



***GUIDELINES AND RECOMMENDATIONS
FOR CORAL REEF RESTORATION
IN THE
FLORIDA KEYS NATIONAL MARINE SANCTUARY***



WORKSHOP REPORT

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PREFACE

The National Undersea Research Center at the University of North Carolina at Wilmington has evolved since its inception in 1980 (through a competitive process) into an environmental research program capable of conducting and supporting undersea research in virtually any coastal or oceanic setting. The Center is funded by a grant from NOAA's Office of Undersea Research to promote, coordinate, facilitate and conduct undersea research in the southeastern United States. The Center defines its role as a facilitator, coordinator and participant in NOAA's stated "health of the oceans" research agenda, with responsibility for superimposing a regional set of research priorities, and then working with the academic community to draw in the best researchers to address environmental problems. The Center expends considerable time and effort in helping to define important and relevant regional science issues, and subsequently participating in the research programs to ensure that results are quickly available to ocean managers and apply to identified issues.

Center research goals reflect changing national and regional research needs. To address applied and fundamental undersea research initiatives the Center uses several approaches. Ad hoc workshops and meetings are conducted to help define and refine current research initiatives, and to help enhance interagency coordination and communication. The most significant 5-year operational plan currently underway involves the Center's Florida program. The Center's Florida program provides state-of-the-art diving technology (including manned submersibles and ROVs), boats, shore-based support and modest funding to scientists through a rigorous and competitive peer review process. Over 75 research projects have been funded since 1991. Research supported by the Center in Florida is directed to increase knowledge of the health and status of nearshore ecosystems in the Keys, particularly coral reef ecosystems. Research addressed in 1991-1993 focused on the threat of nutrient pollution, coral diseases and coral bleaching, feeding biology of corals, erosion of reefs, geological studies related to climate and sea level history of south Florida, effects of ultraviolet radiation on marine organisms and several studies related to fisheries ecology.

The document produced here reflects the Center's continuing efforts to help resource planners address scientific issues of particular relevance to the management needs of the Florida Keys National Marine Sanctuary. Specifically, prior to initiating coral reef restoration efforts to repair injuries caused by several large vessel groundings, NOAA's Sanctuaries and Reserves Division funded the Center to organize a workshop to obtain recommendations from coral reef experts regarding: 1) the appropriateness of various methods to restore reefs; 2) methods to evaluate restoration techniques; and 3) projects to advance knowledge about coral reef restoration ecology. Results of the workshop will also be used by the Center to help define its Florida science program in 1994 and beyond.

EXECUTIVE SUMMARY

The National Undersea Research Center at the University of North Carolina at Wilmington was funded by NOAA's Sanctuaries and Reserves Division to conduct a workshop to develop an independent assessment of coral reef restoration capabilities and methodologies, particularly related to restoring coral reefs damaged by large vessel groundings in the Florida Keys National Marine Sanctuary. Based on existing knowledge, the workshop participants concluded that there is much that they could recommend to accelerate the recovery of reefs damaged by ship groundings. A consensus definition developed by the group defined coral reef restoration as a proactive program designed to speed recovery of a damaged reef to an endpoint that has aesthetic value and is functional as a coral reef system.

Results of the workshop clearly indicate that NOAA should hire additional staff and develop a quick-response capability to meet the needs of injury assessment, mitigation and restoration. Structural damage to reef framework was distinguished from damage caused to living resources, and structural repair to minimize or eliminate the potential for secondary damage must be completed before other restoration activity begins. However, action to restore or mitigate damage to the reef framework must be sufficiently evaluated and supervised to insure that the work does not itself cause significant additional damage, during or after repairs. Regarding restoration of living resources, stresses (natural or anthropogenic) to reefs in the Keys are not considered sufficiently threatening to contraindicate substantial restoration efforts. Immediate replacement and recovery of dislodged or threatened corals and toppled reef fragments that survive grounding events should be accomplished. If time constraints prevent this, survivors should be recovered and set aside in coral gardens or safe areas until they can be reattached. This is particularly important because large slow growing corals that might act as donor populations for transplants are rare in the Keys, if they exist at all.

Restoration efforts must include long-term monitoring components that incorporate (but are not limited to) studies at the community level, the use of indicator species, coral recruitment patterns, sclerochronology and related measurements, metabolic measurements, zooxanthellae loss/stress, reproductive biology and physical oceanographic measurements. Restoration projects that do not include a monitoring component miss a valuable opportunity to advance knowledge about how coral reefs function. This is particularly relevant in Florida because several different physiographic regimes affect the reef tract (reefs in the Keys span two degrees of latitude and are at their extreme northern limit of distribution) and results obtained at one site may not be applicable elsewhere. The best way to ensure that restoration projects of highest scientific merit and relevancy to management goals are supported is to solicit proposals in open competition that are then peer-reviewed by an independent panel of experts.

Each grounding site will require a specific restoration plan, and the goal of the restoration effort should be defined for each site prior to the start of the restoration activity. Recommendations for restoring specific grounding sites in the Keys include the following: 1) A detailed quantitative re-evaluation of natural recovery at the *Wellwood* site. Also, the status of coral transplants attached after the grounding should be assessed to determine whether or not those transplants accelerated natural recruitment processes or provided sufficient habitat complexity to enhance other aspects of community recovery; 2) The use of artificial structures (that mimic coral formations) at the *Wellwood* grounding site is an obvious course of action, especially since the bottom is stable and secondary damage is no longer a threat; 3) The nine-year-old *Wellwood* site is also extremely valuable as a control site for evaluating natural rates of recovery. The nine-year record should be carefully evaluated before any restoration activity begins at the site; 4) Further, at least half the site should be left alone to continue long-term monitoring of natural recovery

rates; 5) Restoration activity at the *Alec Owen Maitland* and *Elpis* grounding sites should be directed to stabilize the bottom to prevent secondary damage at the sites; 6) All these activities should begin as soon as possible after detailed prerestoration monitoring efforts are completed, both inside the injured sites and in reference areas.

