 50 1.2-1.5m boulders that were to be deployed in a two-layer configuration. However, in the actual deployment of the reefs some of the boulders were piled on a third layer. The four concrete with gravel aggregate reefs each were constructed with 50 tetrahedron modules produced by CSR Rinker under license agreement with Stability Reefs Inc. They were made from dense mixtures of 145lbs/ft$^3$ of waste concrete with 1.5 - 0.75 inch gravel (waste concrete is known as the concrete at the end of a batch which cannot be used therefore it is discarded). The use of tire-concrete aggregate in the four remaining artificial reef construction is a propriety technology held by Stability Reefs Inc. However, they were made in the same way as the concrete tetrahedrons but with tire chips in place of some of the gravel aggregate. Tetrahedrons were selected based on their stability characteristics, demonstrated efficacy in acquiring a diverse faunal assemblage, and potential application for use in shoreline stabilization (Spieler et al. 1994). Each of the
concrete reefs was composed of a mix of two different sized modules: 25 large modules (1.5m diameter) and 25 small modules (1.2m diameter) to allow for a mix in interstice sizes. An effort was made to construct all the reefs to a similar size in height and width, and this required some post-deployment reconfiguration.

3.2 Reef Size:

SCUBA divers first measured the circumference of the reef. The end of a 50m fiberglass tape measure was placed on a spot on the outer edge of the reef while the SCUBA diver circled the reef until he or she returned to the origin to determine basal circumference. Since the reefs are ellipsoidal, measurements along the major axis were also required. Then three separate height measurements were taken: one at the apex and one on either side equidistant from the reef margin to the apex. A graduated 20m extendable PVC pipe was used for these measurements. SCUBA divers placed the end of the 20m pipe through the reef until it contacted the underlying sediment and then the height measurements were taken (all measurements can be seen in Table 1). The calculated surface area gives a relative size for each of the reefs so that recruitment measurements can be standardized per area. To calculate the size of the artificial reefs the surface area of an ellipse formula was used (Appendix A). This specific calculation was also chosen because the corals preferentially recruit to the outer portion of the reef. The corals cannot inhabit the areas of the reef where the substrates are touching each other or the ocean floor so they are not included in the area calculation. The surface area formula gives a good approximation of the reef that can be recruited to by the corals.
3.3 Experimental Design

Two reefs, chosen at random, of each design were surveyed on a bimonthly basis for one year from January 2000 through December 2000. This was followed by a survey of all 12 reefs in May 2001. Boulder reefs B1 and B4, the concrete tetrahedron reefs C1 and C2 and the concrete tetrahedrons with tire aggregate reefs T1 and T4 were selected. During this study the reefs were located via GPS coordinates (Figure 5). Each reef was assessed by the same person on all visits. All of the reefs are small enough in size, and in the number of recruits, to allow the survey of the whole reef so that sub-sampling was not necessary. Each survey began by circling the reef on the outer perimeter and continuing circling over the central portion of the reef. Every coral was measured to the nearest millimeter along its major and minor axes and was identified to species in the laboratory. Corals that settled on natural substrata within 1m of the reef were also counted as a separate category. Basic physical parameters were also be recorded such as: visibility (estimated by the observations of the diver in meters), sea state (obtained from www.marineweather.com) and seawater temperature (measured by a SeaQuest Suunto dive computer with an accuracy of ± 2 °C). Each of these parameters can be found in Table 2. Observations of algal cover were also recorded and identified using the field guide: Marine Plants of the Caribbean, Littler et al. 1989 on the surface. The SCUBA diver swam above the reef and estimated algal cover by eye. All of these parameters can be found in Table 3.
3.4 Data arrangement

The raw data was arranged in three separate ways: number of coral / m², area of coral / m² and average area of coral in mm², for each reef. The two calculations (number of coral and area of coral per square meter) for this study were chosen so that the number and area of corals were standardized according to reef size. If this calculation would not have been done there would have been biased results favoring the larger sized reefs and an unfair comparison between reef types. The average area of coral measurement was done in order to see if there was a difference in the size of the corals located of the different reef types. Then the data was combined to compare between treatments. Therefore the weighted mean for each of the three types of reef was calculated. Based on this data an R² value was calculated to show whether or not the data was linear.

3.5 Statistical Analysis

The Kruscal-Wallis test was used to determine if there was a difference in the number of corals recruiting to the reefs. A non-parametric test was used because a parametric test makes certain assumptions about the nature of the distribution of the sampled populations that did not apply in this study (Zar 1996). For example, high variance and non-normality of data was expected due to the small sample size. This was the only test applied because the more tests that the data is put through, the greater the chance error in the analysis will occur. Every time a statistical method performed on a data set has a certain amount of error can occur, therefore the more tests done, the more likely experiment-wise error will result. The reason for the sample size being so small
was due to a limited number of trips to the site and that there was only one diver surveying the corals.

