Marine Sanctuaries Conservation Series NMSP-07-XX

M/V *WELLWOOD*
Coral Reef Restoration Monitoring Report
Monitoring Events 2004-2006
Florida Keys National Marine Sanctuary
Monroe County, Florida

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Ocean Service
Office of Ocean and Coastal Resource Management
National Marine Sanctuary Program

April 2007

About the Marine Sanctuaries Conservation Series

The National Oceanic and Atmospheric Administration administers the National Marine Sanctuary Program. Its mission is to identify, designate, protect and manage the ecological, recreational, research, educational, historical, and aesthetic resources and qualities of nationally significant coastal and marine areas. The existing marine sanctuaries differ widely in their natural and historical resources and include nearshore and open ocean areas ranging in size from less than one to over 5,000 square miles. Protected habitats include rocky coasts, kelp forests, coral reefs, sea grass beds, estuarine habitats, hard and soft bottom habitats, segments of whale migration routes, and shipwrecks.

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Florida Keys National Marine Sanctuary
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COVER

Upper left: M/V *Wellwood* aground on Molasses Reef, Florida Keys National Marine Sanctuary. Photo credit: Florida Keys National Marine Sanctuary.

Lower right: Naturally-recruited *Montastrea cavernosa* colony on reef restoration module, photographed on September 29, 2004, at the M/V *Wellwood* restoration site, Florida Keys National Marine Sanctuary. Photo credit: Jeff Anderson.

SUGGESTED CITATION

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ABSTRACT

This document presents the results of the monitoring of a repaired coral reef injured by the M/V *Wellwood* vessel grounding incident of August 4, 1984. This grounding occurred in Florida state waters within the boundaries of the Florida Keys National Marine Sanctuary (FKNMS). The National Oceanic and Atmospheric Administration (NOAA) and the Board of Trustees of the Internal Improvement Trust Fund of the State of Florida, ("State of Florida" or "state") are the co-trustees for the natural resources within the FKNMS and, thus, are responsible for mediating the restoration of the damaged marine resources and monitoring the outcome of the restoration actions. The restoration monitoring program tracks patterns of biological recovery, determines the success of restoration measures, and assesses the resiliency to environmental and anthropogenic disturbances of the site over time. To evaluate restoration success, reference habitats adjacent to the restoration site are concurrently monitored to compare the condition of restored reef areas with "natural" coral reef areas unimpacted by the vessel grounding.

The monitoring program at the *Wellwood* site includes an assessment of the structural stability of installed restoration modules and biological condition of reattached corals, which is to be performed on the following schedule: two, four, seven, and ten years after restoration. Restoration of this site was completed on July 22, 2002. The Year Two monitoring event for this site occurred between September 29 and November 5, 2004. Between July 18 and October 12, 2006, the Year Four monitoring event occurred. This report presents the results of both monitoring events.

KEY WORDS

Florida Keys National Marine Sanctuary, coral, grounding, restoration, monitoring, *Wellwood*, Molasses Reef, recruitment, Anthozoa, Hydrozoa, Octocorallia, Hexacorallia, Gorgonacea, Anthoathecata (Millepora), Scleractinia

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ACKNOWLEDGEMENTS

The National Oceanic and Atmospheric Administration (NOAA) and the Board of Trustees of the Internal Improvement Trust Fund of the State of Florida, ("State of Florida" or "state") are the co-trustees for the natural resources within the FKNMS and, thus, are responsible for mediating the restoration of the damaged marine resources and monitoring the outcome of the restoration actions. The authors would like to express their appreciation to all Florida Department of Environmental Protection employees who participated in the initial response, damage assessment, restoration, and case settlement associated with this vessel grounding.

INTRODUCTION

This document presents the results of the monitoring of a repaired coral reef injured by the M/V *Wellwood* vessel grounding incident of August 4, 1984. This grounding occurred in Florida state waters within the boundaries of the Florida Keys National Marine Sanctuary (FKNMS). The National Oceanic and Atmospheric Administration (NOAA) and the Board of Trustees of the Internal Improvement Trust Fund of the State of Florida, ("State of Florida" or "state") are the co-trustees for the natural resources within the FKNMS and, thus, are responsible for mediating the restoration of the damaged marine resources and monitoring the outcome of the restoration actions. The restoration monitoring program tracks patterns of biological recovery, determines the success of restoration measures, and assesses the resiliency to environmental and anthropogenic disturbances of the site over time. To evaluate restoration success, reference habitats adjacent to the restoration site are concurrently monitored to compare the condition of restored reef areas with "natural" coral reef areas unimpacted by the vessel grounding.

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Event	**Date**
Vessel Grounding	August 4, 1984
Vessel Removal	August 16, 1984
Injury Assessment: Initial	August 16-25, 1984
Injury Assessment: Post Hurricane Georges	Autumn 1998
Pre-Construction Coral Survey	April 23-24, 2002
Restoration	June 2-July 22, 2002
Year Two Monitoring	September 29-November 5, 2004
Year Four Monitoring	July 18-October 12, 2006
Year Seven Monitoring	Summer 2009
Year Ten Monitoring	Summer 2012

Table 1. Event timeline for the M/V *Wellwood* grounding site; assessment, restoration, and monitoring.

Damage Assessment

[Note: The information in this section was adapted from the National Oceanic Atmospheric Administratation, Draft Environmental Assessment: M/V *Wellwood* Grounding Site Restoration February, 2001]

On August 4, 1984, the M/V *Wellwood*, a 122-meter Cypriot-registered freighter, ran aground on the upper forereef of Molasses Reef, about 6 nautical miles southeast of Key Largo, in a minimum of 6 meters of water (Figure 1). The *Wellwood* remained aground for 12 days, causing more destruction as time went on. Damage occurred as result of initial attempts to power off the reef, from tugboat propellar wash abrasion, from extended periods of shading under the vessel, and from cable abrasion during several failed attempts to remove the vessel from the reef. The grounding destroyed 5,805 m^2 of living corals and injured over 75,000 m^2 of reef habitat, including 644 m^2 of coral reef framework.

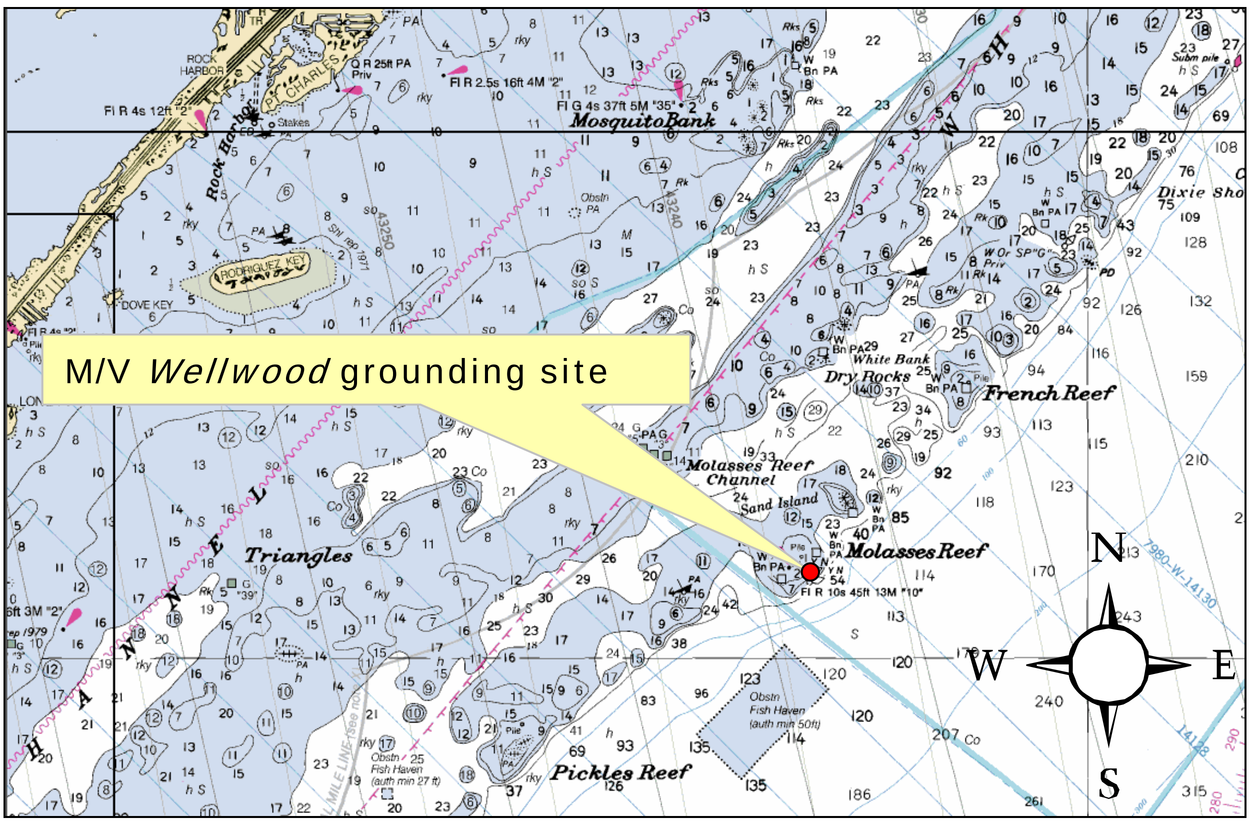


Figure 1. Approximate location (shown on NOAA Chart 11462) that the M/V *Wellwood* ran aground at Molasses Reef on August 4, 1984.

The grounding caused severe biological and physical damage to the reef community and led to widespread mortality of benthic fauna and displacement of mobile fauna. The injury ranged from superficial scraping of the reef surface and toppling of large coral heads to complete crushing of coral heads and severe cracking of the reef framework structure (Figure 2). Additional injury to the reef occurred as a result of Hurricanes Elena and Kate in 1985 and the active 1998-storm season (Groundhog Day Storm, Hurricane Georges).

Figure 2. Fractured reef substrate (left) and split *Montastraea faveolata* colony (right) resulting from the M/V *Wellwood* grounding (photo credit: FKNMS).

As the vessel approached the reef, it created an inbound grounding track approximately 20 m wide and affected bottom substrate up to 6 m deep. The injury toppled or injured 13 large coral heads and left bottom paint embedded in exposed coral skeletons.

The most prominent feature of the injury site was an area known as the "parking lot" where the hull of the *Wellwood* finally came to rest. This entire area was crushed as a result of hull pounding and experienced severe shading for the 12 days the vessel was aground. The combined effects resulted in near total destruction of the coral cover (Figure 3 and Figure 4).

Along the starboard side of the hull resting site there was an extensive area that experienced patchy areas of destruction. This was the original resting area of the vessel before it pivoted during initial removal attempts. At least 6 large boulder coral colonies and numerous smaller organisms were destroyed as the vessel scraped the bottom.

Figure 3. Aerial view of M/V *Wellwood* aground on Molasses Reef (left) and "parking lot" area after removal (right).

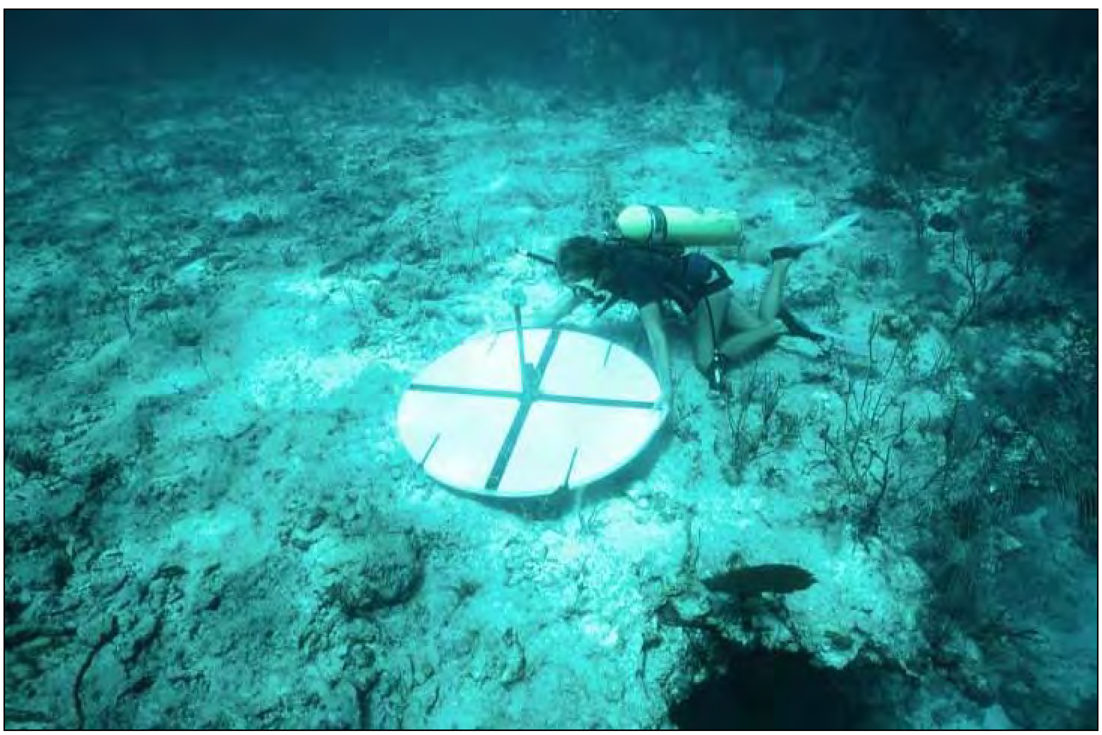


Figure 4. Diver installing reference marker in the "parking lot" for geo-referencing aerial photography (photo credit: FKNMS).

The *Wellwood* grounded in the transition zone between the shallow upper forereef (just seaward of the *Acropora palmata* reef crest) and a deeper forereef zone that is dominated by large head corals. The habitat was primarily moderate to low-relief, but included numerous large heads of boulder corals and had a diverse community of hard and soft corals and other benthic organisms. The principal scleractinian coral species present at the site included *Montastraea* spp., *A. palmata, Dendrogyra cylindrus, Agaricia agaricites, Diploria* spp., *Colpophyllia natans, Porites asteroides, Favia fragum, Meandrina meandrites,* and *Dichocoenia stokesii.* Cover also included a healthy octocoral (gorgonian) community including many sea fans (*Gorgoinia ventalina*) and sea rods, the zoanthid *Palythoa caribaeorum*, and fire coral, *Millepora* spp. In addition to direct physical damage from the vessel, many colonies under the vessel's hull were seriously damaged due to shading and subsequent tissue death. The dominant species injured in the deeper forereef zone during the salvage operations included the large basket sponge *Xestospongia muta,* large *M. annularis* complex colonies, and many octocorals. Coral loss over the entire area was estimated to include the complete destruction of at least 21 large (1 to 2-m diameter) colonies of *M. annularis* complex, four colonies of *D. cylindrus*, and 6 large colonies of other coral species, as well as grazing, abrasion, toppling or other injuries to many other colonies.

A settlement between NOAA and the responsible parties was agreed to on December 22, 1986. Under the terms of the settlement the responsible parties purchased an annuity to be paid to NOAA over 15 years in variable annual installments beginning in 1987 and scheduled to end in 2001. Between 1987 and 1995, the bulk of the payments were allocated to payment of civil penalties and repayment of response and damage assessment costs incurred by NOAA and the U.S. Coast Guard during and immediately following the grounding. Payment allocated for restoration costs did not begin until 1989 and was completed in 2001; the restoration process could then commence. Meanwhile, in 1998 a significant storm, Hurricane Georges, had severely impacted the *Wellwood* site. The storm passed approximately 80 miles to the southwest of the site, with winds approaching 100 mph (Figure 5). At 0800 hours on September 25, 1998, NOAA's National Data Buoy Center's Coastal-Marine Automated Network (C-MAN) recording station on the nearby Molasses Reef Lighthouse recorded sustained 46 kt winds, and a peak gust of 53 kt.

After the hurricane's passage, it was found that large areas of the site had been scoured out. The excavation was due to the fact that the top of the reef framework, the calcified "pie crust" of the reef surface, had been broken during the grounding. This exposed, underlying unconsolidated rubble and sediment which was mobilized during the storm, caused further scour and the formation of large craters at the site. By 2000 it was ascertained that this process would likely continue with each passing hurricane in the absence of prompt restoration. Restoration undertaken in 2002 was planned by National Marine Sanctuary Program (NMSP) headquarters and Florida Keys staff, in collaboration with marine engineers from the commercial firm of Coastal Planning and Engineering Inc. (CP&E). A pre-construction coral survey of the grounding site was undertaken by the Science Coordinator for the NMSP (Gittings 2002).