There was consensus that active intervention to restore reefs can be accomplished within a framework that also advances knowledge about how coral reef ecosystems are structured and function. Basic knowledge about the system is what allowed workshop participants to make recommendations about how best to enhance recovery and restore reefs. A long-term commitment to coral reef restoration by the FKNMS will additionally yield unprecedented data that will help resource planners and managers better protect all coral reef resources in the Florida Keys.

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Dr. Charles Wahle organized several workshop topics and helped by leading some workshop discussions. Dr. Richard Aronson, Dr. Charles Birkeland, Mr. Steven Blair, Dr. Stephen Gittings, Mr. Walter Jaap, Dr. John Ogden, Dr. Paul Sammarco and Dr. Robbie Smith provided comments on the first draft of the report that substantially improved the effort. Special thanks are due to Ms. Darlene Finch, who provided help and inspiration during all phases of the workshop.

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CORAL REEF RESTORATION WORKSHOP REPORT

1.0 INTRODUCTION

The Florida Keys reef tract lies adjacent to one of the world's busiest shipping lanes. To large vessel traffic, the reefs present a significant navigational hazard. To the U.S. government and its people, the reefs are a national treasure. Prior to December 1990, two areas of the reef tract were designated to help protect the unique resources of these marine areas: Key Largo National Marine Sanctuary (KLNMS) and Looe Key National Marine Sanctuary (LKNMS). After November 1990, the entire Florida Keys reef tract and adjacent nearshore waters and ecosystems were designated by Congress as the Florida Keys National Marine Sanctuary (FKNMS, Figure 1). Under the Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA), the National Oceanic and Atmospheric Administration's (NOAA) Sanctuaries and Reserves Division (SRD) manages and protects Sanctuary resources.

Section 312 of the MPRSA authorizes NOAA to pursue civil actions to recover damages for destruction, loss of or injury to Sanctuary resources, including the cost of replacing, restoring, or acquiring the equivalent of the damaged resource. To date, NOAA has recovered over 3.5 million dollars to conduct coral reef restoration activities in the KLNMS as a result of four grounding incidents: 1) The M/V *Wellwood*, a 400 foot Cypriot-registered vessel, which grounded at Molasses Reef on August 4, 1984, and remained on the reef for 12 days. Coral and other Sanctuary resources were injured in an area of approximately 4,865 square meters; 2) The M/V *Mini-Laurel*, a 215-foot Panamanian-registered freighter, which grounded on Molasses Reef on December 11, 1986. Coral and other Sanctuary resources were injured in an area of approximately 513 square meters; 3) The M/V *Alec Owen Maitland*, a 155-foot domestic heavy equipment freighter, which ran aground south of the Carysfort Reef Lighthouse on October 25, 1989. Coral and other Sanctuary resources were injured in an area of approximately 1,610 square meters; and 4) The M/V *Elpis*, a 470-foot Greek registered freighter carrying 14,000 metric tons of sugar, which ran aground near the Elbow Reef light in KLNMS on November 11, 1989. Coral and other Sanctuary resources were injured in an area of approximately 3,073 square meters. The workshop addressed restoration of the *Wellwood*, *Maitland* and *Elpis* grounding sites, which are indicated on charts presented in Figure 2.

Destruction caused to living corals and the reef matrix by the vessel groundings was substantial, and rates of natural recovery have been slow. Indeed, damage to the reefs may be permanent. Good descriptive information of the damage was compiled for the *Wellwood*, *Maitland* and *Elpis* grounding sites (Bright and Andryszak 1984; Curtis 1985; Gittings and Bright 1990; Gittings 1991a,b), and information related to coral transplantation efforts (Hudson and Diaz, 1988) and recovery of algae, fish and corals (Littler et al. 1987, Dennis and Bright 1988, Gittings et al. 1988, Hanisak et al. 1989a,b) at the *Wellwood* site is available. However, the sites have not been re-evaluated in several years and significant restoration efforts have not yet begun. Prior to initiating restoration efforts, SRD funded NOAA's National Undersea Research Center at the University of North Carolina at Wilmington (NURC/UNCW) to organize a workshop to obtain recommendations from coral reef experts regarding: 1) the appropriateness of various methods to restore reefs (ecological and structural considerations); 2) methods to evaluate restoration techniques (monitoring); and 3) projects to advance knowledge about coral reef restoration ecology.

The Coral Reef Restoration Workshop was held in Key Largo April 13 to 15, 1993 (Appendix A). Workshop participants included experts with broad experience in coral reef biology, resource managers and SRD staff (Appendix B). A major reason SRD funded the meeting was to obtain an *independent assessment* of how best to restore reefs damaged by large vessel groundings in the FKNMS.

Recommendations of highest priority identified during the workshop stand alone in the text, are highlighted in bold style and are summarized in Appendix D.