3.6 Survey of all 12 reefs

After the end of the yearlong study all 12 reefs were assessed following the same survey protocols. These two extra trips were to provide a larger sample size of each reef of type (n=4 vs. n=2).

3.7 Collection of corals

Corals were collected on May 29, 2001 to allow species identification. Each coral species was recognized by the SCUBA diver and removed from an artificial reef with a hammer and chisel. Tissues were removed with a 25% sodium hypochloride solution revealing the bare skeleton. Then the corals were studied under a dissecting microscope in lab and identified using identification book or journal articles (Humann 1998, Weil and Knowlton 1994 and Gosner 1978). Species identification was verified by Charles Messing (PhD. Nova Southeastern University) and Stephen Cairns (Smithsonian Institution).
4.0 Results:

4.1 Reef Size:

Although only two modules were surveyed for coral cover and diversity, all four were measured for size. The boulder reefs (228m$^2$) are on average larger than both the concrete tetrahedron reefs (152m$^2$) and concrete with tire aggregate tetrahedron reefs (162m$^2$). However there was no significant difference in the size of the reefs when analyzed by the Kruscal Wallis test, 0.25>p>0.10, n=4.

4.2 Number of corals /m$^2$

4.2.1 January – December 2000, n=2

At the end of one year one of the boulder reefs (B1) had the greatest number of corals with 0.43 corals/m$^2$ and one of the concrete with tire aggregate reefs (T4) had the lowest with 0.09 corals/m$^2$ (Figure 7). The greatest colony densities followed a general trend for the reefs: the boulders had the most, than the concrete tetrahedrons, followed by the concrete with tire tetrahedrons with the least. When the data was combined the boulder reefs had the largest number of recruits with an average of 0.37 corals/m$^2$, followed by the concrete tetrahedron reefs with an average of 0.21 corals/m$^2$ and then the concrete with tire aggregate tetrahedron reefs had the least with an average of 0.09 corals/m$^2$ (Figure 8). There was a significant difference among reef types, 0.05>p>0.025, n=2.

4.2.2 May 2001, n=4

Boulder reef one had the greatest recruitment with 0.505 corals/m$^2$ while concrete reef with tire aggregate three had the least with 0.053 corals/m$^2$ (Figure 9). When the
data was averaged the boulder reefs had the greatest number of recruits with 0.38
corals/m$^2$, followed by the concrete reefs with 0.17 corals/m$^2$ and then the concrete with
tire aggregate reefs with 0.10 corals/m$^2$ (Figure 10). However, there was no significant
difference among the three reef types, 0.5>p>0.25, n=4.

4.3 Area of coral /m$^2$

4.3.1 January – December 2000, n=2

The amount of coral coverage per square meter ranged from a low of 0.09 x
10$^{-4}$/m$^2$ on one of the concrete with tire aggregate reefs (T4) to the highest value of 2.53 x
10$^{-4}$/m$^2$ on one of the boulder reefs (B1) (Figure 11). When the data was combined the
boulder reefs had the largest amount of coverage with 2.21 x 10$^{-4}$/m$^2$, then the concrete
reefs with 1.03 x 10$^{-4}$/m$^2$, and finally the concrete with tire aggregate reefs with 0.73 x
10$^{-4}$/m$^2$ (Figure 12). However, differences among the reefs was not statistically
different, 0.10>p>0.05, n=2.

4.3.2 May 2001, n=4

Boulder reef one had the greatest amount of coral coverage with 5.54 x 10$^{-4}$/m$^2$
while concrete reef two had the least coverage with 5.66 x 10$^{-5}$/m$^2$ (Figure 13). When
the data was combined the coral coverage averages ranged from 4.21 x 10$^{-4}$/m$^2$ for the
boulder reefs, to 1.10 x 10$^{-4}$/m$^2$ for the concrete reefs and finally 0.82 x 10$^{-4}$/m$^2$ for the
concrete reefs with tire aggregate (Figure 14). There was no significant difference
between these values, 0.25>p>0.10, n=4.
4.4 Average area of coral (mm$^2$)

4.4.1 January – December 2000, n=2

At the end of the surveys one of the concrete tetrahedron reefs (C1) had the largest average size corals of 953 mm$^2$ while one of the concrete with tire aggregate tetrahedron reefs (T1) had the lowest average size of 198 mm$^2$ (Figure 15). When the data was combined the concrete reefs had an average of 785 mm$^2$ of coral cover and the concrete with tire aggregate had coral cover that averaged 619 mm$^2$, with the boulder reefs coral cover averaging the least with 603 mm$^2$ (Figure 16). The results of the Kruscal-Wallis test showed no statistical difference among the reef types, $0.75 > p > 0.50$, n=2.

