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University of Miami
Reef Coral Rehabilitation and Research Project:
Land-Based Propagation Facility for Ecologically Important Reef
Corals

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Efficacy of Coral Nurseries for Reef Restoration in South Florida

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Abstract

Coral reef degradation is a worldwide phenomenon. Catastrophic natural events such as coral bleaching and increased prevalence of disease combine with man-made disturbances such as increased siltation, the harvesting of corals for the aquarium trade, and an increased frequency of ship groundings to produce a global problem. Pressures like these have impacted the Florida Keys with loss of coral cover and decreases in overall reef health. The purpose of this project was to assess the effectiveness of two different coral nurseries as a means of providing replacement corals for damaged reef areas and to introduce several new methods for successful coral culture. In June of 1999, colonies of *Montastraea faveolata* were collected at the site of a boat grounding in Biscayne National Park. In February of 2002, six donor colonies were retrieved and cut into 2 cm square fragments. Each piece was fitted with an electronic PIT tag and affixed to a PVC post. One-half of the new fragments were left *in situ*. The other half were brought to a shore-based coral nursery at the University of Miami Experimental Fish Hatchery. Growth was monitored periodically. After nine months, both field-deployed and laboratory corals demonstrated healthy growth but the laboratory corals were growing at a significantly faster rate. These results indicate that environmental parameters in shore-based coral growing facilities can be adjusted to the point that corals grow as fast or faster than those in the wild. Also, shore-based facilities can be used to

nurture damaged corals through critical healing stages before their re-deployment to the affected area.

Introduction

There is an acute need for the establishment of coral nurseries worldwide: as triage facilities to rescue corals damaged by ship groundings, as a source for new explants for reef restoration efforts, and as a source of material for laboratory physiology experiments. Research into this topic has been ongoing for many years. Transplantation of whole colonies and colony fragments has been widely studied as a means of reef restoration and is the method with the highest potential for success (Becker and Mueller 2001).

Fragmentation is a natural means of reproduction in many coral species (Highsmith 1982). The modular body plan of most corals makes artificial fragmentation a practical method for generating large numbers of animals from single donor colonies. Over the past decade, tremendous progress has been made in coral husbandry. New technologies, a better understanding of coral physiology, and a deeper knowledge of the nutritional and environmental requirements of these sensitive animals have paved the way for the success of captive rearing programs. Careful observation and attention to detail have increased our understanding to the point where growth rates of captive corals are on par or even exceed maximum natural growth rates (Calfo 2001). The number of species successfully held in captivity has increased exponentially to the point where nearly all scleractinians can thrive in artificial conditions with only a few notable exceptions, such as members of the genus *Goniopora* (Borneman 1997).

Corals are long-lived animals, yet waiting for natural recruitment to replace damaged reef areas is impractical due to slow growth, long generation times, and poor recruitment to loose rubble and algal-covered substrate. In cases of localized physical damage, such as that caused by ship groundings, the most effective means of resolving the problem may be to collect broken colonies and colony fragments and bring them to a triage facility. After a suitable period of recovery, these colonies could be brought back to their original location and cemented into place. At the same time, the triage facility could be a source of new explants for other reef restoration efforts.

Land-based facilities for the asexual production of interesting specimens for the aquarium trade have been sprouting up across the world, sometimes far from any source of salt water (e.g., Tropicorium in Illinois, Geothermal Aquaculture Research Facility in Idaho, Inland Aquatics near Chattanooga). The Waikiki Aquarium and the Monaco Aquarium have active coral propagation and growth programs. These represent the state of the art in the industry and their success indicates a potential role for similar facilities developed specifically to cater to the needs of reef restoration.

Biscayne National Park and the Coral Aquaculture Program (CAP) at the University of Miami have worked in cooperation to design a facility to fill that role. Using field- and land-based nurseries, corals damaged by ship groundings within the park can be moved immediately to an inshore coral triage area where they are stabilized and given time to recuperate. Once stabilized, the colonies are partially or entirely fragmented and brought to the CAP facility where growth of colony fragments can be monitored and enhanced by maintaining optimal light, temperature, and nutrition parameters. After the

fragments have been grown to a specific size, they can be returned to the triage area for re-acclimation to natural conditions before outplanting (Figure 1).