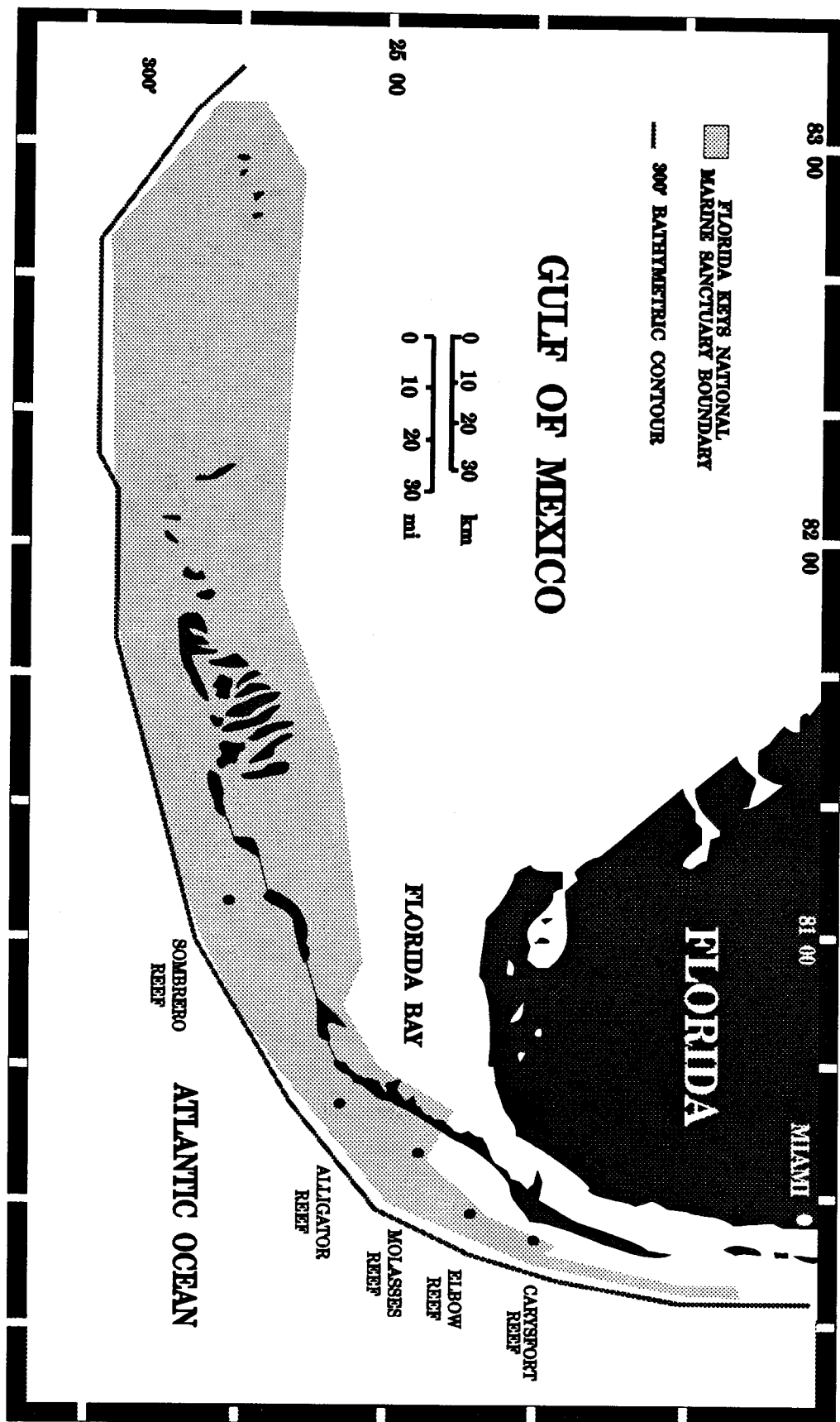


Figure 1. Map of Florida Keys National Marine Sanctuary.