4.4.2 May 2001, n=4

Concrete reef four had the largest average coral colony size with 1583 mm$^2$ while the concrete with tire aggregate one reef had the smallest with 569 mm$^2$ (Figure 17). Each reef type had varying sizes of corals that made it difficult to state which substrate had the greatest average size. When the data was compiled the boulder reefs had the largest average size with 1071 mm$^2$, followed by the concrete with tire aggregate with 976 mm$^2$ and lastly the concrete reefs 900 mm$^2$ (Figure 18). The results showed no significant difference between the reefs with a p-value of $0.9 > p > 0.75$, n=4.

A summary of these Kruscal-Wallis tests can be found in Appendix A.
4.5  Species Diversity

4.5.1  January – December 2000, n=2

Four coral species were found on the artificial reefs. *Solenastrea bournoni* was
pre-dominant, followed by *Cladocora arbuscula*, then *Dichocoenia stokesi* and
*Millepora alcicornis*. Each of the coral species were found on the boulder reefs. Three out of the
four species were found on the concrete with tire aggregate reefs and only two species
were observed on the concrete reefs (Table 4).

4.5.2  May 2001, n=4

The same four species were found on all 12 artificial reefs. *Solenastrea bournoni*
was predominant, followed by *Cladocora arbuscula*, then *Dichocoenia stokesi* and lastly
*Millepora alcicornis*. Each of the coral species were found on the boulder reefs. Three
of the four species were found on both the concrete with tire aggregate and concrete reefs
(Table 4).

4.6  Algal cover observations:

4.6.1  January 2000 – December 2000, n=2

During this period the algal coverage on the reefs was estimated between 30-60%
(Table 3).

4.6.2  May 2001, n=4

The algal coverage for the boulder reefs one, three and four was estimated
between 20-40%. This was different from boulder reef two which had 70-80% coverage.
The other reefs studied had an approximate algal cover between 20-50% (Table 3).
5.0 Discussion:

5.1 Natural vs. Man-made materials

In studies conducted by Fitzhardinge and Bailey-Brock (1989) and Palmer-Zwahlen and Aseltine (1994), natural substrata have been found to be the most favorable for corals and other invertebrates compared to man-made materials. According to Walton and Smith 1979, complexity is an important factor in artificial reef success. Complexity includes design, spatial arrangement, the number of chambers and openings and the amount of interstitial space (Bohnsack and Sutherland 1985). The boulders used in this study possessed crevices, holes or other cavities (Figure 2) that can increase spatial complexity allowing increased benthic diversity. Carelton and Sammarco (1987) found that this type of increased substratum complexity can provide more refuges than simpler substrata. It may also cause micro-turbulences that can influence larval settlement or reduce the foraging efficiency of predators once the corals have already settled. In contrast, the tetrahedron reefs were created from molds that cause them to be more uniform in texture and size (Figures 3 and 4) and possibly more difficult for corals and other benthic organisms to settle upon and inhabit. It has been suggested that increased complexity of substratum is associated with the distribution and abundance of sessile organisms (Bohnsack and Sutherland 1985). Many marine invertebrate larvae preferentially settle on irregular surfaces. Carelton and Sammarco (1987) demonstrated a significant correlation in the successful settlement of corals and increased structural complexity. They found that substratum complexity initially affects community structure by enhancing the number of species present. Then, as time progresses, biological structuring takes over and a benthic community develops as it would on a natural reef.
5.2 Tetrahedron comparison

When comparing the concrete tetrahedrons and concrete tetrahedrons with tire aggregate the concrete reefs had more coral recruits. These results also coincide with previous research by Hadfield (1986) and Fitzhardinge and Bailey-Brock (1989) that corals do not tend to recruit well on tires. Hadfield 1986 found that bacterial films that form on substrates induce settlement of corals and may not develop on tires. In this study one type of tetrahedron had tire aggregate mixed in with the concrete. This could be the reason why the concrete reefs had slightly more corals recruit than the concrete reefs with tire aggregate. Even though there was only a portion of tire in the tetrahedrons, it could have made the difference in the coral recruitment between the two types of tetrahedron reefs.