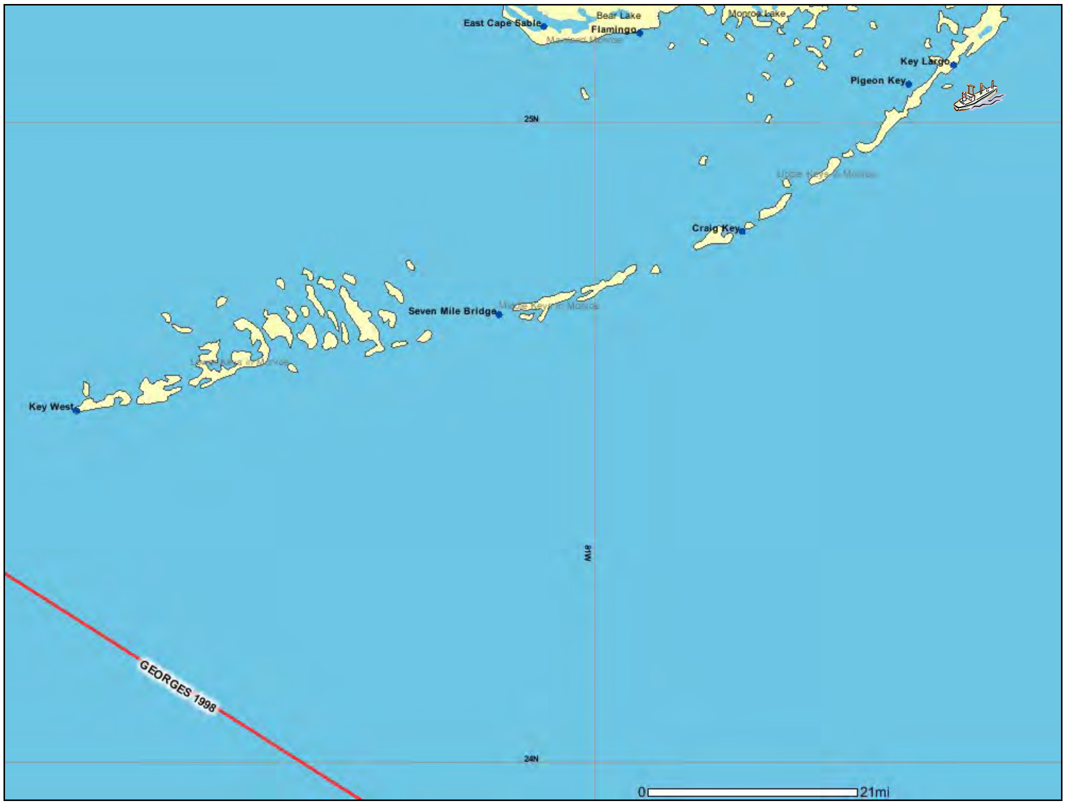


Figure 5. Track of Hurricane Georges (line in red lower left) relative to the M/V *Wellwood* grounding site (ship graphic upper right not to scale).

Coral Reef Restoration

[Note: The information in this section was adapted from the Molasses Coral Reef Restoration Project Post-Construction Engineering Report prepared by Coastal Planning and Engineering, Inc.]

The objectives of the M/V *Wellwood* site restoration were to 1) stabilize damaged reef framework, 2) infill hurricane-excavated craters, and 3) rebuild reef topography. To accomplish these objectives, a design concept featuring artificial reef modules was developed (Figure 6). The artificial reef modules were designed and constructed by Harold Hudson, reef restoration biologist of the Florida Keys National Marine Sanctuary. The artificial reef modules closely replicated the adjacent undamaged reef, rebuilding reef topography that had been lost as a result of the *Wellwood* grounding. Modules were five-sided (from a planar view) with an approximate height of 1.2 m (4 ft), length of 1.8 m (6 ft), and a width of 1.5 m (5 ft). Damp sand was placed inside the form during the fabrication process to create a 30 cm (12 in) high reef cave within the structure (Hudson and Franklin 2005). The hollow interior of each module provided space to be used by fish and sessile organisms, and the rough limestone provided habitat for organisms using interstitial spaces or for boring organisms. The modules minimized the concrete surface exposure and maximized the exposure of limestone surfaces, enhancing the environmental features of the module design.

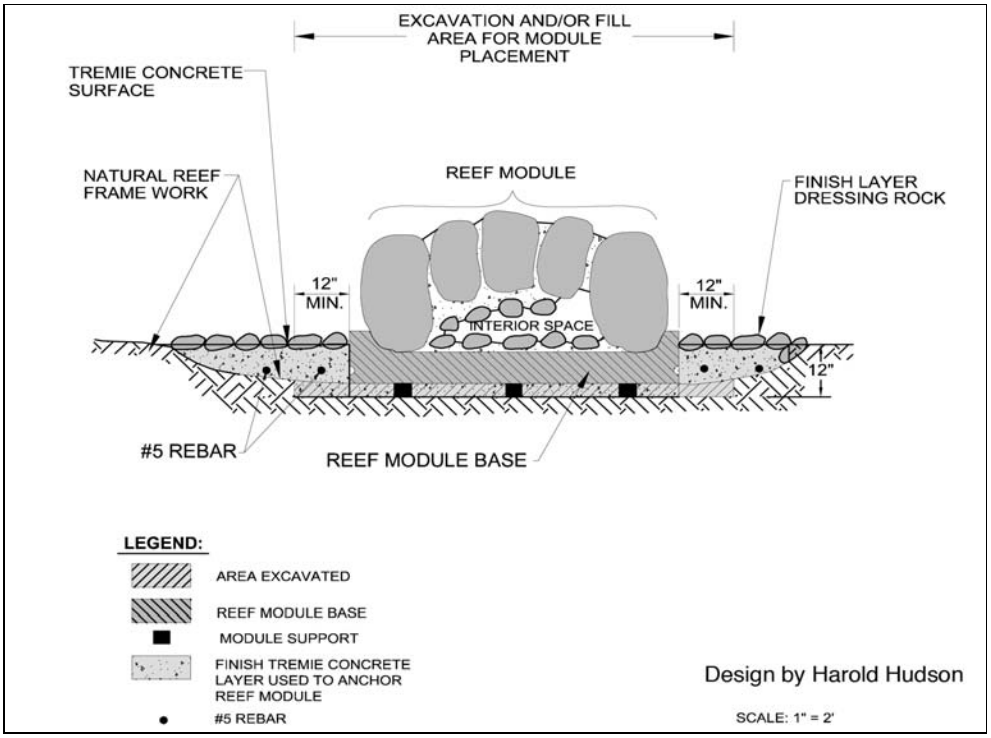


Figure 6. Cross section of installed reef restoration module.

The reef restoration design consisted of the placement of 22 reef modules and/or limestone boulders, stabilized with a tremie pour of concrete within the 14 repair sites depicted in Figure 7. An aluminum frame outline of the reef module, which was constructed by NOAA, was used to determine the exact location, orientation and accurate leveling of each reef module prior to placement at the repair site. Reef module placement was contingent upon placement of the modules in natural and/or excavated receiver sites, allowing tremie pour concrete to secure the module to the reef. Excavation of the existing rock substrate was often conducted to provide the appropriate receiver site for module placement. Each module was placed on 2-inch to 4-inch supports to allow concrete to flow under the module, in addition to providing a minimum 12-inch wide and deep apron entirely around each module (Figure 8). After the reef module was placed, concrete was tremie poured within the excavated depression, cementing the reef module into the existing reef substrate. A total of 9 repair sites received reef modules.

The remaining 5 sites were determined to be too small and/or shallow to accommodate reef restoration modules. At these sites, a combination of 1-2 ton limestone boulders and tremie poured concrete, referred to as a "puddle pour," were used to fill the excavation. Limestone rock dressing stones, 25-45 cm (10-18 in) in diameter were pressed into the fresh concrete at close intervals to increase rugosity and provide a more natural substrate. The concrete embedded boulders projected 50-100 cm (20-40 in) above the dressing stones in all "puddle pour"

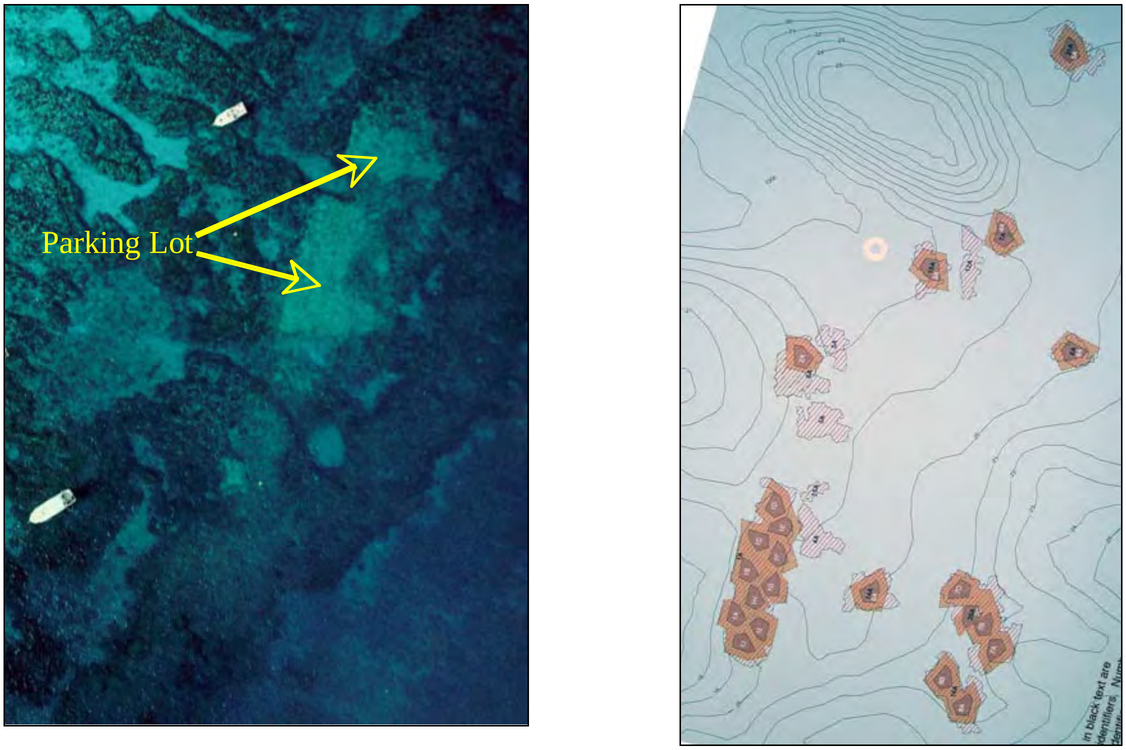


Figure 7. Aerial photograph of "parking lot" damage caused by the M/V *Wellwood* grounding (left) and a bathymetric map depicting locations of reef restoration modules (shaded in brown) and "puddle pour" restoration areas (right).

applications (Hudson and Franklin 2005). A total of 185 m^2 of damaged reef substrate was repaired using these 2 restoration techniques (Figure 9).

Project oversight was provided by Harold Hudson, FKNMS, with the restoration performed by Coastal Planning and Engineering, Inc. (CPE). Field operations by CPE during the habitat restoration utilized a 120 ft. long barge with a 45 ft. beam, equipped with a 4-cubic yard cement mixer and an American 100 ton crane with 120 ft. boom. The barge had sufficient deck space to allow transport of reef restoration modules and limestone boulders and to accommodate SCUBA, communications, and construction equipment.

Figure 8. Reef restoration module and reinforcing rods in excavation crater ready to accept tremie pour concrete (photo credit: FKNMS).

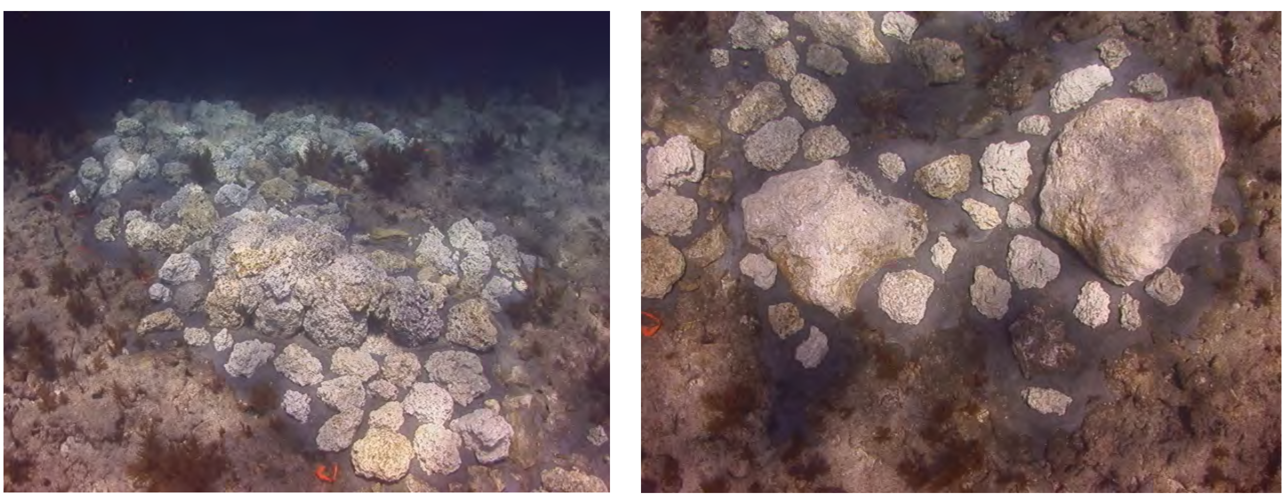


Figure 9. Completed restoration with reef restoration modules (left) and “puddle pour” with boulders (right) each surrounded by limestone “dressing” stones (photo credit: Coastal Planning and Engineering, Inc.).

Restoration Monitoring

The purpose of the coral restoration monitoring program is to evaluate the success of trustee actions in achieving restoration goals and to determine if remedial measures are needed. For a grounding site such as the M/V *Wellwood*, the evaluation of restoration efforts involves the identification of appropriate success criteria and the design and implementation of a sampling and analysis plan. A list of success criteria measures for structural and functional aspects of coral reef restoration as well as a framework for monitoring activities is identified by NOAA (Thayer et al. 2003).

The guiding hypotheses for the evaluation of the "restoration" site reflects the efficacy of the restoration techniques and the condition of the site relative to reference habitats. The monitoring program addresses if the chosen restoration methods are effective and when the site could be considered restored. The structural integrity of the restoration site is evaluated with the following questions:

1. Is the attachment of the reef modules to the substrate stable?
2. Are there any visible cracks in the surface of the reef modules and/or puddle pour concrete?
3. Are corals and other organisms that were transplanted firmly attached to reef modules?

In addition, the biological condition of the restoration site was evaluated with the following question:

> Is there a difference in coral cover and/or new coral recruitment between the grounding site (i.e., both the restored and unrestored areas) and the reference area?

The monitoring program was designed to detect significant changes in coral cover or damage to restoration components (structural enhancements, coral transplants, etc.) as a result of external events, such as major storms or vandalism, and in comparison to the surrounding habitat. In addition, the monitoring assessed the effectiveness of the restoration based upon technical evaluation of appropriate parameters.

METHODOLOGY

YEAR TWO MONITORING EVENT (SEPTEMBER-NOVEMBER 2004)

Field Methods

Between September 29 and November 5, 2004, the *Wellwood* restoration site was monitored using SCUBA from a small vessel (6.4 m). Tactile and visual assessments were performed to evaluate the physical stability of the reef crowns. To determine the biological condition of the site, *in situ* observations, digital images, and digital videos were recorded among the restoration area and the reference area. The restoration area was composed of the 22 reef modules and/or concrete puddle pour areas (area = 185 m^2) and the remaining damaged, but unrepaired section of the grounding site (area = 459 m^2). The reference area was adjacent to the northeast side of the restoration site. Within each sampling area, 25 one m^2 quadrats were surveyed for benthic organism colony populations. Within the restored section of the restoration area, the location of quadrat placements were randomly chosen (by means of a random number generator) in each sub-area of reef restoration module/puddle pour. Within the unrepaired section of the restoration area and the reference area, the location of quadrat placements were similarly randomly chosen from a digital grid of uniquely identified 1 m^2 cells overlain on the grounding site map. Transect lines were used from landmarks to determine cell locations as best as possible. Quadrats were deployed to these cells and visually surveyed for biological variables of interest.