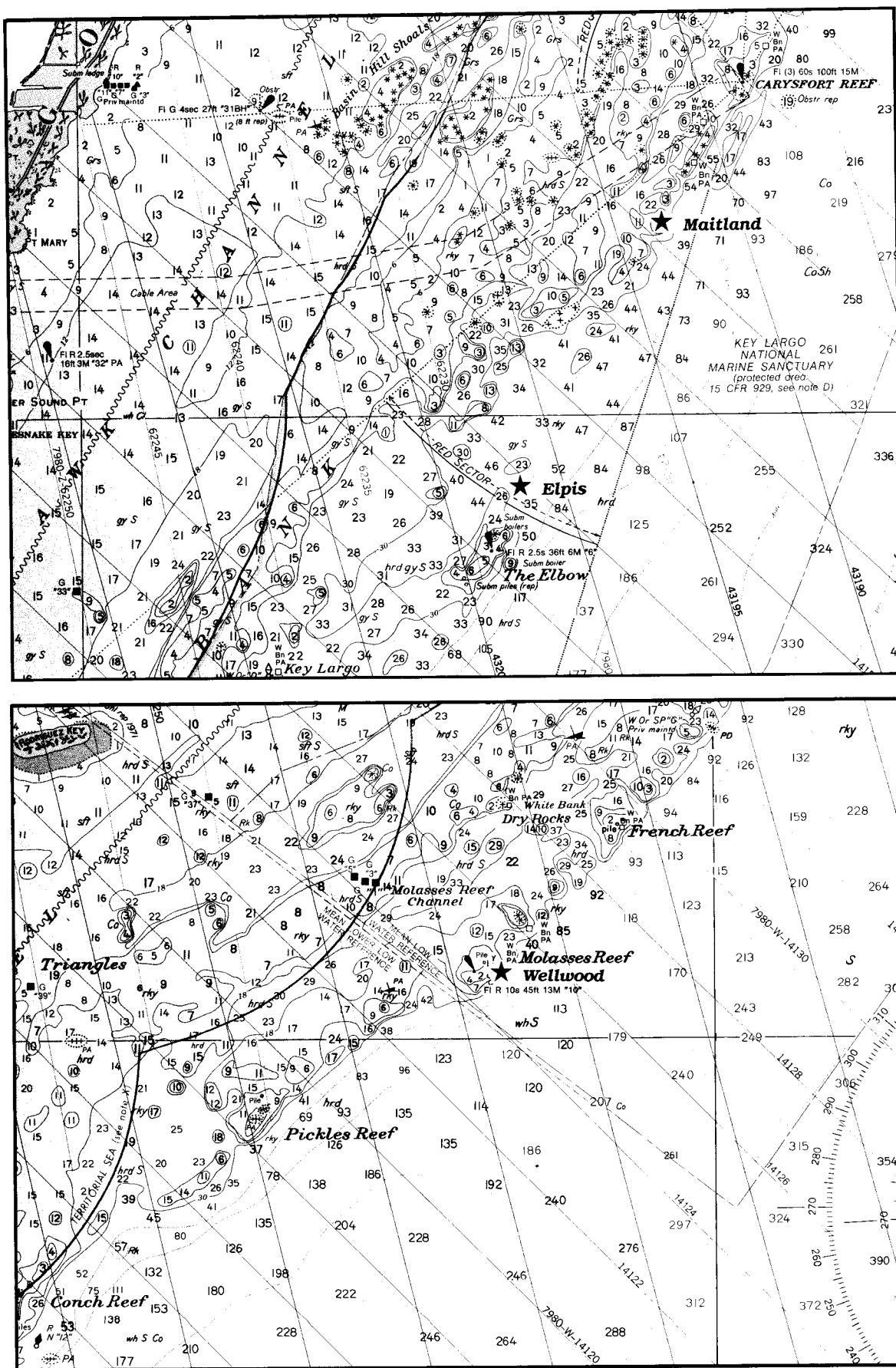


Figure 2. Portions of NOAA chart #11462 that indicate Wellwood (near Molasses Reef), Maitland (near Carysfort Reef) and Elpis (near Elbow Reef) grounding sites.

2.0 INJURY ASSESSMENT

When a major vessel grounding occurs in the FKNMS, the federal government and potentially the State of Florida are the responsible parties for response and injury assessments. There is a memorandum of agreement between NOAA and Florida's Department of Natural Resources (recently reorganized into the Florida Department of Environment Protection) that defines the protocol and responsibilities for responding to vessel groundings. Causey (1990) describes actions taken by Sanctuary biologists to quantify injury to coral reefs at grounding sites. Since large vessel groundings involve salvage operations, the U.S. Coast Guard is also frequently involved. The competing interests of vessel salvage, injury assessment and mitigation often conflict when the ship remains on the reef for more than a few hours or days. Safety must be the paramount consideration until the grounded vessel is removed from the reef.

Within the constraints of the salvage operation and damage assessment needs, action should be taken to save, right or stabilize dislodged coral heads and surviving coral fragments resulting from the grounding.

Salvage and injury assessment activities are labor intensive. A sufficient number of trained staff must be available to meet the quick-response needs of large vessel groundings. The number of people that comprise the injury assessment team (four individuals for the entire reef tract, each with substantial other responsibilities, as well) is not adequate to handle the damage assessment, mitigation and restoration needs of the Sanctuary.

NOAA should hire additional staff and develop a quick-response capability to meet the needs of injury assessment, mitigation and restoration.

Trained, paid personnel are recommended over volunteers. The value of existing staff expertise is substantial, but unless additional personnel are trained there is a real danger that NOAA will lose significant knowledge and capability through retirements and staff turnover.

2.1 PHOTOGRAPHIC/VIDEO DOCUMENTATION

In situ documentation of damage caused by large vessel groundings was not considered a difficult task by workshop participants. Existing technology and methodologies that are compatible with monitoring the long-term recovery of the site (Porter 1972, Weinberg 1981, Rogers et al. 1983, 1988, Hudson and Diaz, 1988, Bythell et al. 1992) should be used whenever possible. In particular, underwater video and 35 mm photography should be used to quantify baseline conditions, both inside the damaged site and in adjacent non-damaged reef areas. A combination of methodologies will be required to adequately document injury and recovery. Since vessel groundings can demolish a reef beyond recognition, two concerns were expressed: 1) what information cannot be derived from underwater video or photography and 2) how do you measure or assess the potential for secondary damage? Secondary damage to the reef and its living resources is caused when boulders, rubble, sand or other material dislodged from the reef by the vessel grounding are moved by waves, particularly during storms, causing additional injury.

There were several categories of damage identified at the *Wellwood* site during a snorkeling trip by workshop participants and in video presentations of the *Elpis* and *Maitland* grounding sites including: cracks in the reef framework, obliterated spurs and other framework destruction; fractured coral colonies; excavations caused by propeller wash; production of rubble, either directly by the ship or secondarily from reef matrix exposed to wave action; and sand produced by the ship grinding on the bottom. Workshop participants were generally impressed by the extent of damage caused at the grounding sites. A portion of the injured *Wellwood* site is indicated in Figures 3, 4 and 5. A rubble pile at the *Maitland* grounding site is indicated in Figure 6.

When baseline data are not available to describe community characteristics prior to vessel groundings, scientifically-based comparisons in undamaged areas on the same reef can reasonably be used to assess the

preinjury condition of damaged resources. Additionally, to help ensure that adequate baseline data exist along the reef tract related to reef structure and community development, especially since few sites have video or photographic documentation,

High resolution aerial photographs should be taken of reefs subject to damage by ship groundings, such as shallow or emergent reefs identified as Sanctuary Preservation Areas in the FKNMS management plan.