This process is important in several respects. First, it enables a rapid response to boat groundings. Colonies and colony fragments that cannot be set upright again can be moved immediately to a predetermined area for recuperation. Second, it provides a method to generate multiple second-generation colonies in a minimum amount of time via fragmentation and growout in a controlled environment. Third, it increases the number of healthy corals available for outplanting back to the original area of damage.

Methods

System Design:

The CAP experimental coral rehabilitation facility is a recirculating, partial exchange seawater system currently with a series of 2m x 0.5m x 0.5m fiberglass tanks (470 liter capacity each) and a 1100 liter sump. Replacement seawater is drawn from Bear Cut, a tidal channel between the Atlantic Ocean and central Biscayne Bay near the city of Miami, Florida. Before being added to our system, this water is sequestered for approximately one hour in settling tanks then passed through sand filters. This effectively removes all particles >50 microns.

Water Flow: Within the system, seawater recirculation is accomplished by a 3/4 hp Little Giant pump, producing a flow rate of 25 gpm. The entire water volume is turned over approximately once every 10 minutes. Each experimental tank is fitted with 6 individually regulated seawater nozzles. This provides an adjustable and directional flow

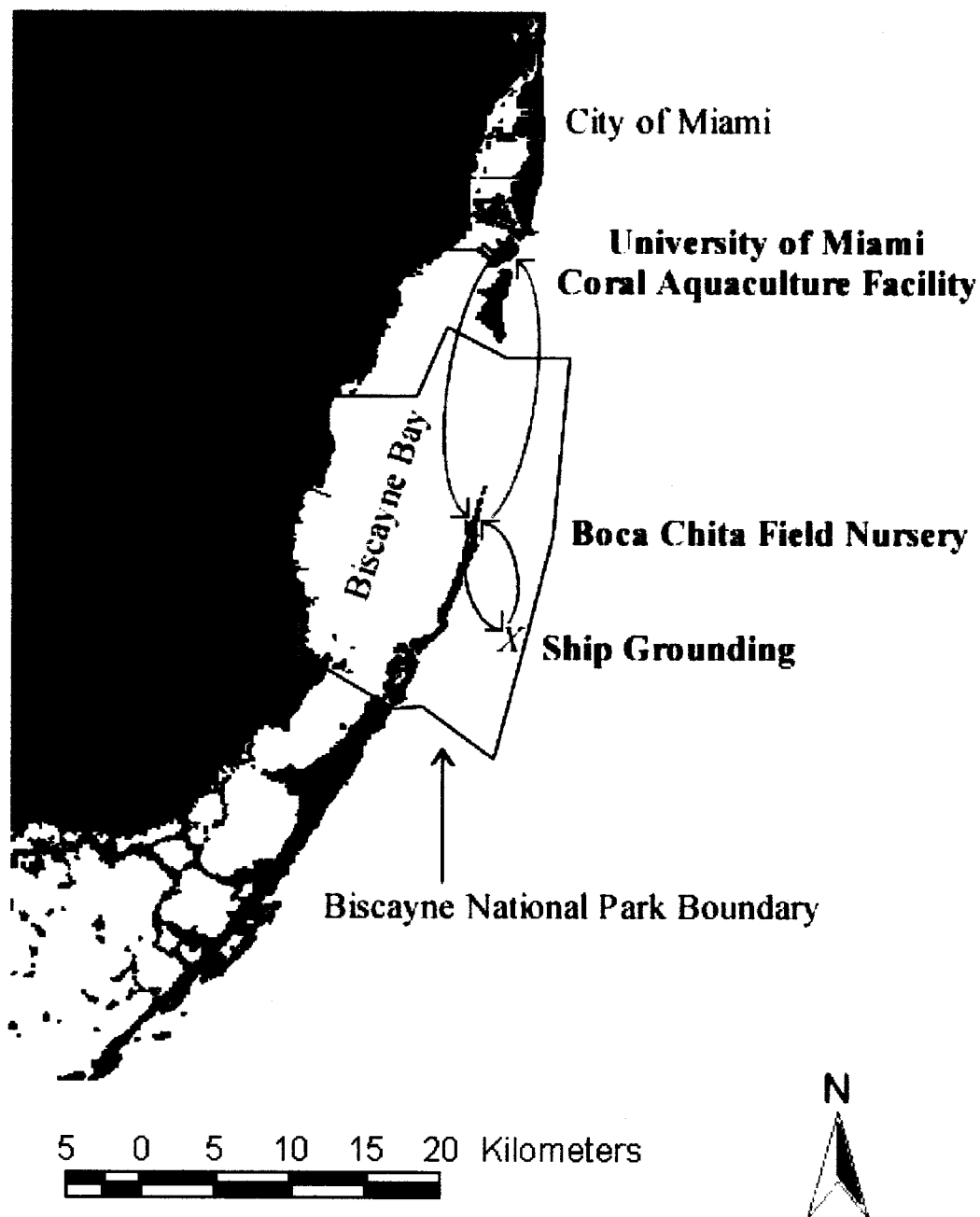


Figure 1: Site Map. After a ship grounding within Biscayne National Park, damaged corals are moved to the Boca Chita Field Nursery where they are stabilized and allowed time to recover. Selected corals are then fragmented and brought to the University of Miami Coral Aquaculture Facility on Virginia Key. After the fragments grow to a suitable size, they can be brought back to the Boca Chita Nursery for re-acclimation to natural conditions before outplanting at the original site of damage.

to keep the floor of the holding tanks clean while supplying an appropriate current for supporting coral growth.

Temperature control: During winter months, water temperature is controlled by two 1 kW submersible titanium heaters (Cleeco, Inc.) located in the system sump. This effectively holds temperatures to $22\pm0.5^{\circ}\text{C}$. During the warmer months, water temperature can be regulated by simply reducing the volume of makeup water entering the system and allowing the building air conditioning to take care of the solar heat load on the outdoor sump. This keeps maximum summer temperatures around $26\pm1^{\circ}\text{C}$.