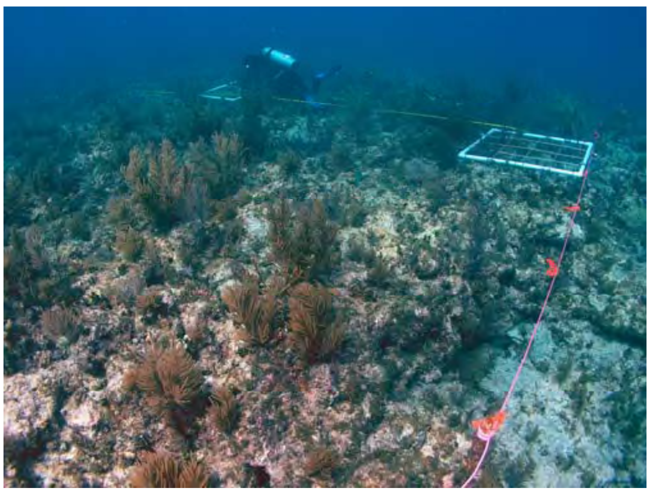



Figure 10. November 2004 photograph of delineated section of the reference area (left) and divers conducting surveys (right) (photo credit: Jeff Anderson).

Planar digital photographs of quadrats were recorded when depth allowed while oblique digital photographs and dGPS coordinates (with a Garmin 76) were taken of each restoration module in the restored area. Underwater digital images were collected with an Olympus C-5050 digital camera in a Light & Motion Tetra 5050 underwater housing and digital videos were collected with a Sony DCR-DVD200 video camera in an Amphibico QuickView DVD underwater housing.

Photo Analysis

Digital images were edited with Adobe Photoshop versions 7 and CS2 (Adobe 2002 and 2005). Image edits included color hue changes to make water look bluer, brightness changes to compensate for original exposure, and sharpness changes to enhance images not in focus. Planar images of quadrats were corrected using the Panorama Tools plug-in for Photoshop to correct for barrel distortion of the extreme wide angle image making it as close to square as possible. Finally, excess image information outside the quadrat boundary was cropped.

Biological Classifications

An initial comparison was made between populations, at the Order level, of benthic organisms that had likely recruited to the site since the restoration. The determination of recruits at the restored area quadrats (the modules) was self-evident—anything present had to have recruited since the restoration. To determine populations of likely recruits to the damaged but unrestored area and the reference area, a necessary assumption was made that there was no differential in growth between areas; i.e., that the maximum size of organisms in the restored area was the maximum size that could have been obtained by recruits in the other two areas.

The organisms hereafter examined in detail constituted the great majority of the benthos present. They were largely comprised of three Orders and most of the comparisons presented are at the Order level. Present were members of the Order Anthoathecata in the Class Hydrozoa (specimens were solely of one Genus in the Family Milliporidae and henceforth referred to by the more familiar name of that Genus—*Millepora*), and the Orders Gorgonacea and Scleractinia of the Subclasses Octocorallia and Hexacorallia respectively (Class Anthozoa). Scleractinians will be further divided into species for various analytical purposes. Almost the only other benthic organisms visible to the eye (besides various algae) was *Palythoa caribaeorum,* of the Order Zoanthidea, Subclass Hexacorallia. However *P. caribaeorum* presence was only recorded in the reference area, and was comprised of only a very few colonies (approximately 10) and their sizes were such as to cast doubt that they were recruits; they will be ignored for comparative purposes. Much the same may be said of Echinoderms; e.g., in 2004 the restored area contained seven (6 *Eucidaris tribuloides* and 1 *Echinometra viridis*); the other two areas had one apiece (a *Diadema antillarum* in the reference and an *Eucidaris tribuloides* in the damaged unrestored areas).

Although not included in rigorous statistical analysis, numerous vagile fauna were observed on, in, and around the restoration modules (Figure 11). This was undoubtedly due to both the benthic organisms already colonizing the module structures, as well as the shelter afforded by the cave intentionally designed within the modules (Figure 6).

Figure 11. Fauna living in and around reef restoration modules. Starting from upper left: cocoa damselfish (*Stegastes variabilis*), blue tang (*Acanthurus coeruleus*), spotted moray eel (*Gymnothorax moringa*), long-spined urchin (*Diadema antillarum*), and Pederson cleaner shrimp in corkscrew anemone (*Periclimenes pedersoni* in *Bartholomea annulata*) (photo credit: Jeff Anderson).

Data Analysis

Data analysis and visualization were performed on a Dell PC with InStat® version 3.0 (GraphPad 2003), Prism 5 for Windows (GraphPad 2007), and Microsoft® Excel 2003 software. Descriptive statistics were generated for samples collected among the restoration, reference, and damaged but unrestored areas, along with various analytic statistics for comparative purposes. For the Order level comparisons a Chi-squared (χ^2) test for independence utilizing a 3X3 contingency table analysis was performed. For the Gorgonian recruit density analysis, since this data was derived from the rate at which relatively rare events (recruitment) occur in space or time, it showed a Poisson distribution, and it was anticipated that a square root transformation would result in a Gaussian distribution. The normalizing transformation was performed, and a Kolmogorov-Smirnov test was used to determine that the assumption was correct, allowing parametric one-way Analysis of Variance (ANOVA) to be utilized, followed by Tukey-Kramer multiple comparisons tests. For both the Millepora and the Scleractina recruit density analyses, the data sets displayed highly significant non-normality (with some sets yielding Kolmogorov-Smirnov $P < 0.0001$) that was not alleviated by square root, natural logarithm, log base10, antilog of natural log, or antilog of log base10 transformations. Thus, Kruskal-Wallis non-parametric ANOVA was conducted, to be followed by Dunn's post-hoc pairwise tests if significant differences were detected.

YEAR FOUR MONITORING EVENT (JULY-OCTOBER 2006)

Another monitoring event occurred between July 18 and October 12, 2006. Methodology utilized was identical to that related above for the previous monitoring event, with the exception that 20 (instead of 25) one meter square quadrats were used. The quadrat placements were again randomly selected, and were not repetitive of those used in the 2004 survey.

Between the November 2004 and the July 2006 monitoring events, four powerful hurricanes passed within less than 300 kilometers of the restoration site; Dennis in July 2005, Katrina in August 2005, Rita in September 2005, and Wilma in October 2005. The possible confounding effects of these hurricanes, if any, are unknown; no monitoring of the site was conducted in the interim. As related below however, no visually or tactilely perceptible damage was done to the restoration, the colonies, or the site in general.

Results of the 2004 and 2006 monitoring are presented in summary fashion below. Complete copies of the datasets are maintained by both the FKNMS monitoring team, and by NMSP headquarters Damage Assessment and Restoration Program staff.

RESULTS

YEAR TWO MONITORING EVENT (SEPTEMBER-NOVEMBER 2004)

Structural Integrity

The preliminary monitoring occurred 2 years after the restoration, at which time the stability and surface of all 22 restoration modules and puddle pour areas were found to be visually and tactilely sound. The modules were found in place with a stable attachment to the substrate and no visible cracks in the cement surface. As part of an unrelated project, *Acropora cervicornis* fragments were attached to module 6A in restoration area 8A. There was no noticeable physical damage to the reattached coral fragments and these colonies were not included in the analyses which follow.

Biological Condition

The biological condition of the restoration site was progressing. Macro algae, crustose coralline algae, soft, and hard corals were all recruiting to the restoration modules and surrounding concrete puddle pour areas (Figure 12). For photographs of all 22 restoration modules, please see APPENDIX 2.

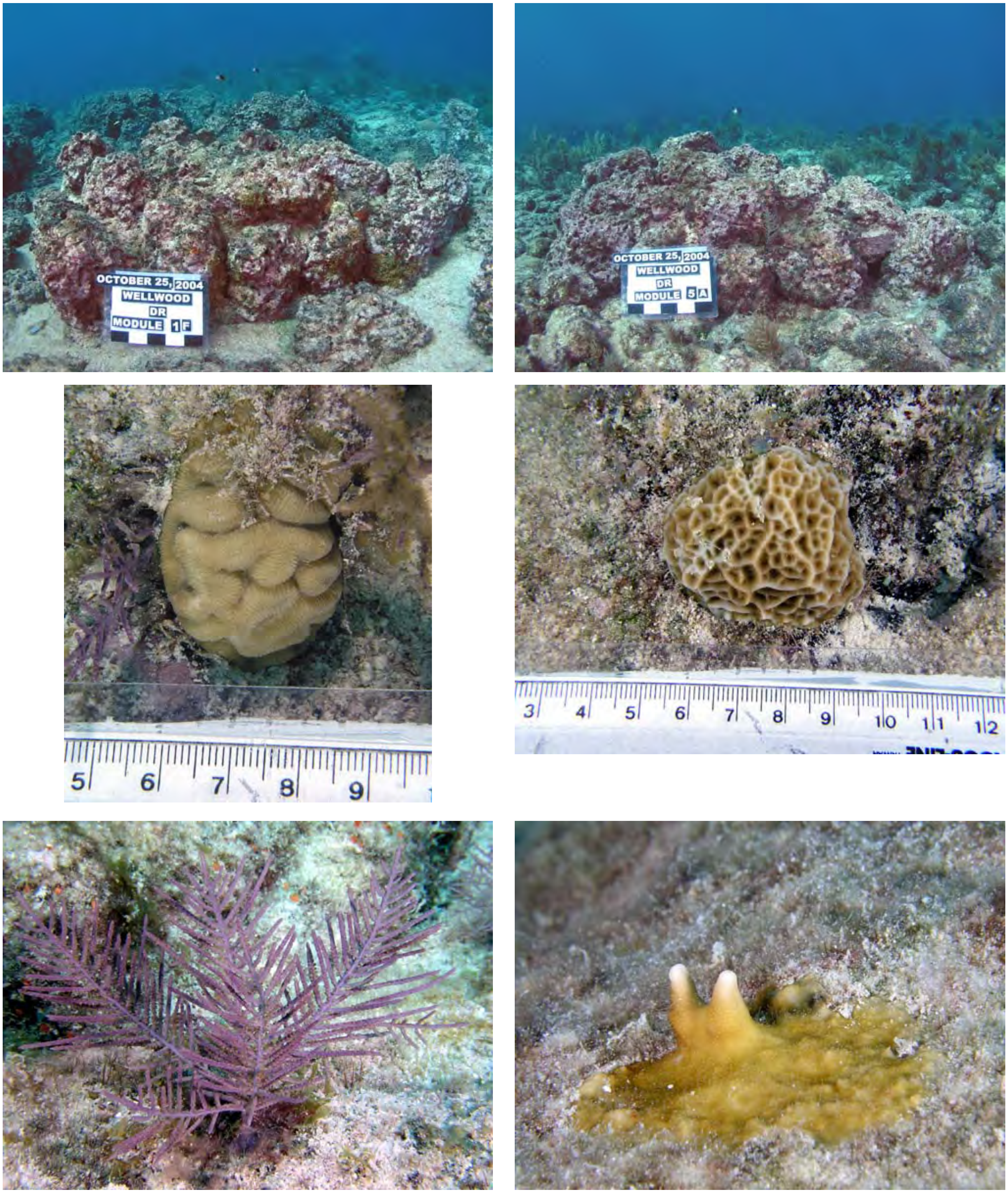


Figure 12. Restoration modules showing biological condition 2 years after installation along with close-up photos of representative benthic organisms surveyed. Starting from middle left: *Diploria labyrinthiformis*, *Agaricia* sp., *Pseudopterogorgia* sp., and *Millepora* sp. (photo credit: Jeff Anderson).

Figure 13 suggests that, except for Gorgonians, the three sampling areas contained reasonably similar recruit populations. Undoubtedly because of the difference in Gorgonian levels, analysis reveals that sampling areas and colony numbers are significantly associated ($P = 0.0005$).

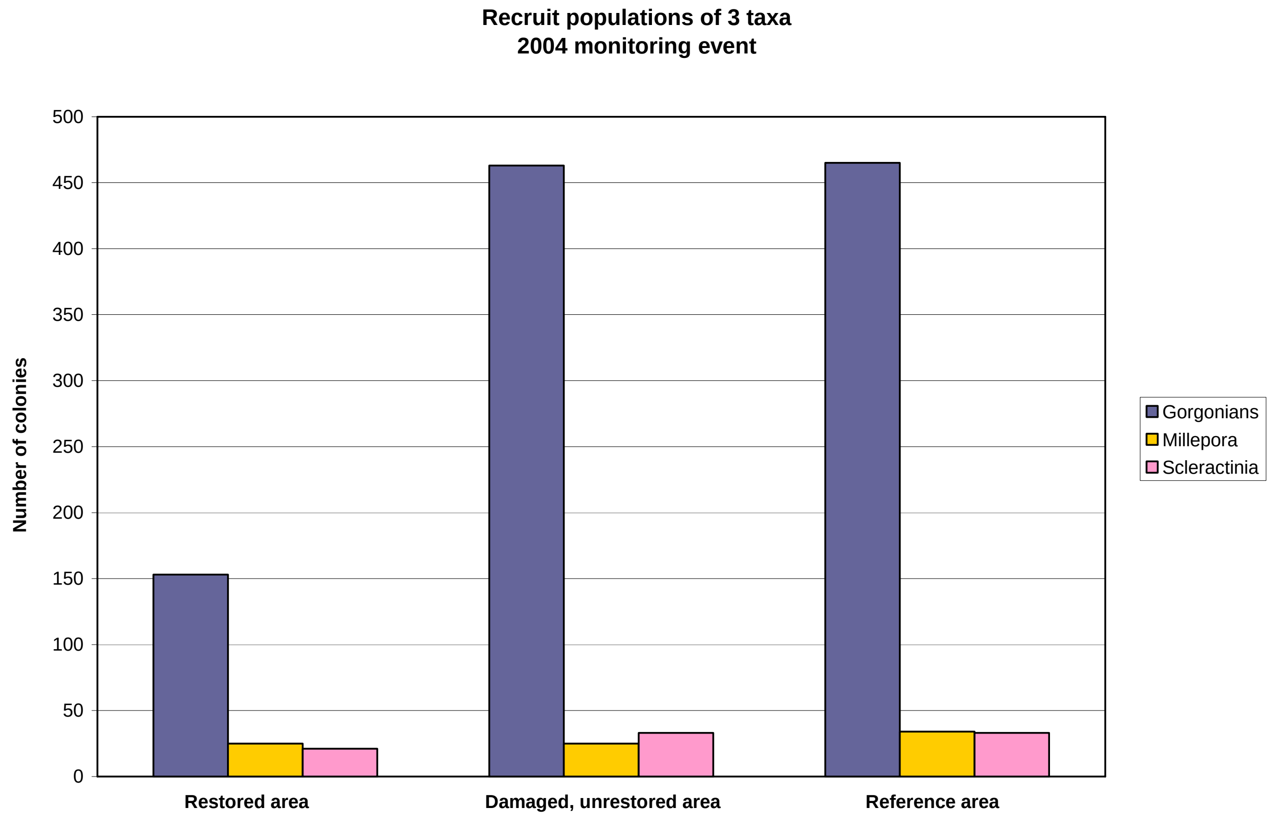
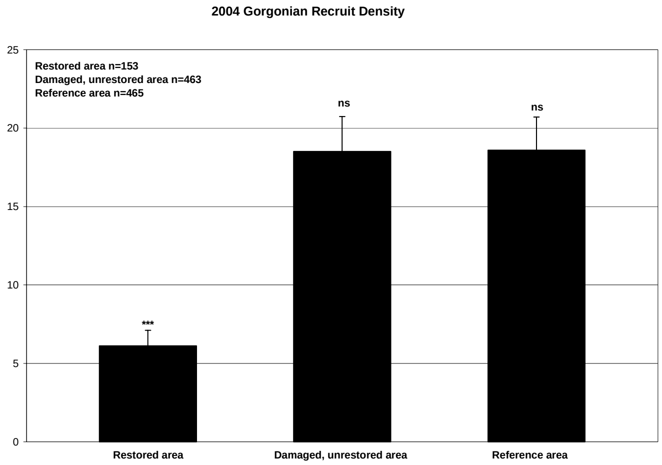


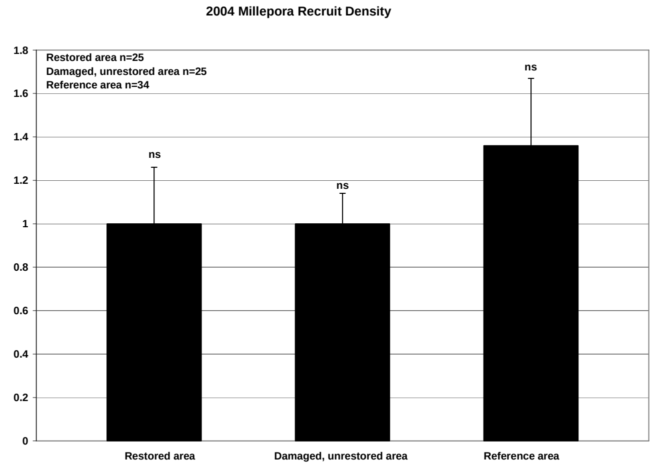
Figure 13. 2004 recruit populations, at the Order level, in the Restored, Damaged, unrestored, and Reference sampling areas at the M/V *Wellwood* restoration site.