2.2 SECONDARY DAMAGE

The potential for small boulders and rubble to cause damage depends on many factors, such as the size distribution of the fragments, the number of fragments, whether or not the rubble is contained in a depression or is lying free on flat bottom, the depth of the site and the frequency of major storms. The potential for sand to cause damage follows similar principles. Mitigating secondary damage is discussed below, but it should be recognized that some secondary damage is probably inevitable.

Secondary damage can also delay reef recovery by preventing or slowing natural recovery processes and restoration efforts. An unstable bottom does not provide suitable habitat for settlement and growth of corals and is likely to be a major reason why damaged sites do not recover naturally.

When the threat of secondary damage is high, rubble and sand that are produced by the grounding or from damaged framework should be monitored to document the amount of material produced and its fate.

A monitoring program that measures rubble production from excavations, and evaluates the threat of secondary damage is warranted when the monetary cost of restoration is high. Sand and rubble are natural components of most reef systems and restoration efforts at each grounding site will need to be evaluated against a background of rubble and sand that is naturally prevalent on the reef.

3.0 GOALS OF CORAL REEF RESTORATION

Restoration was defined by SRD staff as "recovery to conditions that existed prior to damage caused by the ship grounding." This goal directed approach (with a legal rationale) was determined without consideration of whether or not reefs could be directed toward this end, naturally or through intervention. There was unanimous agreement that a working definition of restoration should include both a "mitigation component" and a "recovery enhancement component." Based on existing knowledge, the workshop participants concluded that there is much that they could recommend to accelerate the recovery of reefs damaged by ship groundings.

A consensus definition developed by the group defined coral reef restoration as a proactive program designed to speed the recovery of a damaged reef to an endpoint that has aesthetic value and is functional as a coral reef ecosystem.

In the above statement, "proactive" includes actions that mitigate damage or enhance the rate of recovery. The amount of time required to achieve restoration remains unclear, given the present state of knowledge. Immediate or "instant-reef-restoration" solutions based on transplanting large adult colonies could not be recommended because there are too few large adult colonies in the Keys. Natural rates of recovery in systems that are not recruitment limited can take anywhere from less than a decade to more than a century (Pearson 1981). In Bermuda, Smith (1993) estimated recovery at a rate of 25 cm²/m²/year of coral coverage after 14 years of regrowth at a grounding site. In the Keys, the few studies that have looked at community dynamics suggest that recruitment is limited and that natural recovery from damage caused by ship groundings is slow. However, few long-term studies exist and many site specific factors will affect recovery.

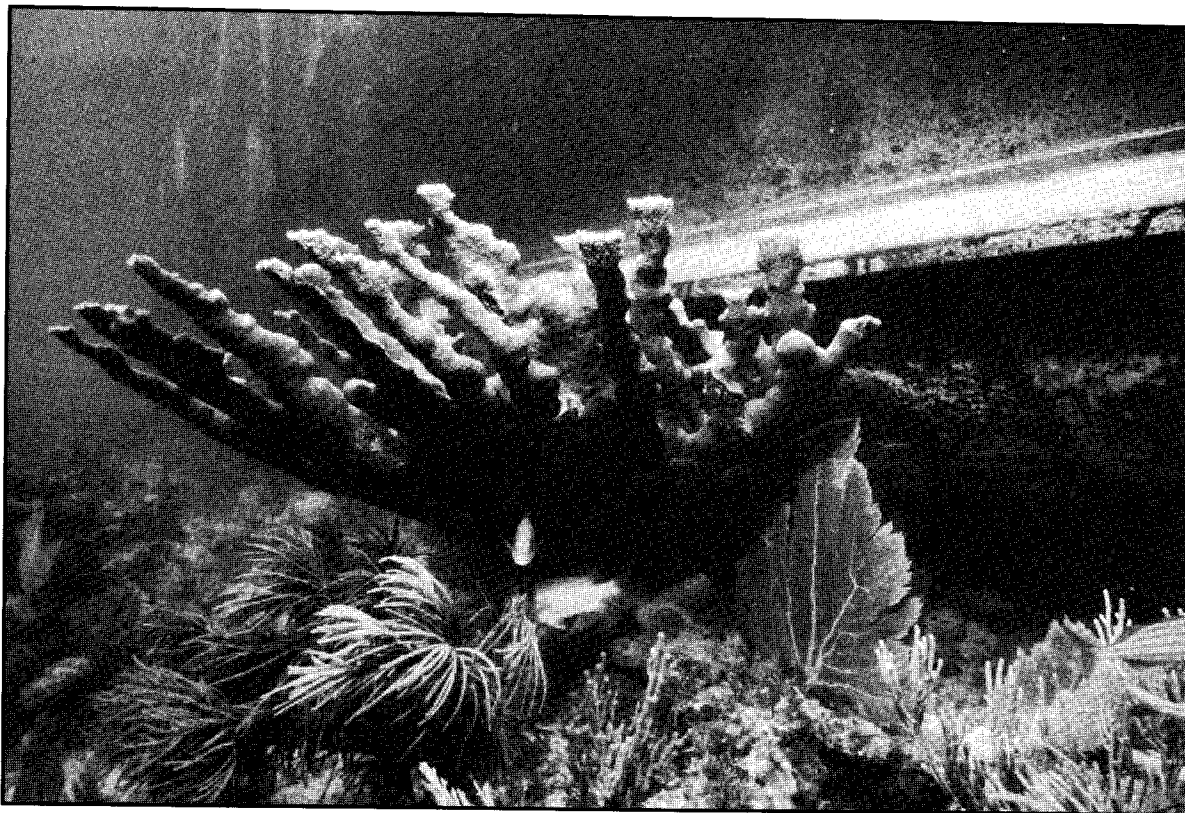


Figure 3. M/V Wellwood aground on Molasses Reef, FKNMS. Contrast healthy coral and three dimensional reef framework adjacent to ship with flattened pavement in Figure 4.