Lighting: Above each tank, two "ultra-actinic" and two "daylight" Power Compact fluorescent bulbs (96 Watt each) provides 300 μE of illumination at the water surface (150 – 200 μE at coral level). The day:night cycle is maintained at 12:12 hours by commercially available timers which are also programmed to come on and off in sequence, creating a "twilight" of blue light every morning and evening.

Salinity Control: The makeup water entering our system is significantly influenced by Biscayne Bay, a shallow body of water adjacent to the city of Miami. During the dry season (November - May), this does not cause any difficulties. However, during the peak of the rainy season (June - July) salinities can drop to 30 or less. We maintain the salinity of our system during these times by diverting the makeup water into 1100 liter holding tanks. When full, salinity is adjusted to 35 with synthetic sea salt (Instant Ocean[®]) before being slowly trickled into the sump. This is done twice weekly.

Ph Control: Replacement seawater provides the major compounds (trace minerals, calcium, etc.) necessary for maintaining the appropriate growth environment

for coral fragments and nubbins. In addition, the present system is equipped with a CO₂-aragonite reactor to stabilize pH, elevate the concentration of carbonate ions, and provide additional solubilized aragonite.

Algae control: We stock the coral tanks with *Diadema antillarum* sea urchins and several species of herbivorous snails. The *Diadema* were raised from larvae during another project at our facility and have grown in the coral tanks (Capo *et al.*, in prep). Presently, there are 10 individuals 25 mm - 50 mm in each aquarium (~5/m²). They keep the coral margins free of algal growth, diatoms being the most pernicious, and keep the coral stands free of crustose coralline algae that would otherwise affect monthly weight measurements.

The field nursery is situated in 4 m of water in a tidal channel on the north side of Boca Chita (Island) connecting South Biscayne Bay to the Atlantic Ocean. Currents are strong in this channel with twice daily reversals. Outgoing tides are cooler in the winter and warmer in the summer than incoming tides due to Biscayne Bay more closely tracking atmospheric temperatures than the open ocean. Salinity and turbidity also fluctuate. Three coral "pyramids" were constructed by tying the ends of 1.5m x 0.2m x 0.2m limestone posts together and standing them upright underwater. These posts were predrilled with holes spaced 0.2m apart for the insertion of the PVC rods to which the corals were affixed.