Next, overall recruit densities (colonies/m^2) were examined (Figure 14). Statistical analysis (see METHODOLOGY) demonstrated that for Gorgonians, the densities were extremely significantly different ($P < 0.0001$). The restored area evidenced difference; the other two areas were not shown to be significantly different.

Millepora recruit density was subsequently evaluated (Figure 14). Analysis was conducted in a somewhat different fashion than for Gorgonians (see METHODOLOGY) and revealed no significant difference ($P = 0.5911$).

Finally in this series of comparisons, densities of Scleractinian recruits was compared (Figure 14). Analysis proceeded exactly as for Milleporans. Again, as for that group, no significant difference was detected ($P = 0.5023$).





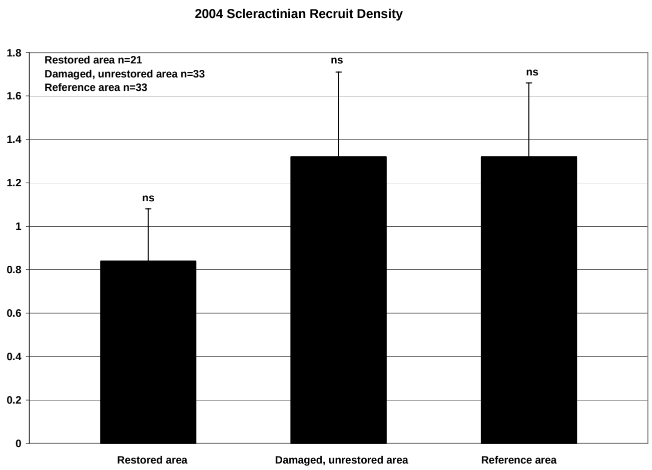


Figure 14. Density of recruits (colonies/m^2) for all size classes of: Gorgonians, Milleporans, and Scleractinians (Note differing scales used for Gorgonians vs. others).

± SE; *** indicates highly significant difference, ns indicates non-significance.

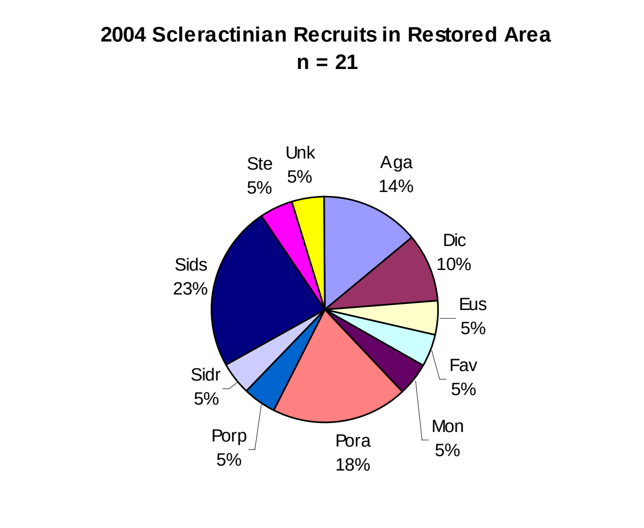
The next investigation undertaken was a comparison of the biodiversity of Scleractinian recruits among the three areas within the M/V *Wellwood* restoration site. Table 2 and Figure 15 display the data showing the Scleractinian species break-out. Table 3 lists the results of a number of standard biodiversity indices performed for the recruit population.

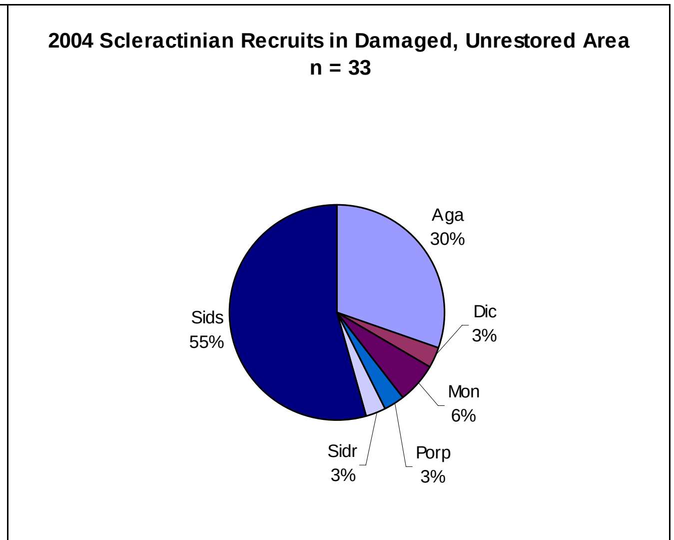
Species	Restored area	Reference area	Damaged, unrestored area
Agaricia spp.	3	13	10
Dichocoenia stokesii	2	0	1
Eusimilia fastigiata	1	0	0
Favia fragum	1	0	0
Montastrea cavernosa	1	1	2
Porites astreoides	4	3	0
Porites porites	1	0	1
Siderastrea radians	1	2	1
Siderastrea siderea	5	10	18
Stephanocoenia michilini	1	3	0
Unknown/unrecorded	1	1	0
Total	**21**	**33**	**33**

Table 2. Number of Scleractinian species recruits surveyed in 2004 in each of the three areas of the M/V *Wellwood* restoration site.

Name of Index (along with formulas)	Restored area	Reference area	Damaged, unrestored area
Species Richness: S = #	11	7	6
Simpson's index: $D = \Sigma(P_i^2)$	0.138	0.269	0.396
Shannon-Weiner: $H = - \Sigma(P_i \log[P_i])$	2.174	1.547	1.180
Evenness: $E = H/\log(S)$	0.907	0.795	0.659

Table 3. Common Biodiversity indices of the 2004 Scleractinian recruit population in each of the three areas of the M/V *Wellwood* restoration site.





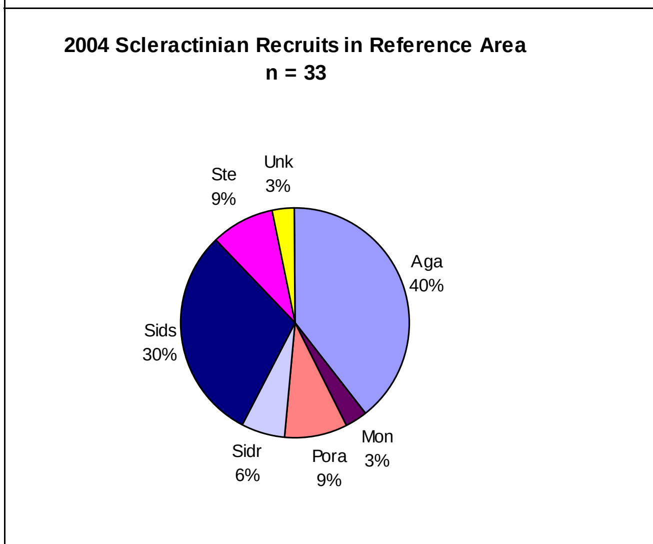


Figure 15. Species (by percentage) of Scleractinian recruits. Abbreviations: Aga=*Agaricia* spp.; Dic=*Dichocoenia stokesii*; Eus=*Eusimilia fastigiata*; Fav=*Favia fragum*; Mon=*Montastraea cavernosa*; Pora=*Porites astreoides*; Porp=*Porites porites*; Sidr=*Siderastrea siderea*; Sids=*Siderastrea siderea*; Ste=*Stephanocoenia michilini*; Unk=unknown/unreported

The size class frequency distribution of some of the taxa were next determined. Figure 16 shows the relative frequencies of the Gorgonians, divided into size classes, the maxima of which being determined by the maximum size of the colonies in the restored area. Figure 17 shows the same information—ascertained according to the same rationale—for Millepora.

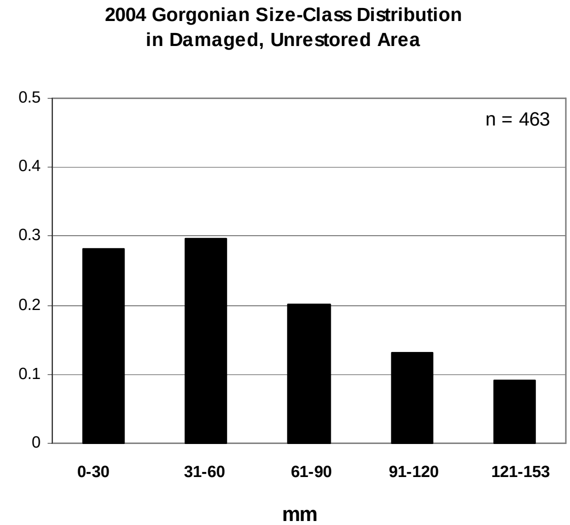
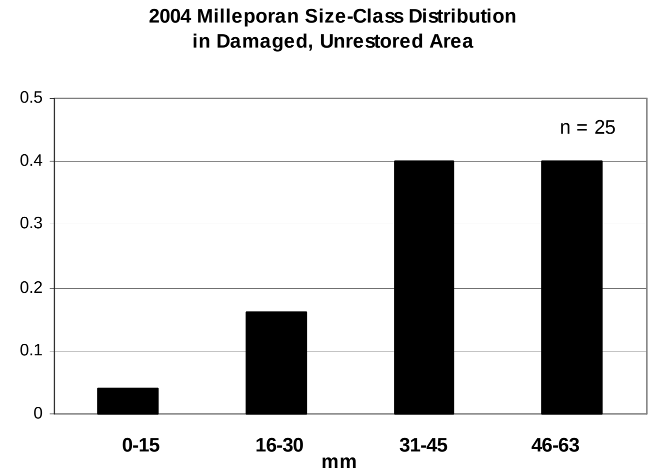


Figure 16. Gorgonian recruit size (height) class frequency distribution in each of the three areas of the M/V *Wellwood* restoration site. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield five reasonably spaced and populated categories.



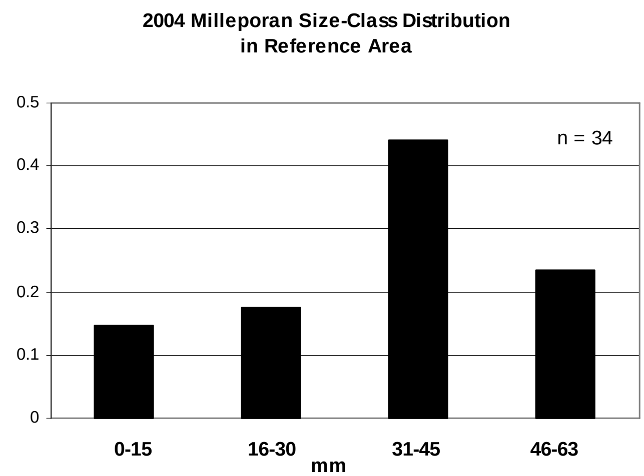


Figure 17. Milleporan recruit size (height) class frequency distribution in each of the three areas of the M/V *Wellwood* restoration site. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield four reasonably spaced and populated categories.

There are two reasons for not utilizing an analysis rationale similar to the one used for Gorgonians and Milleporans, and applying it to the Scleractinans. First, the overall number of Scleractinia recruits is fairly low, making an determination of relative frequency distribution less than robust. Actually this was a characteristic shared by the Milleporans. However, in the case of the Scleractinians, another limitation was imposed by the life histories of the species involved. It was felt not to be proper to compare recruits sizes across species, given the disparity in growth rates among juvenile corals (Vermeij 2006). Thus, only the species with the greatest number of recruits was selected for analysis and depiction, and the results for *Siderastrea siderea* are shown in Figure 18.

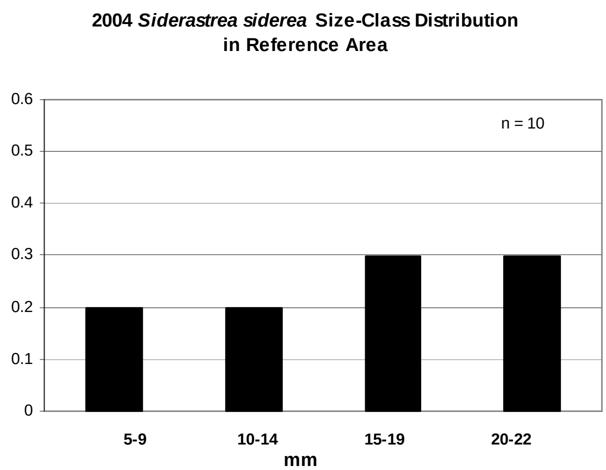
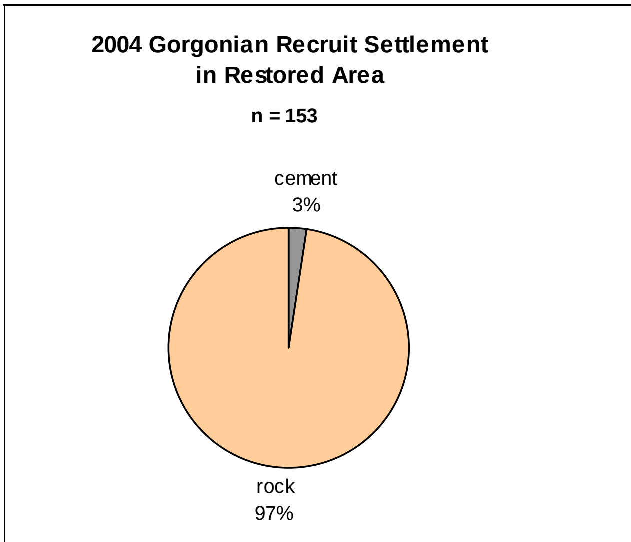
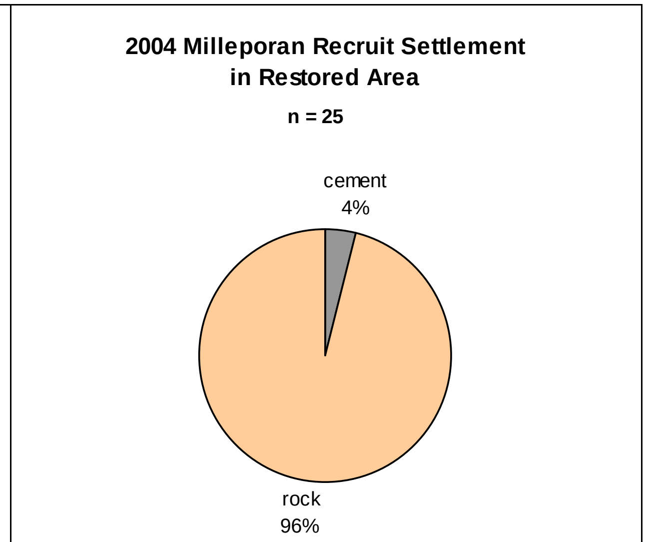


Figure 18. *Siderastrea siderea* recruit size (maximum diameter) class frequency distribution in each of the three areas of the M/V *Wellwood* restoration site. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield four reasonably spaced and populated categories.

The final analysis done for the 2004 data was a determination of how many of the recruits settled on the limestone rock versus concrete substrate in the restored area (see Figure 9 for visual reference, METHODOLOGY for textual explanation). This analysis would have provided more useful information if were possible to normalize the results; i.e., if the relative proportions of cement v. rock area available for settlement had been determined (sensu Miller and Barimo 2001). However, manpower and expense factors rendered such a determination infeasible; thus, only absolute numbers of recruits were used for calculation in the percentages presented in Figure 19. Nonetheless, some qualitative sense of the relative space available may be ascertained from examination of the accompanying photographs, located in APPENDIX 1.





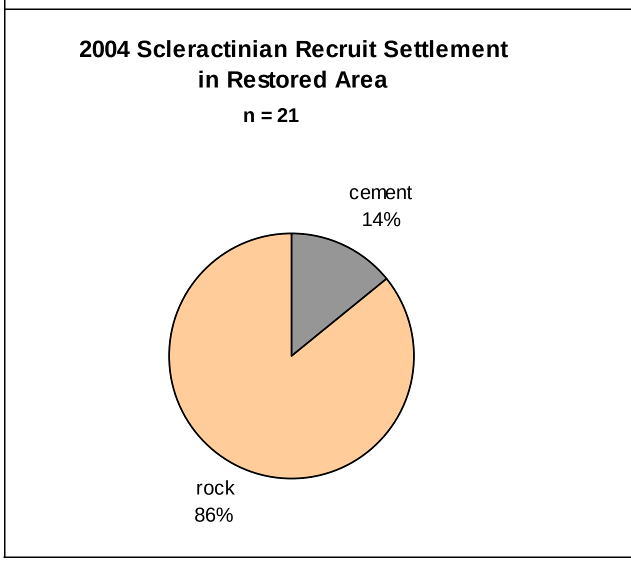


Figure 19. Percentage of Gorgonian, Milleporan, and Scleractinian recruits settling on limestone rock versus concrete substrate in the restored area of the M/V *Wellwood* restoration site.