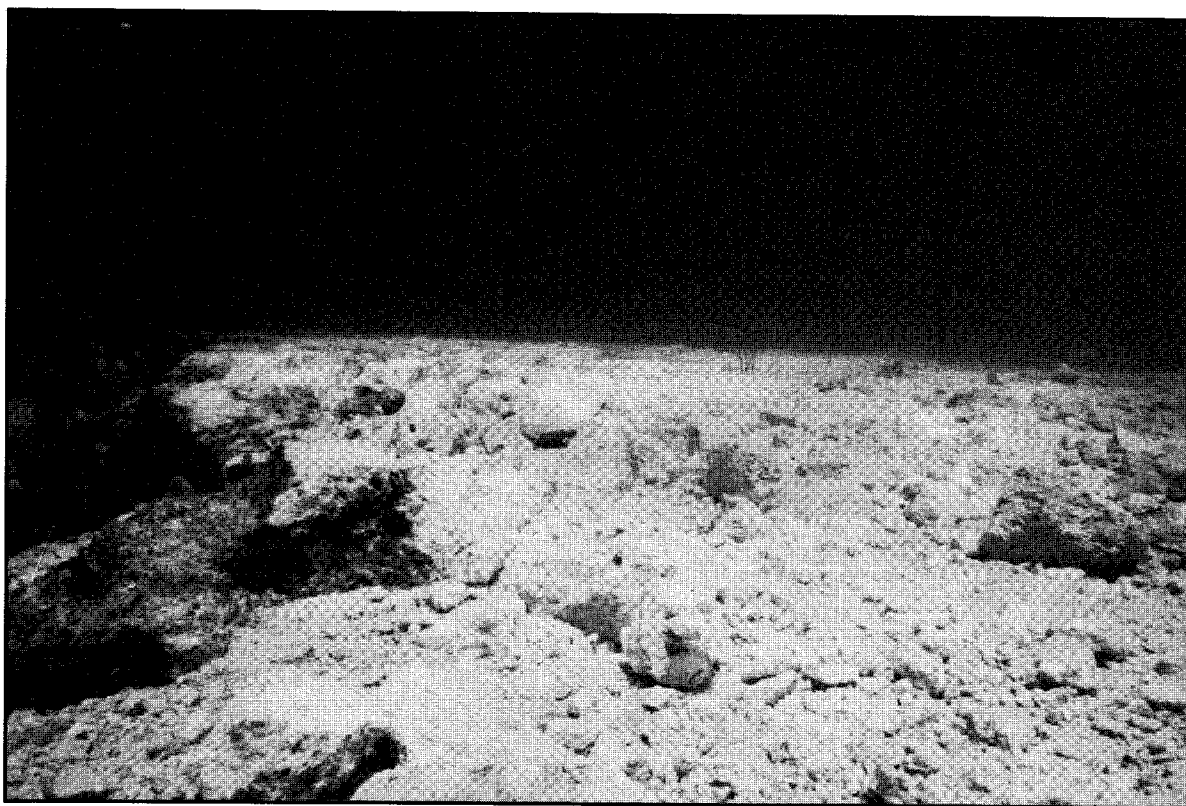


Figure 4. Scoured and flattened pavement that was caused when the the M/V Wellwood grounded on Molasses Reef, Florida Keys National Marine Sanctuary.