5.3 Fluctuations in data

Both the number of coral /m² and area of coral /m² calculations produced similar results. In the number of coral per square meter calculation the boulder reefs had more corals recruit to their reefs than the other tetrahedron reefs (Figure 7). The abundance of corals on the boulder reefs had nearly two or four times the amount of corals on the tetrahedron reefs. Comparable results followed for the area of coral per square meter. The boulder reefs had the most coral coverage with two to three times the coverage on the tetrahedron reefs (Figure 11). However, only the number of corals measurement was found to be significant. The linear relationship for both of these measurements can be found in Figures 8 and 12.
There was no significant difference found in the average coral area between any of the three artificial reef types. However, the boulder reefs were less variable in their average size than the tetrahedron reefs. The two types of tetrahedron reefs had variable average sizes, each had a large average size coral while the other reef of the same type had an unusually small average size coral. The boulder reefs had only a small difference in their average size corals (Figure 15). This average area calculation shows no difference in the size of corals recruiting to the three different artificial substrates. The largest corals recorded were found on all three types of artificial reefs. The linear relationship for this measurement can be found in Figure 16.

In order to make comparisons among the three different artificial reef types the data for each individual reef was averaged within three categories: boulders, concrete tetrahedrons and concrete tetrahedrons with tire aggregate. For the number of coral per square meter and the area of coral per square meter calculations the boulders had the greatest number of corals and coverage of all the artificial reefs. The average area of coral measurement shows that there is almost no difference between the artificial reefs in average colony size. However, the fluctuations in the graph, where the average size of corals drops substantially (Figure 12) can be attributed to the algal blooms, coral bleaching and possible predation.

When comparing coral recruitment to the different artificial reefs over the course of the year there were some fluctuations in the data between sampling months. These variations could have occurred because of a few different reasons. One reason was due to the algal blooms during the warmer months between May and August. On visual observations red and green algae such as: Laurencia, Halimeda and Codium covered
approximately 30-60% of the reefs during the summer months. When these blooms took place the algae covered up some of the corals making them difficult to count. If the small corals were covered up by the algae during these blooms, only the larger sized corals were counted, making the average size coral greater than it should have been. Even when the corals were found underneath the algae many of the corals were partially bleached. Another reason for the variance in the data could have been due to predation. Certain fish, such as parrotfish (Littler et al. 1989) or damselfish (Kaufman 1977), may have predated on the corals or benthic organisms could have outcompeted the corals on the reefs. Fairfull and Harriott (1990) studied successional changes in a fouling community on settlement patterns in a subtropical area. They found that algae and bryozoans were the first organisms to colonize the subtropical site. Subsequent successional patterns increased spatial recruitment by a diverse assemblage of flora and fauna. Corals than recruited in low numbers and had high post-settlement mortality rates. Fairfull and Harriott (1990) concluded that competition for settlement space with a fouling community may limit the success of coral recruitment. During this study estimations showed that some of the tetrahedron reefs contained more algae than the boulder reefs which could account for the greater abundance of corals. Certain studies (Glynn 1976, Kaufman 1977, Neudecker 1979 and Wellington 1982) have shown significant effects of corallivorous fishes on local distributional patterns of corals. Such predation by fishes may restrict the wider occurrences of some coral species if located in the area (Nuedecker 1979 and Wellington 1982). Littler et al. (1989) conducted a study on fish predation of reef building corals in a Caribbean back reef system. They found that the success of the corals was closely related to the low numbers of coral-eating parrotfish predators of the
genera *Scarus* and *Sparisoma*. This could be significant because these genera of parrotfish (identified by Brian Walker, NSU graduate student) were found on these artificial reefs in Miami Beach. However, more studies would need to be conducted to attribute the variations in corals on the reefs to parrotfish predation.

5.4 Statistical Analysis, January – December 2000, n=2

The data from the number of coral measurements was significant, 0.05>p>0.025, n=2. Meaning that there were significant differences in the number of corals among the artificial reef types. These results are similar to the Fitzhardinge and Bailey-Brock (1989) and Palmer-Zwahlen and Asletine (1994) studies which reported that natural materials are more favorable for coral recruitment than man-made structures.

The was no significant difference in the coral coverage between the reefs, 0.10>p>0.05, n=2. However, this p-value is only marginally non-significant. The coral coverage on the boulder reefs was higher than the tetrahedron reefs. A possible explanation why there was not a significant difference was the small sample size. With and increased sample size the difference in the data would have been more apparent, as long as the data stayed consistent.

When the average area of coral was analyzed the Krusal-Wallis test showed no statistical difference between the artificial reefs. Thus, all of the reefs contained similar sizes of corals. Larger corals did not favor a certain artificial substrate over any other. Coral settlement rates can be influenced by the local availability of larvae and if the larvae settle (Hunte and Wittenberg 1992). Certain studies (Harriott 1985 and Van Moorsel 1989) suggest that settlement rates are influenced by larval availability and
hence by the local abundance of adult corals. Then as the corals settle they are exposed to various environmental factors which affect their growth rate (Rice and Hunter 1992). Water temperature, light and food supply can influence the growth rate of corals (Tomascik and Logan 1990). In this study it is possible that since the artificial reefs were close enough to each other (20-30m) they all experienced similar environmental factors. This may explain why the artificial reef types average colony size did not vary much.