YEAR FOUR MONITORING EVENT (JULY-OCTOBER 2006)

Structural Integrity

Despite the near passage of 4 hurricanes during the 2005 storm season, the stability and surface of all 22 reef restoration modules and puddle pour areas were again found to be visually and tactilely sound.

Biological Condition

The biological condition of the restoration site continued to progress. Macro algae, crustose coralline algae, soft, and hard corals were all still present on the restoration modules and surrounding concrete puddle pour areas (Figure 20). For photographs of all 22 restoration modules, please see APPENDIX 2.

Figure 20. Restoration modules showing biological condition 4 years after installation (photo credit: Jeff Anderson). Compare to the same 2 modules shown in Figure 12.

Figure 21 suggests that the three sites contained reasonably similar recruit populations, although as in 2004, analysis revealed that areas and colony numbers are significantly associated ($P = 0.0161$).

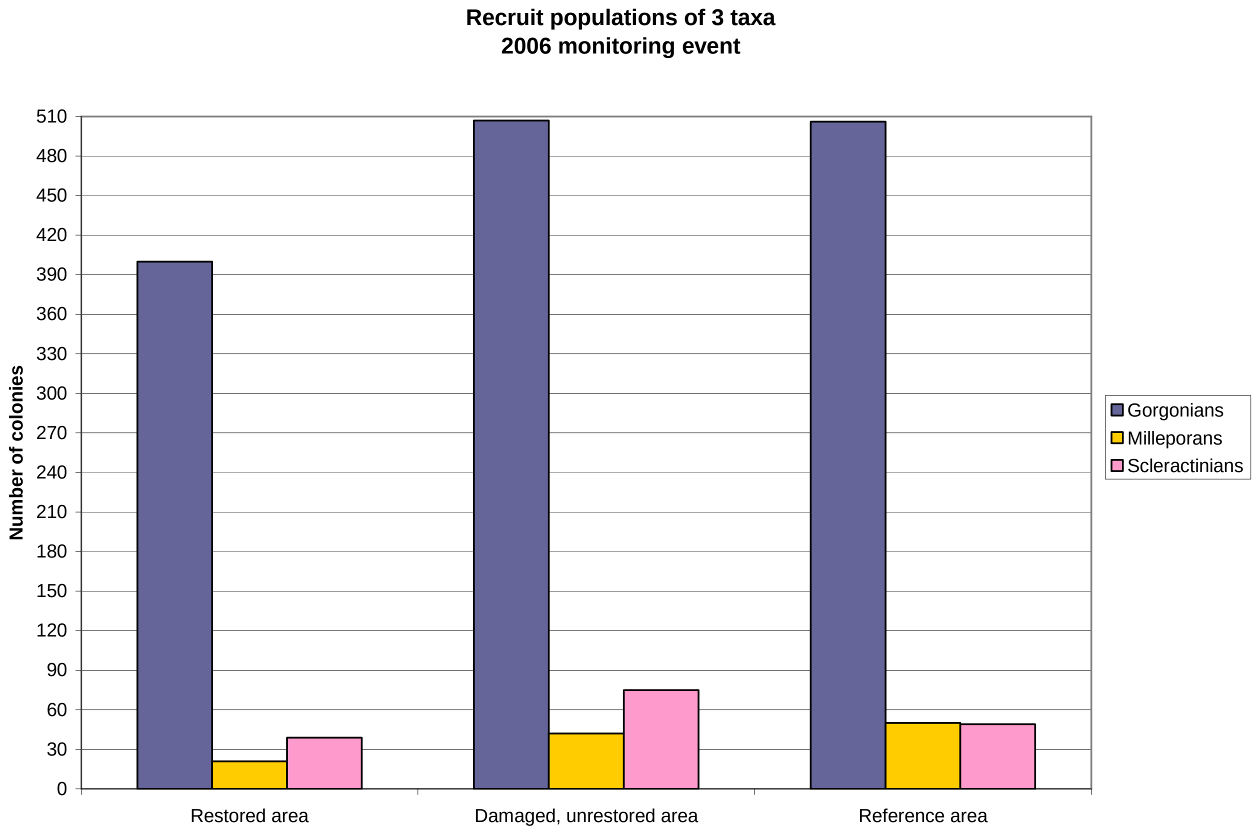
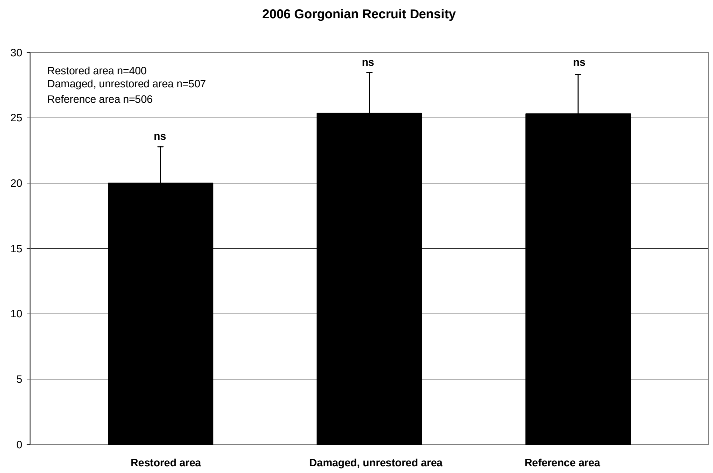


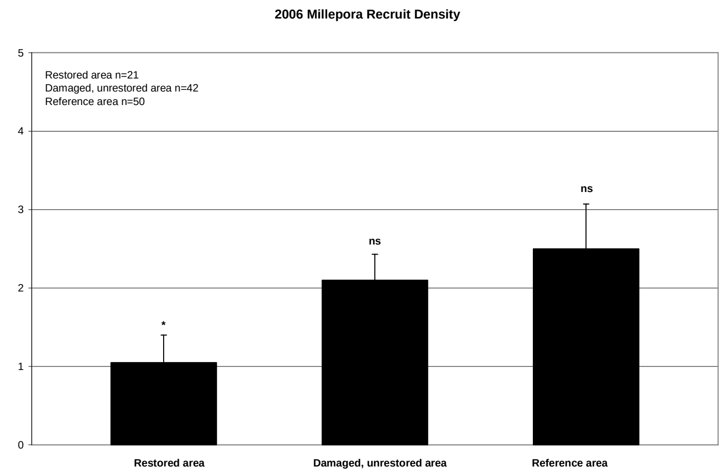
Figure 21. 2006 recruit populations, at the Order level, in the Restored, Damaged, unrestored, and Reference sampling areas at the M/V *Wellwood* restoration site.

Again, overall recruit densities (colonies/m^2) were examined (Figure 22). This time, analysis demonstrated that for Gorgonians, the densities were not significantly different ($P = 0.3517$).

Millepora recruit density was next evaluated (Figure 22). The analysis revealed overall significant variation ($P = 0.0412$), though there were no significant differences found by the pairwise comparative tests.

Density of Scleractinian recruits was then assessed (Figure 22). Analysis proceeded as for Milleporans. As opposed to that group, no significant difference was detected ($P = 0.3852$).





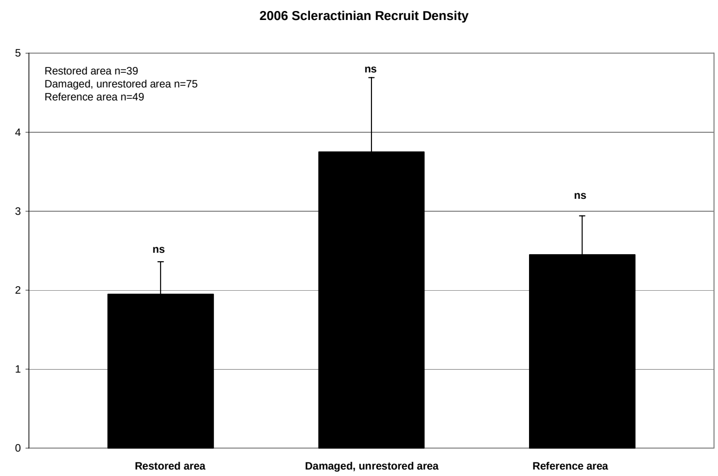


Figure 22. Density of recruits (colonies/m^2) for all size classes of: Gorgonians, Milleporans, and Scleractinians (Note differing scales used for Gorgonians vs. others).

± SE; * indicates significant difference, ns indicates non-significance.

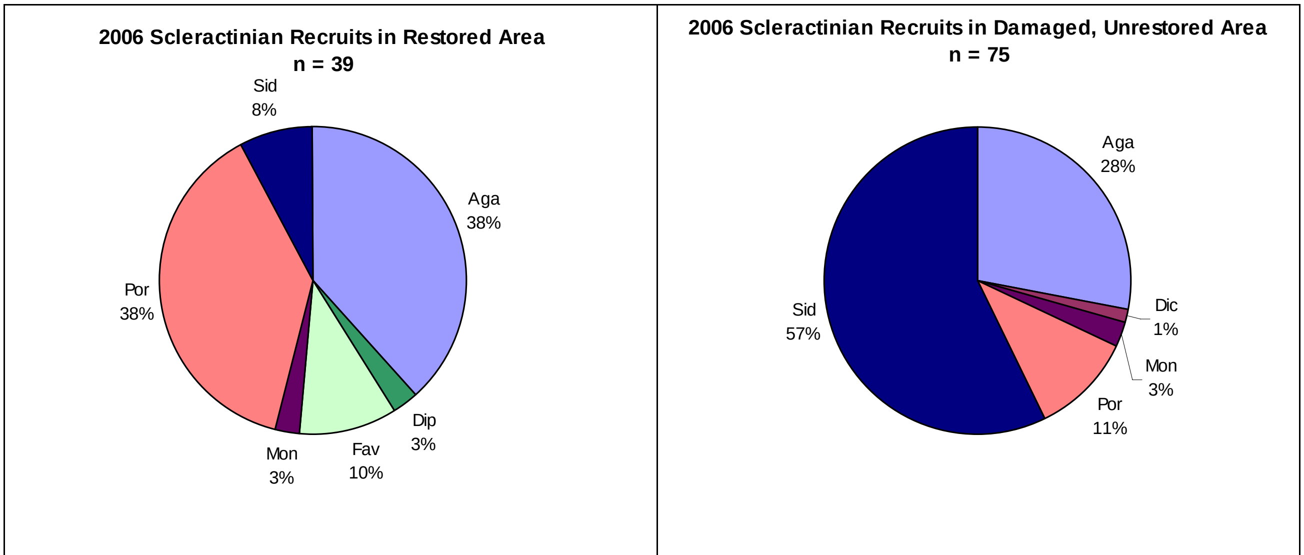
Table 4 and Figure 23 show a comparison of the biodiversity of Scleractinian recruits among the three areas within the M/V *Wellwood* restoration site. Table 5 lists the results of a number of standard biodiversity indices performed for the recruit population.

Species	**Restored area**	**Damaged, unrestored area**	**Reference area**
Agaricia spp.	15	21	21
Diconocenia stokesii	0	1	0
Diploria spp.	1	0	0
Favia fragum	4	0	2
Montastrea cavernosa	1	2	0
Porites astreoides	15	8	7
Siderastrea siderea	3	43	19
Total	**39**	**75**	**49**

Table 4. Number of Scleractinian species recruits surveyed in 2006 in each of the three areas of the M/V *Wellwood* restoration site.

Name of Index (along with formulas)	**Restored area**	**Reference area**	**Damaged, unrestored area**
Species Richness: S = #	6	5	4
Simpson's index: $D = \Sigma(P_i^2)$	0.314	0.424	0.356
Shannon-Weiner: $H = - \Sigma(P_i \log[P_i])$	1.354	1.12	1.839
Evenness: $E = H/\log(S)$	0.756	0.696	0.822

Table 5. Common Biodiversity indices of the 2006 Scleractinian recruit population in each of the three areas of the M/V *Wellwood* restoration site.



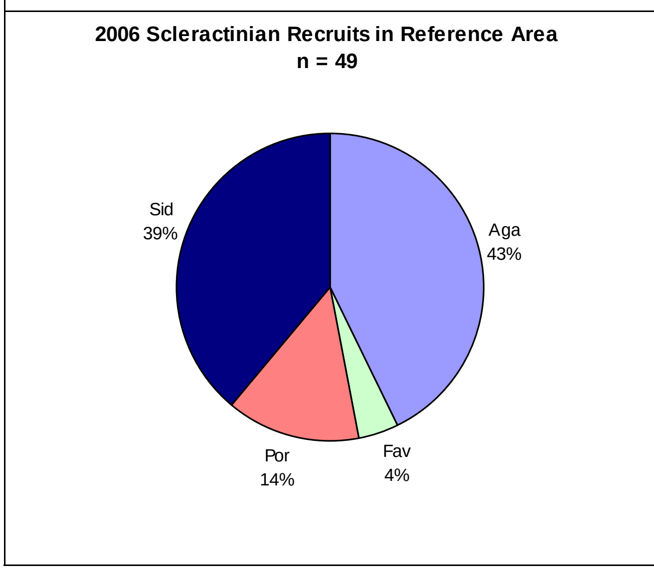
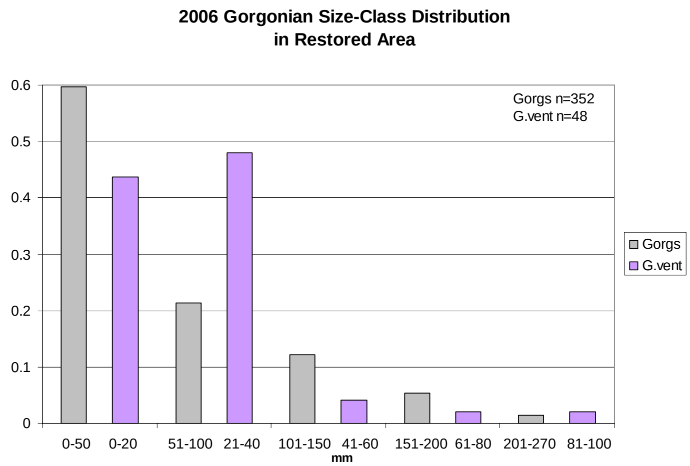


Figure 23. Species (by percentage) of Scleractinian recruits. Abbreviations: Aga=*Agaricia* spp.; Dic=*Dichocoenia stokesii*; Fav=*Favia fragum*; Mon=*Montastraea cavernosa*; Por=*Porites astreoides*; Sid=*Siderastrea siderea*

Regarding the size class frequency distribution of the Gorgonians, the data is presented somewhat differently than it was for the 2004 results. The change was necessitated because of the increased presence of the common sea fan, *Gorgonia ventalina*; in 2004 it comprised only about 1% of the Gorgonian populations, in 2006 it made up as much as 12% (in the restored area) of the totals (Note: practically all others in the Order were comprised of the Genus *Pseudopterogorgia*—sea plumes.). Since growth rates between the Genera differ greatly, *G. ventalina* is depicted separately. Figure 24 shows the relative frequencies of the Gorgonians, divided into size classes, the maxima of which being determined by the maximum size of the colonies in the restored area. Figure 25 shows the same information—ascertained according to the same rationale—for all species of *Millepora*.