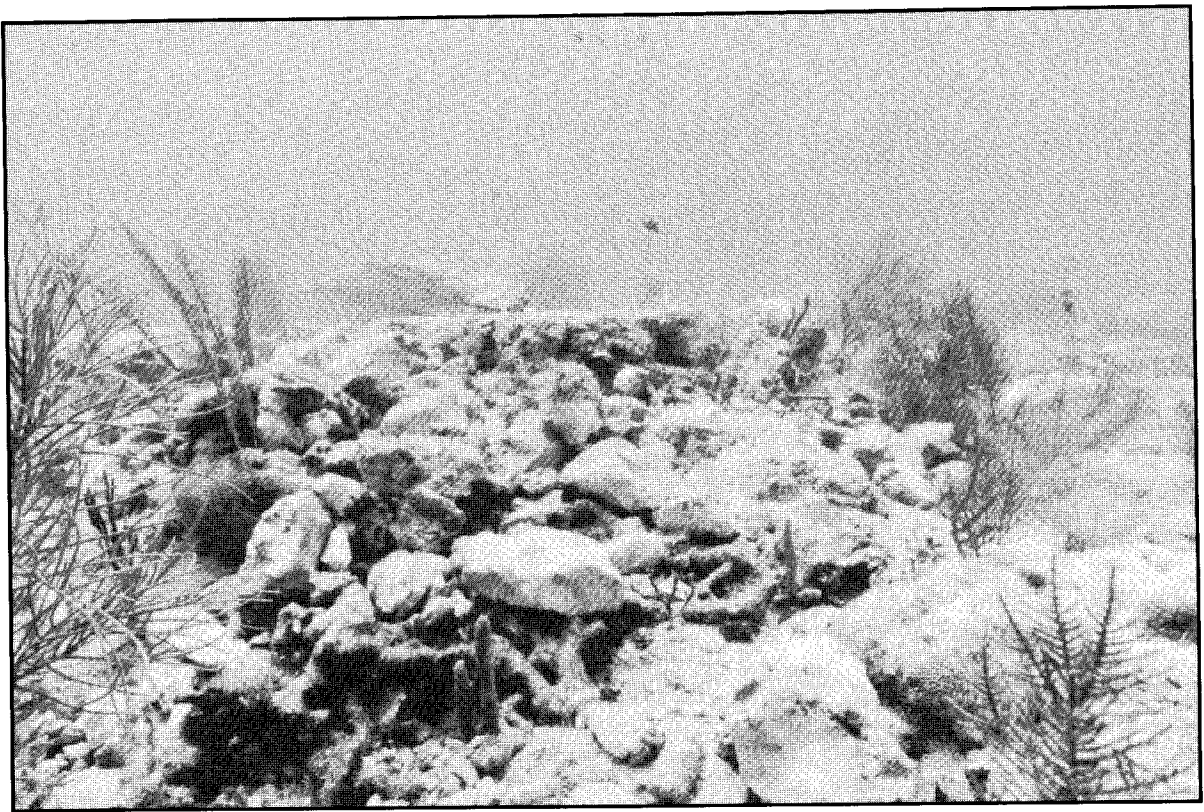


Figure 5. Damaged framework materials, overturned coral heads and broken sea fans caused when the M/V Wellwood grounded on Molasses Reef, Florida Keys National Marine Sanctuary.

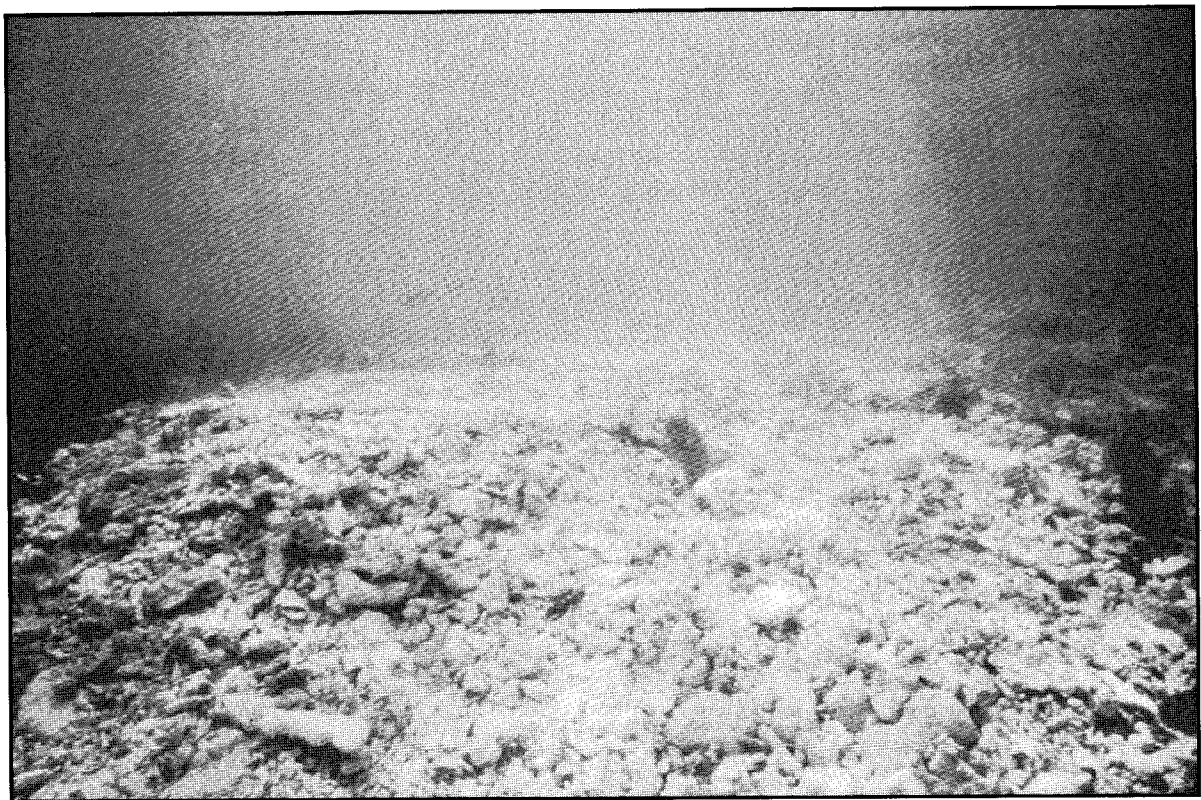


Figure 6. Rubble pile produced from a blow-hole excavated by prop wash when the M/V Maitland grounded in the Florida Keys National Marine Sanctuary.

4.0 STRUCTURAL RESTORATION

4.1 FRAMEWORK AND SECONDARY DAMAGE

Structural damage to reef framework was distinguished from damage caused to living reef resources. Destruction caused by large ship groundings can be explosive, particularly when a large moving mass, like a ship, is forced directly into a carbonate reef framework (Hudson and Diaz, 1988). Hurricanes also inflict considerable damage to reefs, but they rarely damage reef framework or cause damage due to spilled cargo or fuel. Destruction can also result when a ship scrapes along the surface, destroying coral spurs or shattering cemented coral rock that makes up the reef matrix.

The amount of effort expended to minimize the threat of secondary damage must be measured against the cost of letting nature take its course. Grounding sites without major framework damage will eventually stabilize because storms, currents and waves will redistribute boulders, rubble and sand. However, the redistribution of these components, or the continual production of rubble and sand from damaged framework, can significantly increase the magnitude and extent of injury at the grounding site and adjacent reef habitats. Resource managers should be particularly concerned about damage that has long-term (decades rather than years) consequences, both for the damaged sites and adjacent healthy systems.