5.5 Assessment of all 12 artificial reefs, May 2001, n=4

After these tests were performed, and there was no significant difference among reef types, a decision was made to survey all twelve artificial reefs. This was done to increase the sample size to four reefs of each type rather than just two. As the sample size increases the sample will become a better estimate of the parameter it is estimating (Zar 1996). Over the course of the one-year study there was a large difference in boulder reefs B1 and B4 compared to the concrete tetrahedron reefs for coral recruitment. This decision to survey all twelve artificial reefs was to increase the sample size and see if the boulders continued to display similar results of higher coral recruitment.

The data for all 12 reefs produced similar results as the six artificial reefs previously surveyed. The boulder reefs seemed to follow the same trend as the most favorable substrate for coral recruitment. Both the number of coral recruits and coral coverage were greatest on the boulder reefs, with the exception of one boulder reef, B2. B2 was the only boulder reef that did not surpass all of the tetrahedron reefs in coral recruitment. Each of the boulder reefs, one, three and four, had a noticeable difference in
coral recruitment compared to all of the other tetrahedron reefs. There was not much of a
difference between either of the tetrahedron reefs in both of these measurements. The
main difference was comparing the boulder reefs to the tetrahedron reefs. When the
average area of coral was compared between the reef types, no real difference was found
in any of the three artificial reefs.

When the data was compiled there was a distinct trend of higher coral recruitment
on the boulder reefs compared to the tetrahedron reefs. The coral recruitment was
highest on the boulder reefs for every measurement. Coral recruitment (number of
coral/m²) nearly doubled that of the tetrahedron reefs and almost quadrupled the concrete
tetrahedrons with tire aggregate. The area of coral with the greatest coverage was on the
boulder reefs. The boulder reefs almost quadrupled the coverage of the concrete
tetrahedrons and had greater than five times the coverage of the concrete tetrahedrons
with tire aggregate reefs. From these two reef measurements it seemed that the boulder
reefs were the best substrate for coral recruitment. The average area of coral
measurement did not show any significant difference between the size of the corals and
the different substrates. However, the boulder reefs did have the largest average size of
coral out the three artificial reef types.

5.6 Statistical Analysis, May 2001, n=4

After these three calculations were completed for all 12 artificial reefs the
Kruscal-Wallis test was performed on each of them. None of the calculations for all 12
artificial reefs showed a significant difference. The increased sample size from two to
four artificial reefs did not produce a significant difference in coral recruitment.
5.7 Boulder reef two

5.7.1 Algal cover

An explanation why there was no statistical difference among the 12 artificial reefs was due to B2. Three of the other boulder reefs had higher recruitment and coverage than any of the tetrahedron reefs, however B2 had much less. There are a few possible reasons for this unusually low coral recruitment on boulder reef two. The estimation of algal cover (Table 3) showed that B2 was covered with 70-80% algal growth, mainly consisting of: *Laurencia*, *Halimeda*, *Codium* and *Caulerpa* (Littler et al. 1989). Whereas the boulder reefs one, three and four’s algal growth ranged from approximately 20-40%. This algal bloom could have covered up all of the corals or, outcompeted the corals for space on the reef. Some of the other reefs also experienced algal growth coverage from anywhere between 20-50%, but not to the same extent as B2. When the tetrahedron reefs with more algal growth were compared to the other tetrahedrons with less algal growth there was not as much of a difference as there was when boulder reefs two was compared to the other boulder reefs.

5.7.2 Location

The 12 artificial reefs were deployed in two parallel transects to the shore. One end of the transect began at the jetty. B2’s location was one of the two artificial reefs closest to the jetty (Figure 5). One of the hypotheses was that the reefs closer to the jetty would favor coral recruitment because the jetty already had established corals present. B1 was the other artificial reef near the jetty and it had the highest number of coral
recruits and the most coverage of any of the 12 reefs. However, B2 had one of the lowest numbers in coral recruitment. Thus, the relation of the artificial reef nearest to the jetty does not mean that these reefs have an advantage over the other reefs furthest from the jetty. Boulder reefs three and four were not near the jetty and both of these reefs had higher coral recruitment all of the tetrahedron reefs.