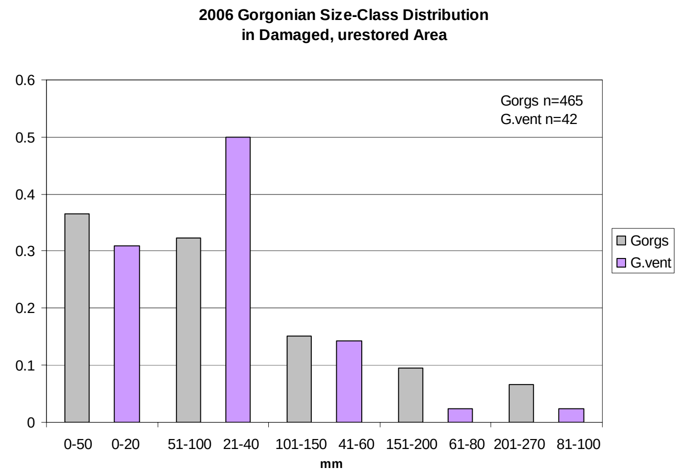
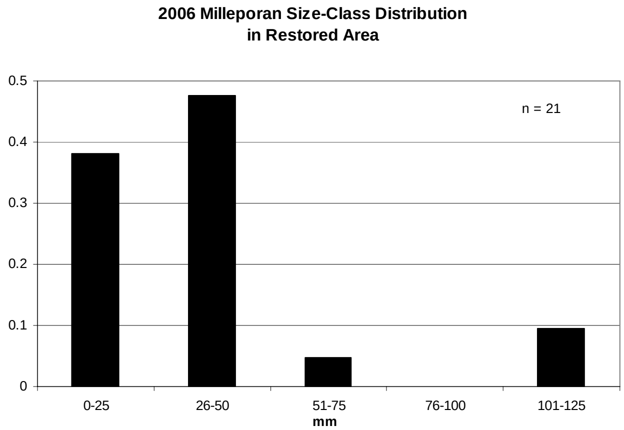


Figure 24. Gorgonian recruit size (height) class frequency distribution for *Gorgonia ventalina* (G.vent), and all other Gorgonians (Gorgs). The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield five reasonably spaced and populated categories.



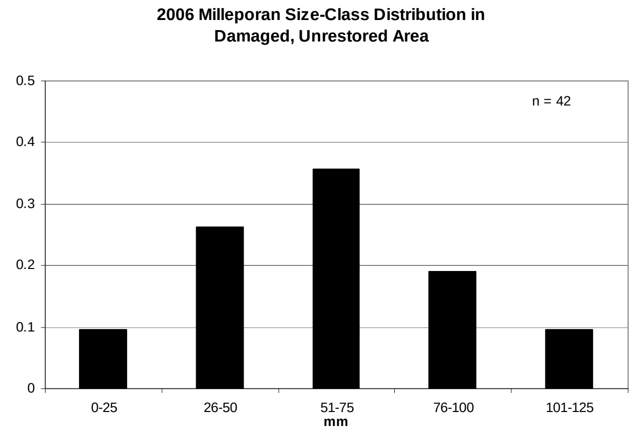
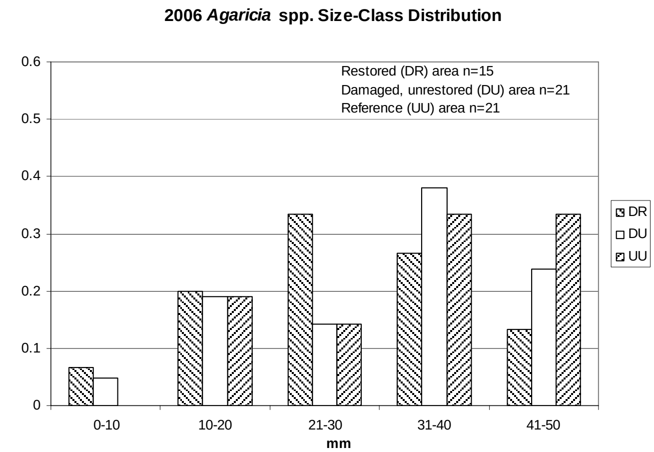
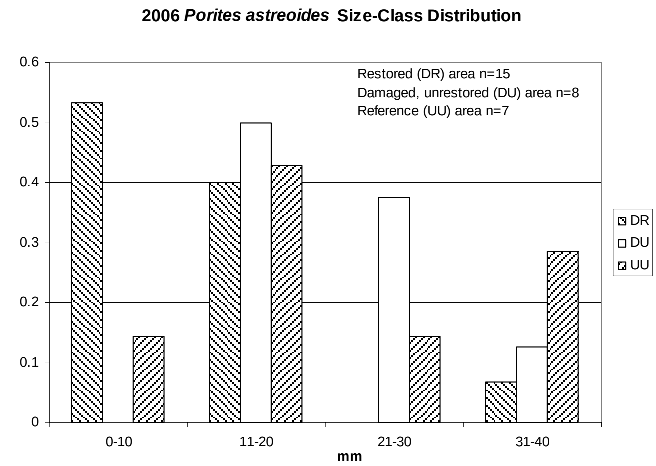


Figure 25. Milleporan recruit size (height) class frequency distribution in each of the three areas of the M/V *Wellwood* restoration site. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield five reasonably spaced and populated categories.

As regards Scleractinians, at the 2006 monitoring event, three species were present in sufficient numbers so as to make a size class frequency distribution analysis among them relatively meaningful. The species referred to are: *Agaricia* spp.; *Porites astreoides*, and *Siderastrea siderea*. This information is presented in two different fashions. Figure 26 shows the data categorized by location while Figure 27 depicts it grouped by species.

Figure 26. Recruit size (maximum diameter) class frequency distribution for three species of Scleractinians: *Agaricia* spp.; *Porites astreoides*, and *Siderastrea siderea*, grouped by location. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield five 10 mm range categories (*Agaricia*) or four categories (ending at 40 mm) for the other two species.





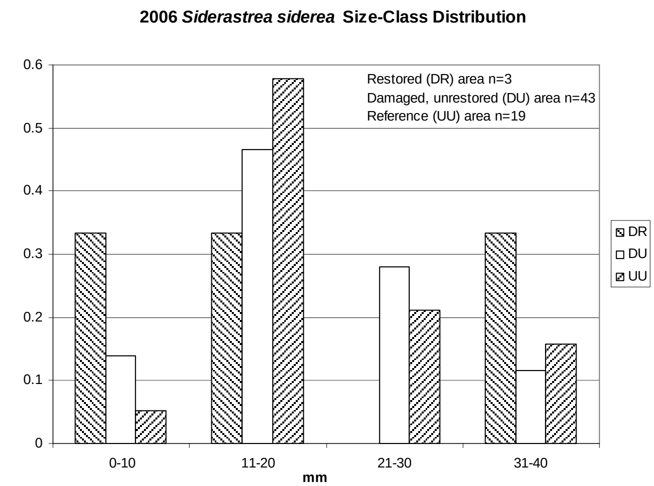
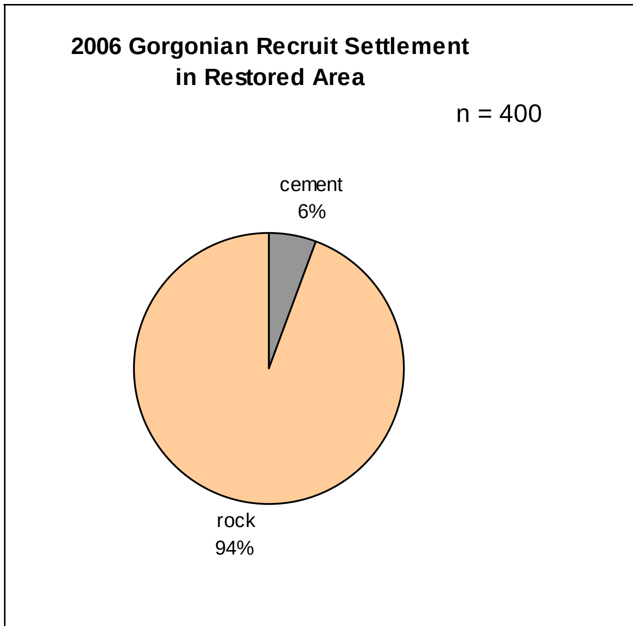
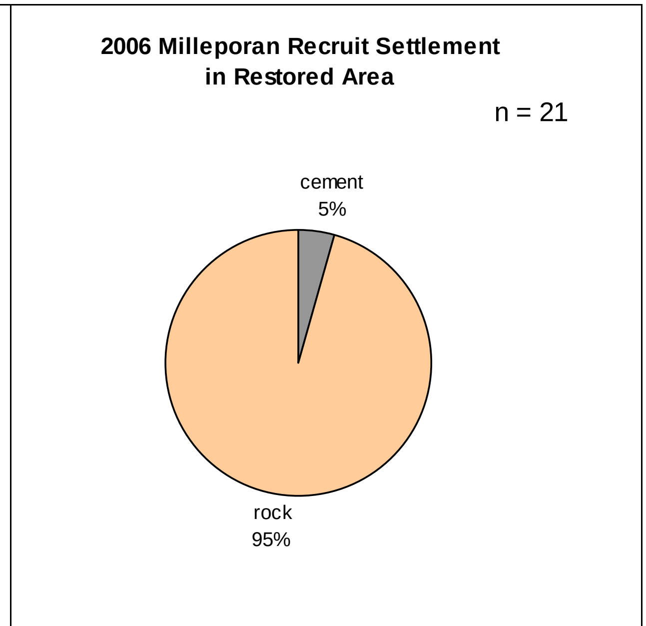


Figure 27. Recruit size (maximum diameter) class frequency distribution for three species of Scleractinians: *Agaricia* spp.; *Porites astreoides*, and *Siderastrea siderea*, grouped by species. The y-axis shows relative frequency (proportion). The largest size was determined by the maximum achieved in the restored area. Size classes were then selected so as to yield five 10 mm range categories (*Agaricia*) or four categories (ending at 40 mm) for the other two species.

As in 2004, the final analysis done for the 2006 data was a determination of how many of the recruits in the restoration area settled on the limestone rock versus concrete substrate. All limiting qualifications stated with respect to the 2004 information applies with equal force to the 2006 analysis. A qualitative sense of the relative space available may be ascertained from examination of the accompanying photographs, located in APPENDIX 1.





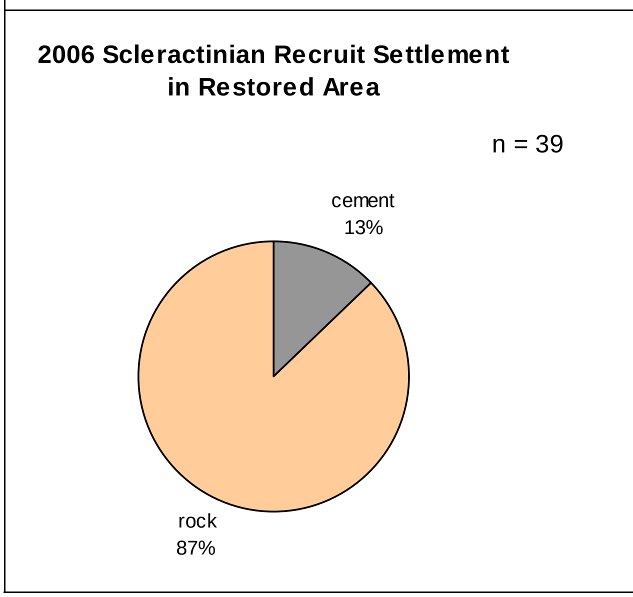


Figure 28. Percentage of Gorgonian, Milleporan, and Scleractinian recruits settling on limestone rock versus concrete substrate in the restored area of the M/V *Wellwood* restoration site.

DISCUSSION

The first overall impression one has from the data is that the damaged, unrestored and the reference areas are relatively similar, but that either is fairly distinguishable from the restored location. This is borne out by examination of both the 2004 and the 2006 data (Figure 13 and Figure 21). It is a rather unremarkable finding, given the fact that by 2006, the damaged, unrestored area had been undergoing recovery for some 22 years. More surprising is that by 2006, the restored area, despite having been restored only 4 years previously, was converging on the recruitment state of the other two locations (Figure 21)—at least as regards the parameters being monitored.

It should be noted at the outset that this suspected convergence (more about shortly) does *not* refer to the overall state of the area; either in appearance, percent coral cover, health, or any other parameter of the wellbeing of a reef, except the one being monitored for; namely, populations of recruit- (or at least "small-") size category organisms. Thus, the status of the damaged, unrestored and the reference areas are relatively similar in that regard, and the restored area is rapidly "catching up." It is not surprising that it should have lagged a bit behind the damaged, unrestored area, which—as noted above—had a long head start. Further, it is recognized that after placing artificial substrate, often a period must elapse before it becomes "conditioned" to the reef environment (through the deposition of biofilms and other mechanisms beyond the scope of this paper) so as to become receptive to the settlement of potential coral recruits.

Other qualifying factors that must be recognized upfront are that much of the methodology utilized here was constrained by certain necessary assumptions, as well as some restrictions imposed by practical considerations. For instance, it has been assumed that the maximum size attained by recruits in the restored area was the max. attainable in either of the other two areas. This is probably not entirely accurate, due to the conditioning period mentioned above, which could last for several months (Thus only the 2004 data would be significantly affected; the delay becomes proportionately less a factor over time). Once settlement occurs however, growth rates at the restored site were assumed to be as vigorous as at the other two. A converse assumption was likewise necessary; that is, that recruit growth at the damaged, unrestored and reference areas was equivalent to that in the restored area, such that there could be no possibility of fewer—but slower growing—recruits at those sites. These were felt to be reasonable assumptions (there being no growth-rate data leading one to presume otherwise), though their veracity has not been subjected to experimental confirmation. It need hardly be mentioned that the various assumptions incorporated constitute less than optimal monitoring methodology. More precision could have been obtained had the protocol provided for more specific (following individual recruits) as well as more discriminating (examination every few months) sampling. However, NMSP monitoring team budget, time, and manpower limitations precluded such possibilities.

Given the qualifying statements noted, what story does the data tell?

First, as noted above, recruit populations are becoming more similar, though still significantly different. In particular the population of Gorgonians, which had been extremely significantly different in 2004 ($P < 0.0001$) (Figure 13), were by 2006 no longer different, at least statistically (Figure 21).

Biodiversity had been a good deal greater at the restored area in 2004 as compared to the other sites (Table 3), but was somewhat lessened by 2006 (Table 5) such that all areas were relatively the same—in that regard—at that time (perhaps generally confirmatory of the intermediate disturbance hypothesis?).

One of the most interesting and potentially important results demonstrated was the fact that in 2006, the size-class frequency distributions revealed that the restored area always had a greater proportion of all taxa populations in the smallest size category (Figure 24, Figure 25, Figure 26, and Figure 27). Perhaps this is indicative of the fact that by this time, the modules had become preferential recruitment substrate. If so, in the coming years, as the absolute number of recruits to the areas continues to converge, and as the proportionately greater restored area small recruit cohort progresses through the size categories, overall populations in the restored area should overtake those at the other locations (assuming no differential mortality).

Turning attention to just the Scleractinians, what was said above applies with equal force to that group. However, with regard to *Siderastrea,* the observation is probably not very meaningful, as only five colonies were found among the Restored area quadrats in 2004 (Table 2), and only three in 2006 (Table 4).

This last statement gives rise to some intriguing questions: Why was the proportion (8%) of recruiting *Siderastrea* so paltry in the restored area relative to the damaged, unrestored and reference areas, where it comprised 57% and 39% respectively in 2006 (Figure 23)? Is there something about the area that is not conducive to settlement by the species? Focusing on the other two substantial recruiters, *Agaricia* and *Porites,* no such differential is exhibited. In fact, looking solely at those two species, recruitment across the three areas was almost exactly equal; cumulatively 30, 29, and 28 colonies at the restored, damaged, unrestored, and reference areas respectively (Table 4).

The questions are of more than academic interest. *Agaricia* and *Porites* are small species which brood their larvae, while *Siderastrea* is a large frame-building broadcast spawner (Edmunds et al 2004; Miller et al 2000). Because of the relatively small number involved, one must be guarded with respect to over interpretation of this data, and should probably consider the results conservatively as preliminary. Nonetheless, certainly this anomaly warrants heightened scrutiny; hopefully an answer may be discovered during the course of future monitoring episodes.

One aspect of coral recruitment appears capable of answer, if only a somewhat tentative one, at present. Settlers seem to prefer limestone rock, rather than concrete, as substrate. This apparent preference was remarkably consistent across taxa and time. In 2004, Gorgonians, Milleporans, and Scleractinians recruited to concrete at rates of only 3, 4, and 14% respectively; the respective proportions for 2006 were 6, 5, and 13% (Figure 19 and Figure 28). As previously mentioned, a determination regarding the strength of this preference would be more robust if certain quantitative techniques had been employed (see text accompanying Figure 19). Further, the apparent preference may or may not be due to the materials themselves, but perhaps to their configuration. That is to say, the rock displays a high degree of topographic complexity, while the concrete does not. The rock is highly crenellated, while the surface of the concrete is comparatively smooth. Also the rocks are packed fairly close together (see Figure 8, Figure 9, and Appendix 1) so their projections form niches under which recruits may shelter. This type of cryptic habitat is often favored by coral recruits (Adjeroud et al 2007; Perkol-Finkel & Benyahu 2007).