In June of 1998, large fragments of *Montastraea faveolata* (Ellis and Solander 1786) were collected in Biscayne National Park, Florida, USA after a ship grounding and moved to the field nursery. The fragments were stabilized and allowed to grow for a

period of three years. In February of 2002, five of the colonies were retrieved for fragmentation. Colonies were kept in shaded bins filled with seawater on the boat deck before being cut into approximately square fragments (4.24 cm^2 average) with an electric ceramic tile saw. Each fragment was weighed on an electronic balance (accuracy $\pm 0.1 \text{ g}$) and the volume of each was calculated by measuring water displacement in a graduated cylinder. The fragments were affixed to 0.5" PVC dowels with marine epoxy (Z-Spar brand). A Passive Integrated Transponder electronic ID (or PIT Tag) was inserted into the epoxy while attaching each coral, giving every colony a unique 10 digit alphanumeric code that could be read with an Avid "Power Tracker II" electronic tag reader. The corals were then placed in bins filled with seawater containing 10 mg/l alizarin red (Dustan 1975). After 1.5 hours, the affixed and stained corals were reweighed and the volume remeasured. The donor colonies were returned to the nursery area. One-half of the fragments were placed on the limestone pyramids within the nursery area. The remaining fragments were placed in air-filled plastic bags with a small amount of water to keep the coral tissues from drying out. They were transported in a cooler to the CAP experimental coral rehabilitation facility and placed in one of the coral holding tanks.

After two days, the corals were weighed on a Metler 3600 electronic balance (accuracy $\pm 0.01 \text{ g}$) both while submerged ("buoyant weight") and in air after shaking off excess water ("air weight"). The two methods of determining weight were used to check for the accuracy and applicability of each for laboratory measurements. Digital photographs were taken of each fragment in order to measure surface area and to have a record of individual growth patterns over time.

The initial surface area of each coral fragment was calculated using two different methods. First, by measuring the dimensions of each fragment with a pair of calipers, assuming each piece was flat and approximately rectangular, and using simple geometry. On March 21, 2002, a photograph was taken of each fragment using a digital camera. The camera position was fixed in order to maintain the camera-coral distance and a ruler was included in each frame. A computer program for measuring the area of a manually selected portion of a digital image was written by R. Carter in Visual Basic (Microsoft) and used to calculate the surface area of each fragment from its digital image. The ruler in each frame was used to calibrate the number of pixels per centimeter. The number of polyps on each fragment was counted on each animal and in each image to the nearest half-polyp.

Due to lateral growth of tissue margins, the final surface areas were calculated using the aluminum foil technique (Marsh 1970). Duplicate measurements were made of each animal. The final surface area measurements were performed after all weight data was collected because it was felt that the stress of being exposed to air for several minutes while being repeatedly covered in aluminum foil would negatively affect growth for several days to weeks.

The corals in the land-nursery were fed a diet of freshly hatched *Artemia salina* nauplii, frozen *Artemia* adults, and blood worms by hand and they were able to capture various particulates and small organisms circulating within the aquarium system. The corals in the field-nursery fed naturally on any particulate material they could capture in the current.

After three months of acclimation, a four-month feeding trial was performed on the laboratory corals. Corals were randomly assigned to one of two groups, fed and unfed, and then placed in random order in a single experimental tank. Assigned animals were fed daily using a turkey baster to place food directly onto the animals' surface. A gentle stream of water was used to remove stray food particles from the surface of corals assigned to the unfed group.

Buoyant and air weight data were collected for the lab-corals monthly, totaling 10 measurements over 269 days. Three trips were made to the field-nursery to collect weight data. Two-way repeated measures ANOVA (SigmaStat, Jandel Scientific) was performed on the data after square root transformation using date and location as factors. Tukey's multiple comparison procedure was used to calculate significant differences (pair-wise) between each growth period. For the feeding experiment, two-way repeated measures ANOVA was performed using date and feeding status as factors.

Results

All corals relocated to the land-nursery survived. No signs of disease appeared, and, besides the death of some marginal polyps that had been damaged in the cutting process, no tissue necrosis was evident. After three months in the field-nursery, one coral died *in situ*, and another showed significant tissue loss. After six months in the field nursery, an additional 4 colonies disappeared and the colony in poor health died, leaving four missing and two dead colonies at the end of the experiment, a 23% mortality rate.

The corals in the land-nursery showed an initial weight increase over the first month but no sign of growth for the next two months. Corals in the field-nursery did not

grow significantly over the first three months but did display healthy growth for the remaining summer months. After this three month recovery and acclimation period, growth was significant for both sets of animals with new tissue encrusting the epoxy and vertical growth of the colony center. Month-to-month weight increases were significant for both laboratory and field corals ($p < 0.001$, 2-way RM ANOVA), though there was no significant growth until the fourth month (Tukey's). Growth in the laboratory was significantly greater than in the field ($p = 0.004$, 2-way RM ANOVA). There was a significant interaction between location and date ($p = 0.002$), indicating that the rate of growth was increasing faster in the laboratory than in the field.