5.7.3 Circulation

Another explanation for low coral recruitment on B2 could be the circulation around the reef. B2 is located in an area that is adjacent to the jetty and along the parallel transect closest to the beach. This area might not receive a lot of circulation from nearshore currents. Certain inshore areas can either show patterns of stagnation or rapid flushing depending on the interaction of currents with reefal bathymetry (Andrews et al. 1988). Currents can affect the transport of coral planulae during their planktonic phase. Another possibility was that the coral eggs were transported off the reef by wind driven surface currents prevailing at the time of spawning (Babcock 1988).

5.7.4 Eutrophication

Eutrophication could also be a reason why coral recruitment is so low on B2. B2 is one of the reefs closest to the beach and could have been exposed to more runoff from the shore than other reefs. Corals are sessile organisms that are subject to the varying conditions of the surrounding environment. Therefore, coral communities under eutrophic conditions must depend on the relative success of coral species which both as adults and larvae can tolerate reduced water quality and secondary effects associated with
eutrophication processes. For example, turbidity which reduces light intensity and
sometimes increases nutrient concentrations can promote benthic invertebrate
assemblages which inhibit coral growth (Tomascik 1991). There is strong possibility of
this based on the fact B2 showed large amounts of algal growth cover.

5.7.5 Fish predation

Another possible reason for the low number of corals found on B2 could be due to
fish predation. Certain species of fish, which are considered herbivores, have been
known to predate on corals. In studies conducted by Littler et al. (1989) and Miller and
Hay (1998), they have found direct predation on coral by parrotfishes. Miller and Hay
(1998) reported that the grazing of the parrotfish is not generalized. The grazing
depended greatly on the coral species, location and parrotfish species. Sometimes the
coral transplants by Miller and Hay (1998) on cinder blocks were consumed rapidly
while those transplanted only a few meters away did not appear to be grazed upon as
much or at all. This could be related to this study because of the close proximity of the
12 artificial reefs (approximately 30m) and the presence of parrotfish on the reefs.
Meaning, B2 could have been a reef subjected to the grazing of parrotfish while the other
reefs were either minimally grazed upon or left untouched. This would correspond with
the findings of the Miller and Hay (1998) study.

5.7.6 Allelopathic effects

A final explanation as to why boulder reef two did not recruit as many corals is
allelopathic effects. Many plants and animals in terrestrial, freshwater and marine
environments produce secondary metabolites which can be used as chemical signals between interacting species. When released into the environment, these secondary metabolites can either promote or inhibit other organisms sharing the same habitat. The inhibitory influences are termed allelopathy (Rice 1984 and Gauthier and Aubert 1981). Certain species of alcyonaceans are known to release toxins (Coli et al. 1982) which can act as allelopathic agents in competitive interactions with nearby scleractinian corals (Sammarco et al. 1983). Coll and Sammarco (1983) established that certain secondary metabolites cause tissue necrosis and mortality in scleractinian corals in the laboratory. This is not saying that these specific organisms are located on boulder reef two, but some other organisms could be reducing coral recruitment through allelopathic agents.

5.8 B2 as an outlier

B2’s low recruitment could have made the difference between the boulder and the tetrahedron reefs statistically non-significant. Therefore, B2 was considered an outlier and excluded from the analysis. Both the number of coral and area of coral per square meter differences between the reef types became significant $0.01 > p > 0.005, n=3$. Thus, if B2 is considered an outlier the boulder reefs were the most favorable for coral recruitment by a statistically significant margin.

5.9 Summary

In general, the boulder reefs were the most favorable substrate for coral recruitment. Even though the Kruscal-Wallis test only showed significance for one of the tests there was still a definite trend favoring the boulder reefs for coral recruitment.
However, without the inclusion of B2 a more definitive statement can be made as to which substrate was the best for coral recruitment.
6.0 Conclusion

Based on the results gathered in this study the boulder reefs seemed to be a better artificial substrate for coral recruitment compared to concrete and concrete with tire aggregate tetrahedrons. The boulder reefs had more coral recruits than either other reef type in the 12 month study (January – December 2000). There were significantly more corals per square meter, \(0.05 > p > 0.025\), \(n=2\), and the coral coverage was only slightly non-significant, \(0.10 > p > 0.05\), \(n=2\), among reef types for the one year study. However, when all 12 artificial reefs were surveyed in May 2001 neither the number of corals, \(0.50 > p > 0.25\), \(n=4\), or the coral coverage, \(0.25 > p > 0.10\), \(n=4\), were significant. B2’s low recruitment was inconsistent with the other boulder reefs and caused the data analysis to be insignificant. When B2 was treated as an outlier the number of coral and the coral coverage were both found to be significant, \(0.025 > p > 0.01\), \(n=3\). Thus, the boulder reefs were the best substrata for coral recruitment in the early stages of artificial reef development with the exclusion of B2.