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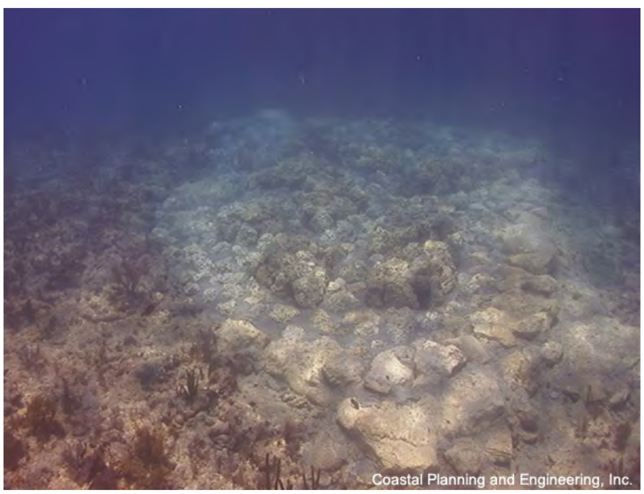
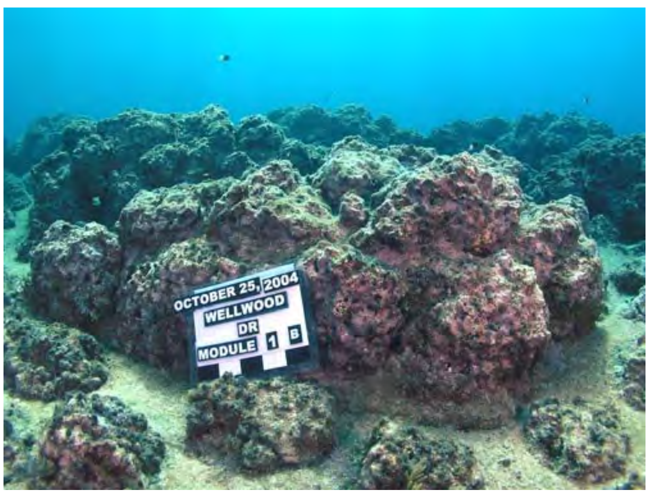
APPENDIX 1

Photographs of completed reef restoration module and puddle pour installations from June-July 2002 (photo credits: Florida Keys National Marine Sanctuary and Coastal Planning and Engineering, Inc.).



APPENDIX 2

Comparative photographs of reef restoration modules from October 2004 (left) and September 2006 (right) (photo credits: Jeff Anderson).



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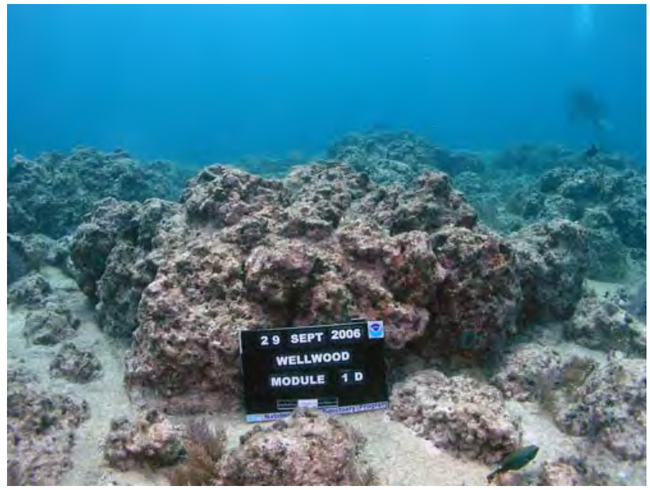

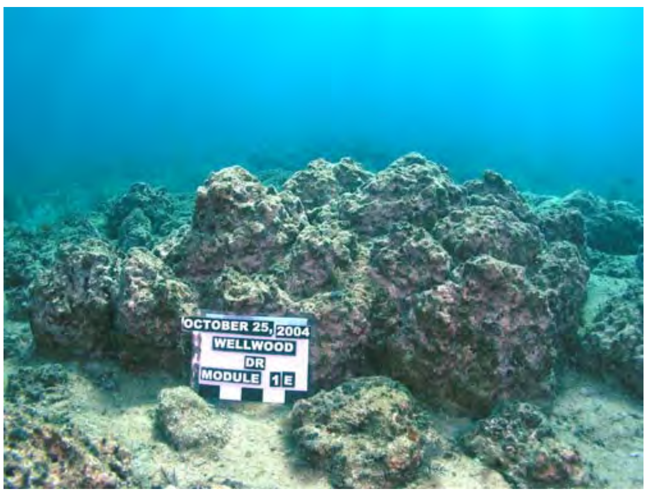

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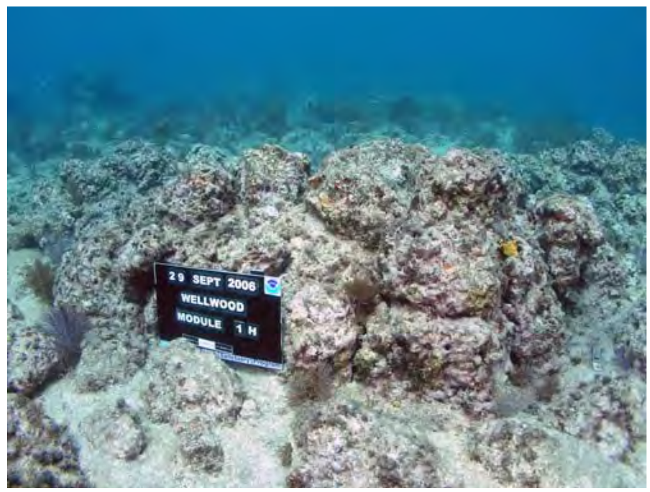

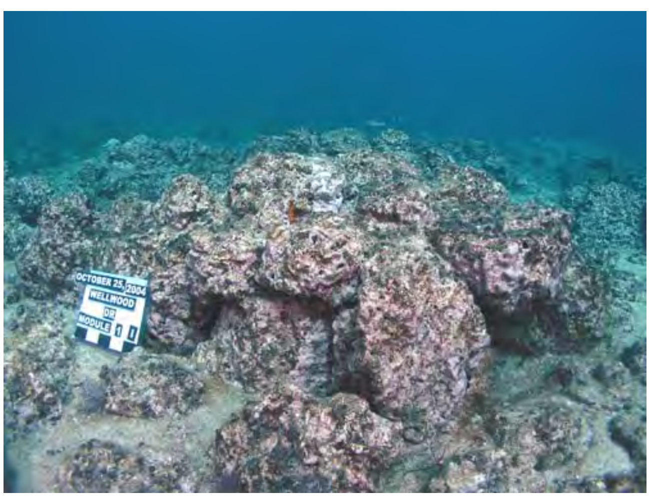

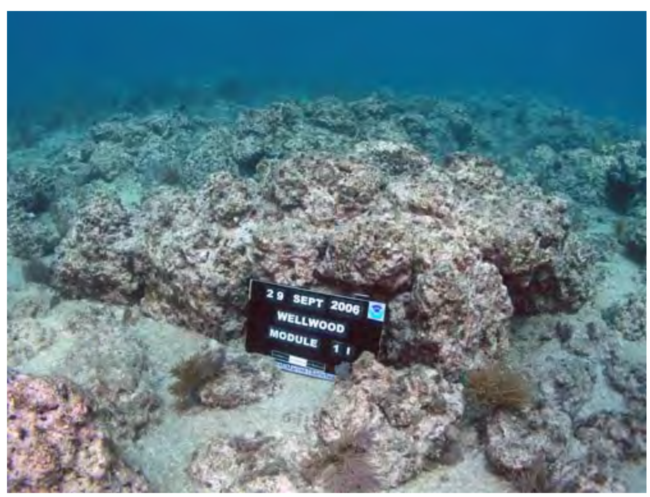

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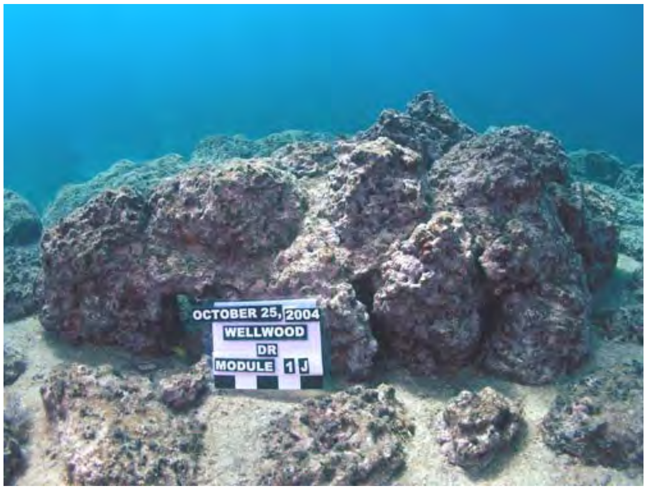

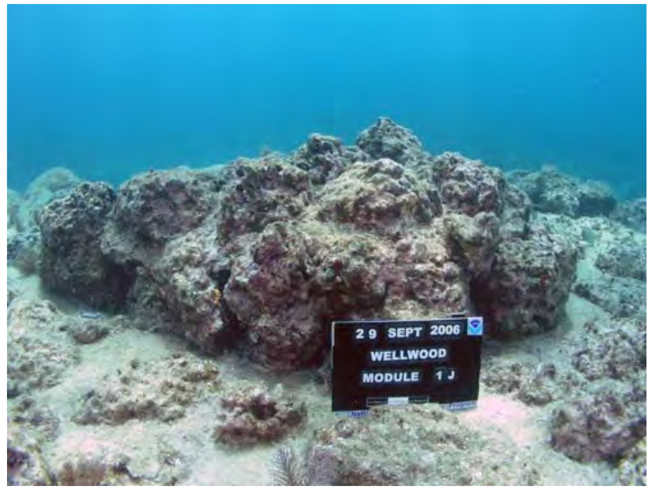

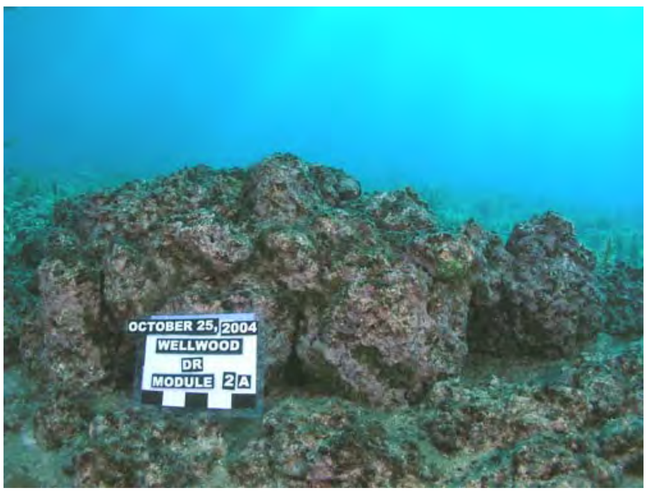

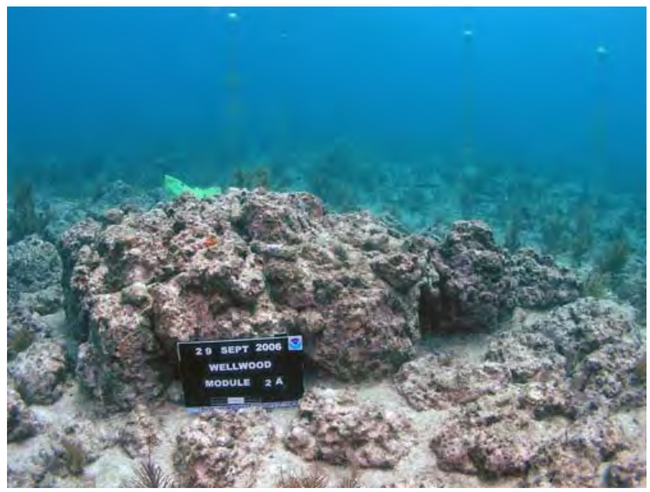

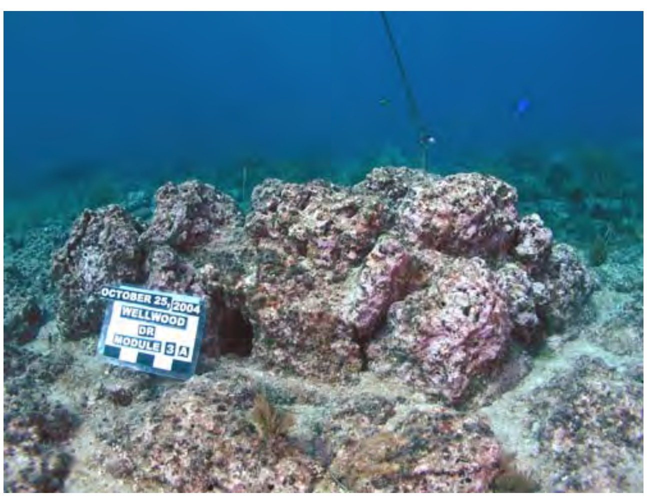

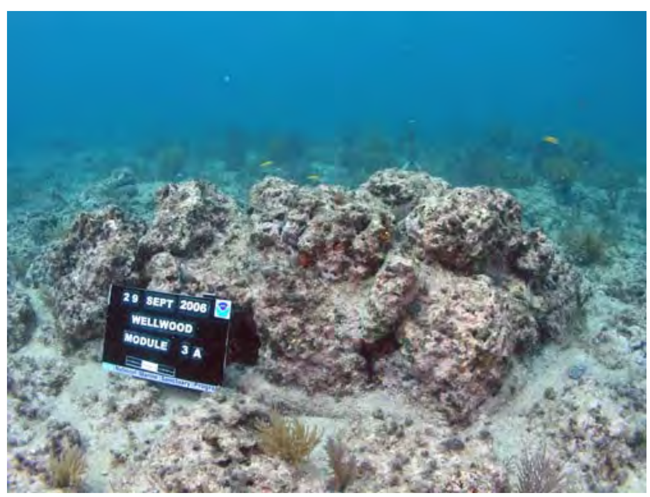

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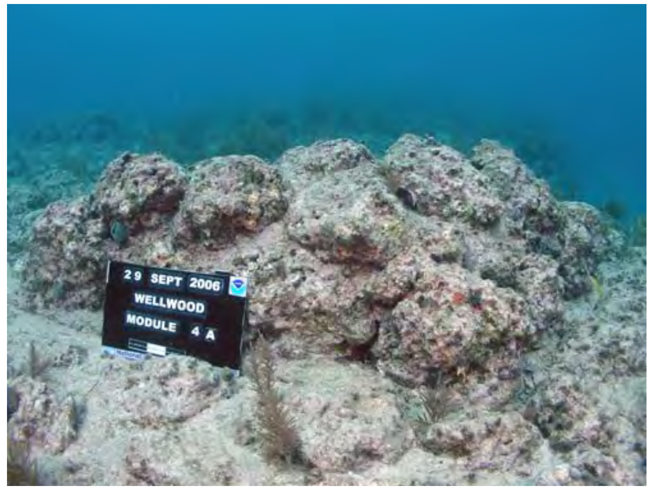

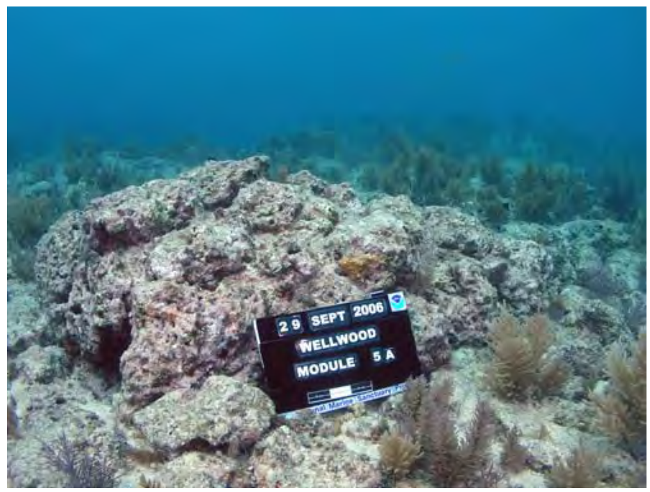

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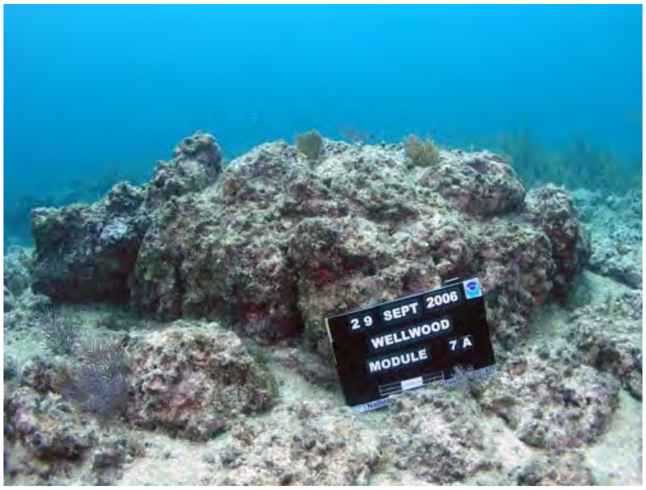