Average weight increase (g) over the entire experimental period, average growth (g/d), and maximum growth (g/measuring period) for laboratory and field corals are given in Table 1. Growth rate data (mg/cm²/day) using the three different surface area calculations for the laboratory corals are given in Table 2. Weight data for field and laboratory corals are reported in Figure 2.

Table 1: Growth Data for Field and Laboratory Corals

Location	Initial n	Final n	Average Weight Increase (g)	Average Growth (mg/day)	Maximum Growth (mg/day)
Laboratory	27	27	3.87 +/- 1.49	13.88 +/- 6.18	33.94 +/- 17.62 Jul 31 - Aug 11
Field	26	20	2.45 +/- 1.08	9.66 +/- 4.47	15.16 +/- 7.17 May 25 - Aug 17

Table 2: Growth Rates (mg/cm²/day) of Laboratory Corals

Surface Area Method	Total (269 days)	Post-Acclimation (174 Days)	Maximum Jul 31 - Aug 11
Geometric (initial)	3.01 +/- 1.14	3.82 +/- 1.48	6.97 +/- 3.67
Photo (initial)	3.42 +/- 1.33	4.32 +/- 1.61	8.12 +/- 4.35
Aluminum Foil (final)	1.00 +/- 0.21	1.26 +/- 0.24	2.48 +/- 1.35

Using the initial surface area of the laboratory corals as an estimate for the average field coral surface area, growth of the field corals would be approximately 1.53 mg/cm²/day with a maximum of 2.28 mg/cm²/day between May 25 and August 17.

There was no statistically significant difference in the growth rates of the fed and unfed laboratory corals during any of the measurement periods ($P = 0.605$).

Discussion

There are few published experiments that report growth data for *M. faveolata* as weight change normalized to surface area. Most earlier studies used skeletal extension as a measure of growth rate. For the studies that did report weight changes normalized to surface area, most of those did not discriminate between the three sibling species within the *Montastraea annularis* species complex (Carricart-Ganivet *et al.* 2000). Considering this, Carricart-Ganivet *et al.* (2000) reported growth rates between 1.8 mg/cm²/d and 4.3 mg/cm²/d for *M. annularis* and/or *M. faveolata* in the field using data from various papers.

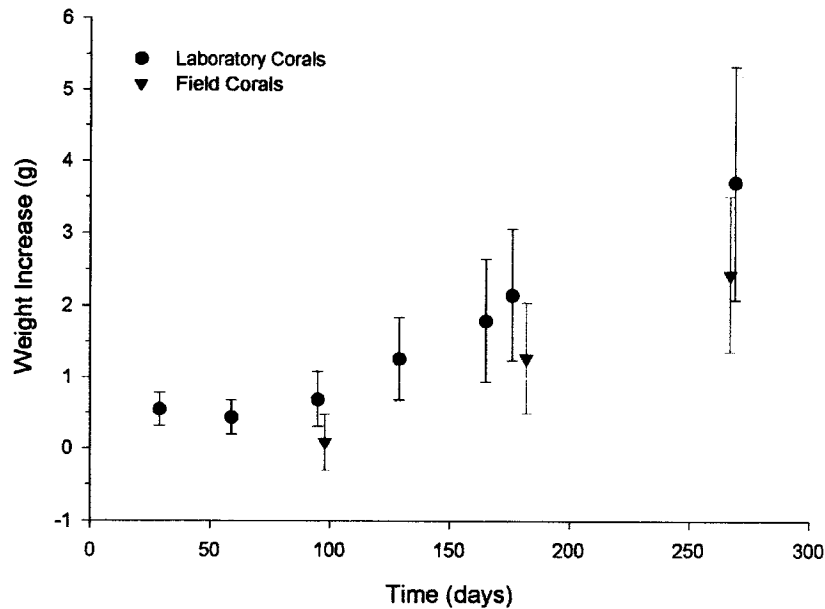


Figure 2: Growth of laboratory and field corals over 269 days reported as weight change from initial measurement. Note the three month acclimation and recovery period from the time of cutting before active growth resumed. Laboratory corals grew significantly faster than field corals.