6.1 Recommendations

Recommendations for future artificial reef development would be to use boulders as the building material. However, these artificial reefs should be monitored in following years to see which reef material favors coral recruitment in the long-term development of the reefs.
Quantification Measurements for Artificial Reefs in Miami

<table>
<thead>
<tr>
<th></th>
<th>Circumference</th>
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<th>Right side of apex</th>
<th>Left side of apex</th>
<th>Width</th>
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<tbody>
<tr>
<td>B1</td>
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<td>1.55</td>
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<tr>
<td>B2</td>
<td>29.9</td>
<td>2.00</td>
<td>1.60</td>
<td>1.70</td>
<td>8.53</td>
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<tr>
<td>B3</td>
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<td>2.40</td>
<td>2.00</td>
<td>2.10</td>
<td>7.85</td>
</tr>
<tr>
<td>B4</td>
<td>23.9</td>
<td>2.60</td>
<td>1.50</td>
<td>1.60</td>
<td>7.92</td>
</tr>
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<td>2.40</td>
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<td>1.90</td>
<td>1.30</td>
<td>1.40</td>
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</tr>
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<td>C4</td>
<td>23.0</td>
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<td>0.95</td>
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<td>T4</td>
<td>24.2</td>
<td>1.70</td>
<td>1.20</td>
<td>0.90</td>
<td>8.23</td>
</tr>
</tbody>
</table>

* All measurements are in meters

Table 1: Reef measurements of the boulder (B1-B4), Concrete-gravel aggregate (C1-C4) and Concrete-tire aggregate (T1-T4) reefs taken in June 2000.

<table>
<thead>
<tr>
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<th>Physical Variables</th>
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<tbody>
<tr>
<td>Conditions</td>
<td>2/17/00 4/21/00 6/6/00 8/15/00 10/30/00 12/8/00 5/18/01 5/29/01</td>
</tr>
<tr>
<td>Wind (mph)</td>
<td>10-15 5-10 &lt;10 5-10 10 12-15 2-5 5-10</td>
</tr>
<tr>
<td>Visibility (m)</td>
<td>3-4 6-7 6-7 9-10 &lt;3 6-7 8-9 3-4</td>
</tr>
<tr>
<td>Seas (m)</td>
<td>&lt;1 &lt;1 &lt;1 &lt;1 &lt;1 &lt;1 &lt;1 1-2</td>
</tr>
<tr>
<td>Temp. (°F) - Water</td>
<td>73 73 76 81 74 75 80 79</td>
</tr>
<tr>
<td>Temp. (°F) - Air</td>
<td>79 78 82 86 79 80 88 85</td>
</tr>
<tr>
<td>Tide</td>
<td>Low High to Low High to Low High to Low High to Low High to Low High to Low High to Low</td>
</tr>
</tbody>
</table>

Table 2: Physical variables recorded for each day of reef assessment.
### Table 3: Algal cover observations on the artificial reefs for January 2000 – December 2000, n=2 and May 2001, n=4.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=2</td>
<td>n=4</td>
</tr>
<tr>
<td>All reefs - 30-60%</td>
<td>B1, B3, B4 - 20-40%</td>
<td>B2 - 70-80%</td>
</tr>
<tr>
<td></td>
<td>Other reefs - 20-50%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: Species found on the artificial reefs between January 2000 – December 2000, n=2 and May 2001, n=4.

<table>
<thead>
<tr>
<th>Species</th>
<th>All 12 Reefs</th>
<th>6 Reefs - One year study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boulder</td>
<td>Concrete</td>
</tr>
<tr>
<td>Solenastrea boumoni</td>
<td>62.5%</td>
<td>71.0%</td>
</tr>
<tr>
<td>Cladocora arbuscula</td>
<td>31.8%</td>
<td>26.5%</td>
</tr>
<tr>
<td>Dichocoenia stokesi</td>
<td>2.5%</td>
<td>-</td>
</tr>
<tr>
<td>Millepora alcicornis</td>
<td>3.2%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>Boulder</th>
<th>Concrete</th>
<th>Concrete w/ tire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenastrea boumoni</td>
<td>77.5%</td>
<td>69.2%</td>
<td>63.9%</td>
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<tr>
<td>Cladocora arbuscula</td>
<td>18.7%</td>
<td>30.8%</td>
<td>30.6%</td>
</tr>
<tr>
<td>Dichocoenia stokesi</td>
<td>2.2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Millepora alcicornis</td>
<td>1.6%</td>
<td>-</td>
<td>5.5%</td>
</tr>
</tbody>
</table>
Figure 1: Reef deployment June 18, 1998. Photograph shows deployment of a concrete-gravel aggregate tetrahedron module.
Figure 2: Limestone boulder reef module, pre-deployment