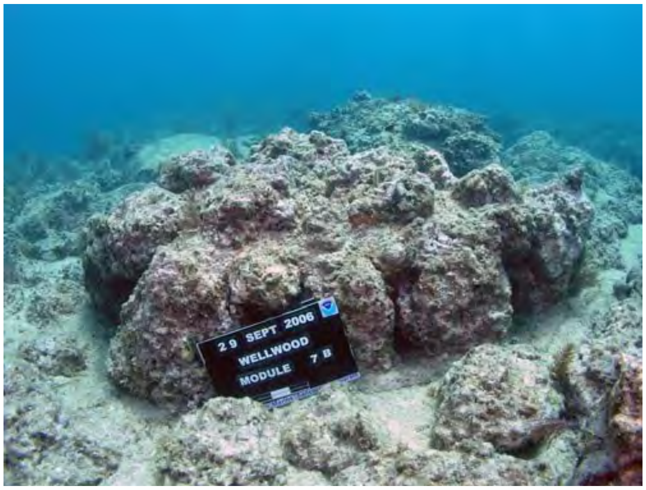

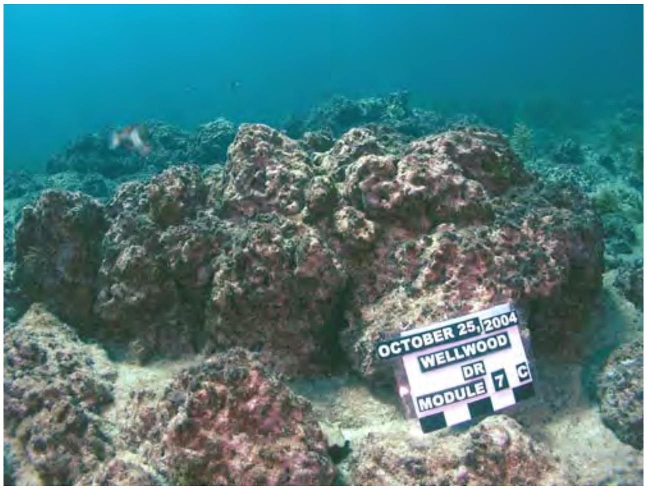

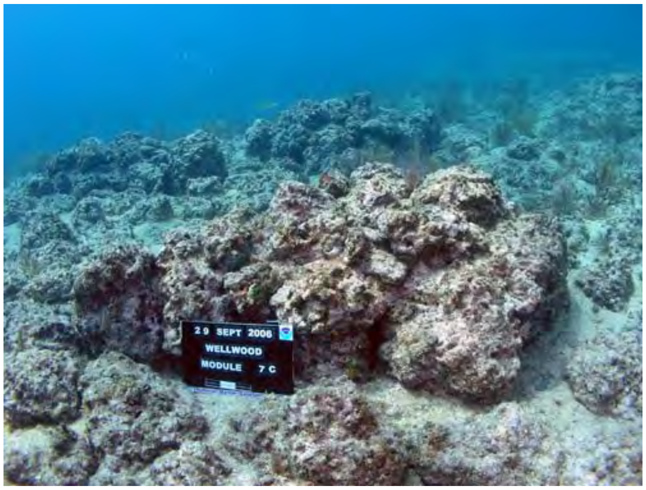

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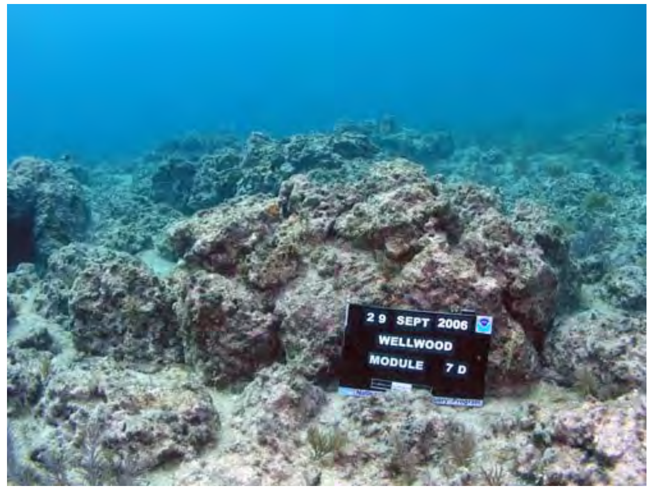

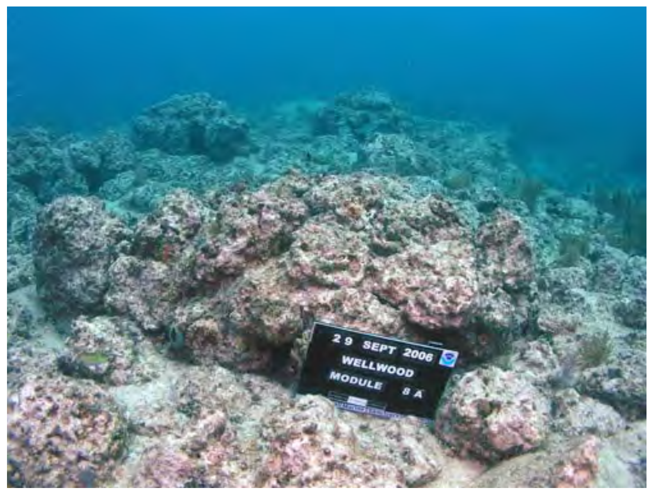

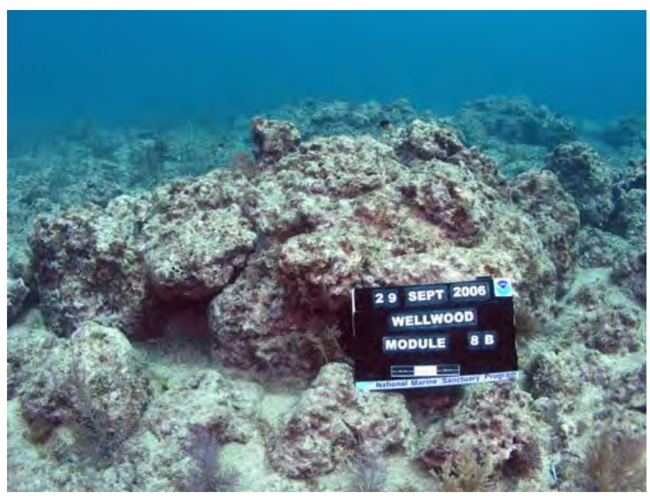

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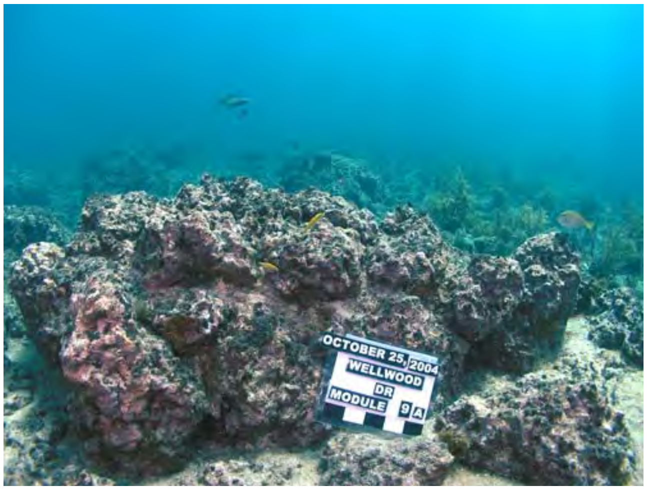
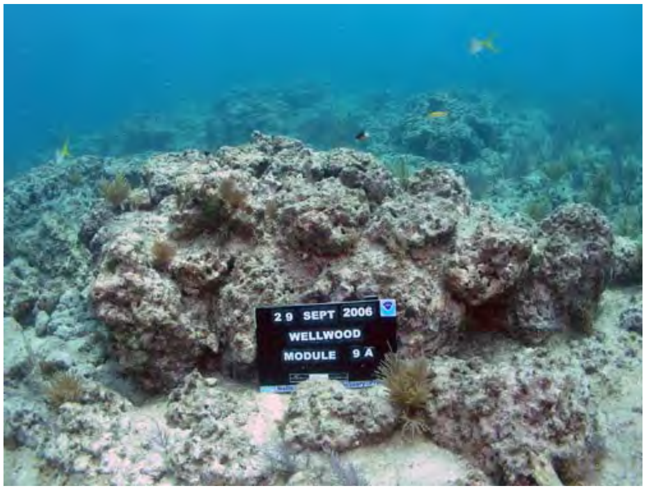
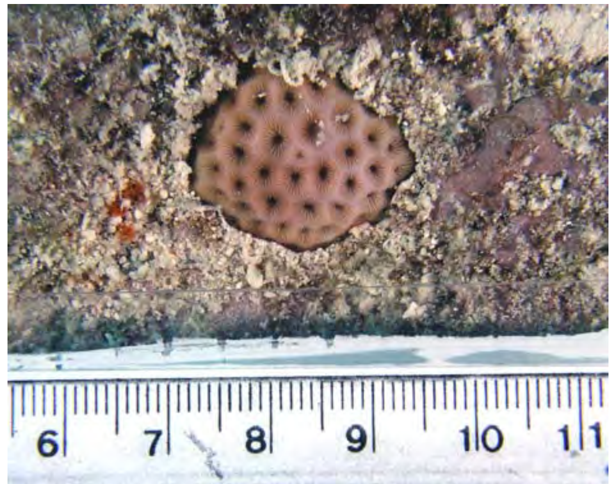
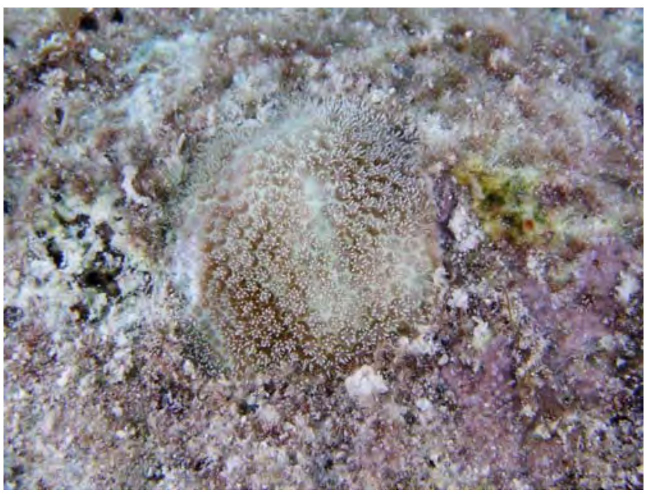


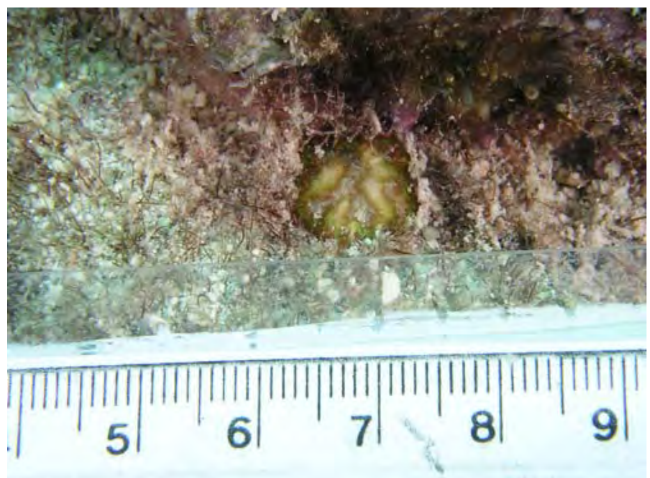


APPENDIX 3

Photographs of benthic species surveyed on reef restoration modules during September to November 2004 monitoring event (photo credits: Jeff Anderson).







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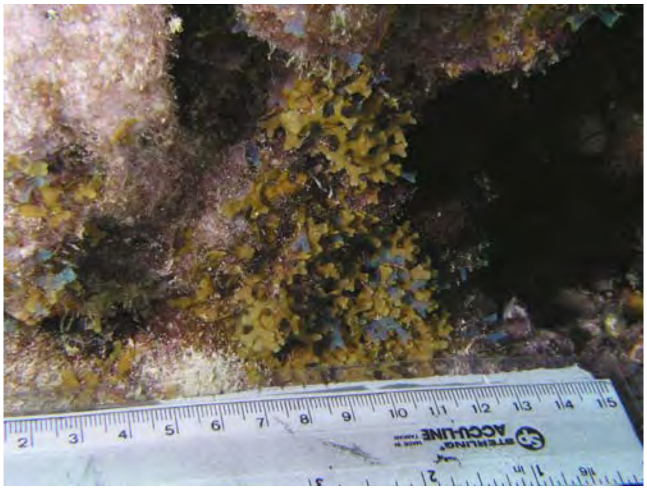

NMSP CONSERVATION SERIES PUBLICATIONS

To date, the following reports have been published in the Marine Sanctuaries Conservation Series. All publications are available on the National Marine Sanctuary Program website (http://www.sanctuaries.noaa.gov/).

2002 - 03 Florida Keys National Marine Sanctuary Science Report: An Ecosystem Report Card After Five Years of Marine Zoning (NMSP-06-12)

Habitat Mapping Effort at the Olympic Coast National Marine Sanctuary - Current Status and Future Needs (NMSP-06-11)

M/V *CONNECTED* Coral Reef Restoration Monitoring Report Monitoring Events 2004-2005 Florida Keys National Marine Sanctuary Monroe County, Florida (NMSP-06-010)

M/V *JACQUELYN L* Coral Reef Restoration Monitoring Report Monitoring Events 2004-2005 Florida Keys National Marine Sanctuary Monroe County, Florida (NMSP-06-09)

M/V *WAVE WALKER* Coral Reef Restoration Baseline Monitoring Report - 2004 Florida Keys National Marine Sanctuary Monroe County, Florida (NMSP-06-08)

Olympic Coast National Marine Sanctuary Habitat Mapping: Survey report and classification of side scan sonar data from surveys HMPR-114-2004-02 and HMPR-116-2005-01 (NMSP-06-07)

A Pilot Study of Hogfish (*Lachnolaimus maximus* Walbaum 1792) Movement in the Conch Reef Research Only Area (Northern Florida Keys) (NMSP-06-06)

Comments on Hydrographic and Topographic LIDAR Acquisition and Merging with Multibeam Sounding Data Acquired in the Olympic Coast National Marine Sanctuary (ONMS-06-05)

Conservation Science in NOAA's National Marine Sanctuaries: Description and Recent Accomplishments (ONMS-06-04)

Normalization and characterization of multibeam backscatter: Koitlah Point to Point of the Arches, Olympic Coast National Marine Sanctuary - Survey HMPR-115-2004-03 (ONMS-06-03)

Developing Alternatives for Optimal Representation of Seafloor Habitats and Associated Communities in Stellwagen Bank National Marine Sanctuary (ONMS-06-02)

Benthic Habitat Mapping in the Olympic Coast National Marine Sanctuary (ONMS-06-01)

Channel Islands Deep Water Monitoring Plan Development Workshop Report (ONMS-05-05)

Movement of yellowtail snapper (Ocyurus chrysurus Block 1790) and black grouper (Mycteroperca bonaci Poey 1860) in the northern Florida Keys National Marine Sanctuary as determined by acoustic telemetry (MSD-05-4)

The Impacts of Coastal Protection Structures in California's Monterey Bay National Marine Sanctuary (MSD-05-3)

An annotated bibliography of diet studies of fish of the southeast United States and Gray's Reef National Marine Sanctuary (MSD-05-2)

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A Review of the Ecological Effectiveness of Subtidal Marine Reserves in Central California (MSD-04-2, MSD-04-3)

Pre-Construction Coral Survey of the M/V Wellwood Grounding Site (MSD-03-1)

Olympic Coast National Marine Sanctuary: Proceedings of the 1998 Research Workshop, Seattle, Washington (MSD-01-04)

Workshop on Marine Mammal Research & Monitoring in the National Marine Sanctuaries (MSD-01-03)

A Review of Marine Zones in the Monterey Bay National Marine Sanctuary (MSD-01-2)

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