Comparisons of growth rate between the various studies that report growth per day per square centimeter are even more difficult due to the fact that surface area changes over the course of the experiments. If one normalizes the data from Becker and Mueller (2001) to starting surface area, one obtains a growth rate of 1.82 mg/cm²/day for *M. faveolata* growing in the laboratory and 1.76 mg/cm²/day for the same corals after one year in the field. These are at the low end of the range reported by Carricart-Ganivet *et al.* (2000).

After normalizing the growth data for the laboratory corals used in this study to initial surface area, the values obtained for *M. faveolata* growing in the laboratory are at the high end of the range reported by Carricart-Ganivet *et al.* (2000) with maximum growth rates nearly double the largest values given. Normalized to final surface area, the laboratory corals in this study grew at approximately the same rate as those in Becker and Mueller (2001), although this is not the best comparison.

The laboratory corals took several months to recover from fragmentation and adjust to the new conditions. After that, growth was significant and the rate of growth increased over time (Figure 2). This suggests that the corals used stored energy reserves to repair damaged tissue and deposit some new skeletal material. However, that energy store was limited and it took several additional months to fully acclimate to the light, temperature, and other laboratory parameters before active growth could resume.

Meesters *et al.* (1994) reported a depression of calcification in experimentally damaged *M. faveolata* colonies lasting at least 56 days, the length of the study. Of course, they only waited three weeks from the time of fragmentation to start their study. They also did not collect weight data during the recovery period. We would caution any person using corals in manipulative experiments to give the animals sufficient time to adjust to the experimental conditions. This is especially true if the animals have been recently fragmented. Without long-term growth history data for the experimental animals, it would be nearly impossible to attribute experimental results to any particular treatment.

Growth of the field corals was not as rapid as the laboratory corals. These results indicate that environmental parameters can be controlled in laboratory situations to the point where corals will grow at least as fast as those in nature. However, laboratory

culture costs more and there is a greater reliance on critical components (e.g., pumps, pipe fittings, etc.). Yet even though field culture may be less costly and less technology-dependent, there is an increased risk associated with environmental perturbations (e.g., storms, cold and warm water events, predation, etc.). Thus the high mortality of the field corals in this experiment.

The four-month feeding experiment did not produce any significant differences between the fed and unfed corals. This may have been due to many factors: poor food choice (*Artemia* is not a natural prey item), poor food quality, inability to ingest food particles due to large size, or scavenging by sea urchins. The unfed corals may have also been able to pick up small particles of food during feeding times. Or, the amount of available food items (particulates, small organisms) in the water column may have been sufficient to supply the needs of both sets of corals and so feeding was unnecessary. The feeding needs of any aquacultured organism is important to understand and this subject will be explored more in the future.

Experiments with smaller colonies (unpublished data) did indicate that below a certain minimum size, fragmented animals become much more difficult to successfully cultivate. The corals used in this study averaged 4.24 cm². This is in agreement with the 1" (5 cm²) minimum suggested by Becker and Mueller (2001).

Becker and Mueller (2001) also reported problems with coral disease. During the initial building and design period, we had several episodes of coral disease while working with test colonies of *M. faveolata*. The disease process involved a rapid tissue necrosis starting at the lower margins of the affected colony. A single colony could die within a matter of days but several colonies survived long periods of slow necrosis. As a last

resort, a freshwater rinse was used to wash away dead tissue. This halted disease progression in several instances but the corals did not recover active growth and eventually died.

We believe the problem was due to a buildup of diatoms or another alga that caused the tissue loss. Disease appearance seemed to be reduced by properly maintaining lighting, current, and salinity but the largest factor was the use of *Diadema antillarum* sea urchins. The disease disappeared after addition of sufficient numbers of laboratory-reared *Diadema*. The *Diadema* keep the colony margins clean and the problem has not shown up for over 18 months, though we have continued to use the same tanks and have taken no additional steps for cleaning or sterilization. The main difficulty with these animals is the constant danger of a handler being jabbed with their sharp spines and their penchant for climbing up on the corals after feeding to steal food from the corals' mouths.

This was the first in a series of studies looking at the feasibility of using field- and land-based coral nurseries as triage facilities for reef restoration in South Florida. Future studies will involve testing of how well laboratory raised corals acclimate to field conditions and testing which factors are most important for maximizing coral growth in the laboratory.

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