Figure 3: Concrete-gravel tetrahedron reef module, pre-deployment.
Figure 4: Concrete-tire aggregate tetrahedron reef module, pre-deployment.
Figure 5: Artificial Reef Array, 200m offshore, and 100m north of Government Cut, Miami, FL., 100m apart in 7m depth.
Figure 6: Reef site map with coordinates plotted on NavTrek™.
Number of Corals Recruiting to Various Substrates, Miami Beach FL

Figure 7: Number of corals per square meter found on artificial reefs in Miami Beach, FL
Combined Data of the Number of Corals Recruiting to Various Substrates, Miami Beach, FL

Figure 8: Average number of corals recruiting to each artificial substrate in Miami Beach, FL, over one year, n=2.
Number of Corals Recruiting to Various Substrates in May 2001, Miami Beach, FL

![Bar graph showing the number of corals per square meter found on artificial reefs in Miami Beach, FL, in May 2001, n=4.](image)

Figure 9: Number of corals per square meter found on artificial reefs in Miami Beach, FL, in May 2001, n=4.
Combined Data for all 12 Reefs of the 
Number of Corals Recruiting to Various 
Substrates in May, 2001, Miami Beach, FL

Figure 10: Average number of corals recruiting to each artificial substrate in Miami Beach, FL, in May 2001, n=4.
Figure 11: Area of corals per square meter on artificial reefs in Miami Beach, FL, for one year, n=2.
Combined Data from Various Substrates Showing the Area of Corals, Miami Beach, FL

Figure 12: Average area of corals per square meter on three different substrata in Miami Beach, FL over one year, n=2.
Figure 13: Area of corals per square meter in Miami Beach, FL, in May 2001, n=4.
Combined Data for all 12 Reefs from Various Substrates Showing the Area of Corals in May 2001, Miami Beach, Fl

![Bar graph showing the average area of coral per square meter on three different substrata in Miami Beach, FL, May 2001, n=4.]

Figure 14: Average area of coral per square meter on three different substrata in Miami Beach, FL, May 2001, n=4.
Figure 15: Average area of corals calculated on each artificial reef in Miami Beach, FL for one year, n=2.
Combined Data of the Average Size of Coral Colonies, Miami Beach, FL

Figure 16: Average size of corals on each artificial reef type in Miami Beach, FL for one year, n=2.
Average Size of Coral Colonies in May 2001, Miami Beach, FL

Figure 17: Average area of corals calculated on each artificial reef in Miami Beach, FL, in May 2001, n=4.
Combined Data for all 12 Reefs of the Average Size of Coral Colonies in May 2001, Miami Beach, FL

Figure 18: Average size of corals on each artificial reef type in Miami Beach, FL, in May 2001, n=4.
References:


Appendix A

Kruskal-Wallis Test

1. Rank all observations from smallest to largest when pooled together into a single sample. When there are ties, compute the average ranks.
2. Replace each observation in the original data table by its rank or average rank.
3. Sum the ranks separately for each group. Enter in row \((\Sigma n_i R)_i\)
4. Compute Expression listed below. The number 12 and 3 are constants

\[
H = \frac{12}{(\Sigma n_i)(\Sigma n_i + 1)} \left( \sum \left( \frac{R_i^2}{n_i} \right) - 3 \left( \Sigma n_i + 1 \right) \right)
\]

For example:

The number of coral per meter squared for the one-year study.

Step 1.

B1 - 0.431...Rank 1
B4 - 0.259...Rank 2
C1 - 0.249...Rank 3
C2 -0.111...Rank 4
T4 -0.095...Rank 5
T1 - 0.092...Rank 6
Step 2.

<table>
<thead>
<tr>
<th>Boulder reefs</th>
<th>Concrete reefs</th>
<th>Concrete w/tire reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bl-1</td>
<td>C1-3</td>
<td>T4-5</td>
</tr>
<tr>
<td>B4-2</td>
<td>C2-4</td>
<td>T1-6</td>
</tr>
</tbody>
</table>

Step 3.

Total = 3 7 11

Step 4.

\[
H = \frac{12}{6(6+1)} \left( \frac{3^2 + 7^2 + 11^2}{2} \right) - 3 (6+1) \]

\[
= \frac{12}{6(6+1)} \cdot \frac{195}{2} - 3 (6+1)
\]

\[
= \frac{12}{6(6+1)} \cdot 97.5 - 3 (6+1)
\]

\[
= 4.5
\]

Confidence Interval = 80 - 90%

*Each data set for every measurement was computed this way.*