Few specific recommendations for repair of each grounding site were developed during the workshop because the briefings were short and only one site was visited by snorkeling. However, general principles (Table 1) were defined that are broadly applicable and there was consensus that active intervention at the three grounding sites was feasible. Management goals, financial and personnel constraints, and ecological value must all be considered before implementing any of the measures outlined below (Gittings 1991c,d). In some accidents it may be impossible, or prohibitively expensive, to repair structural damage. Two important recommendations were:

- 1. Framework damage that periodically produces rubble and sand causing widespread secondary damage should be repaired.**
- 2. Structural repair to minimize or eliminate the potential for secondary damage must be completed before other restoration activity begins.**

Underwater cements can be successfully used to attach transplanted corals or surviving fragments, secure broken reef rock or to pack crevices (Hudson and Diaz 1988). In addition, restoration efforts in the Maldives (Clark and Edwards in press, Edwards and Clark in press), suggest that prefabricated concrete structures can be used to help stabilize mobile bottom elements. Techniques to repair framework damage to minimize or eliminate secondary damage are not "off-the-shelf," and care must be taken not to damage reefs during the repair process.

4.2 THREE DIMENSIONAL RELIEF

Adding three dimensional structure to sites flattened by vessel groundings will facilitate natural recovery because structural complexity attracts fish and may create favorable hydrodynamic conditions for successful recruitment of corals and other sessile organisms. Aesthetic concerns about the "naturalness" of artificial structures should be balanced against the value (e.g., to tourists or to restoring ecosystem function) of accelerated recovery. The cost of prefabricated concrete structures is likely high and deployment of the structures will be difficult and may also be costly. See section 5.2 for additional discussions related to the ecological value of increasing three dimensional complexity at grounding sites.

Restoration and recovery enhancement activities	Effectiveness in minimizing secondary damage (priority/recovery)	Effectiveness in promoting reef development (priority/recovery)	Feasibility (priority/recovery)
<u>Cement fractured reef framework</u>			
loose boulders, rubble	H	H	H
rubble producing framework cracks	L/H	L/H	S
<u>Remove rubble</u>			
transport to holes/depressions	M/H	M/H	S
by hand/suction	L/H	M/H	S
<u>Remove fine sediments</u>			
low energy site	L/M	L/H	S
high energy site	L	L	L
<u>Repair sand/rubble producing excavations</u>			
fill and cap	L/H	L/H	S
sides and bottom only	L/H	L/M	S
<u>Coral transplantation</u>			
within damaged site:			
cement fragments/colonies	H	H	H
into damaged site from undamaged areas:			
slow growing/infreq recruits	NA	M/H	H
weedy species	NA	L/M	L/H
soft corals	NA	L	L/H
<u>Monitoring</u>			
damage assessment	H	NA	H
recovery	NA	H	H

Table 1. Structural repair categories and effectiveness. Notation: Priority refers to relative rankings for response after grounding (H=High, M=Medium, L=Low), and Recovery refers to relative rankings for long-term affect on recovery. SS = Site Specific, NA = Not Applicable.

4.3 TIME FRAME AND PRIORITIES

The time frame in which to begin structural repairs will vary according to the extent and type of damage. It is reasonable to postpone action until: 1) natural processes redistribute rubble to more stable configurations; 2) sand and silt are carried from the site by currents; or 3) structural damage stabilizes. If the threat of significant secondary damage is great, due to rubble generated directly by the ship grounding or from the exposed reef matrix, consideration should be given to remove the threat.

However, removing large volumes of rubble is technically difficult, time consuming and expensive. Rubble might be moved from sites by lift bags or with suction dredges. If rubble is moved into holes in damaged framework, stabilization of the surface of the excavation holes must be addressed at the same time. Rubble might also be moved to deeper water where surge will generally not affect it. If rubble cannot be removed it may be possible to stabilize the material using cement or prefabricated concrete mesh (Edwards and Clark 1992). Another method to help stabilize rubble might involve sponge-mediated consolidation, if the process occurs fast enough to reduce secondary damage. (Wulff 1984). If rubble is naturally abundant at the site, from long-term accumulation or the recent demise of acroporids, nature should be left to take its course.

Excavations (e.g., caused by propeller wash) that continually produce silt or rubble should be stabilized, either by re-establishing the crust or by repairing the sides and bottom without filling the hole.

The goal is to prevent further excavation of the holes and to prevent export of sand and rubble that might cause secondary damage. Whichever approach is used, the repair itself should not cause additional damage during implementation.

Framework destruction, such as major fissures, fractures and large dislodged boulders should be repaired or reattached, especially if associated with secondary damage or if the possibility exists that the hardened overlying crust will be undermined and collapse.

Large blocks, such as those produced at the *Elpis* site, should be stabilized if possible, to prevent damage during hurricanes or large storms. Restoration of obliterated spurs to original conditions is not reasonable, for ecological, geological and engineering reasons. Many spurs formed due to coral growth (mostly acroporids) during the last five to six thousand years when sea level was lower (Shinn et al. 1981). Because the hydrographic (mostly related to sea level) conditions that caused spurs to form are not present today, spur loss due to vessel groundings is permanent in an ecological context. While the object of restoration is to restore what was there if technically possible, it is difficult to imagine a cost-effective way to rebuild spur and groove systems.

Proposals to conduct major structural repairs should be evaluated according to their: 1) effectiveness in minimizing secondary damage to living coral reef resources, both inside and outside the grounding site; 2) ability to enhance recovery; and 3) feasibility (Gittings 1991c,d).

Action to restore or mitigate damage to the reef framework must be sufficiently evaluated and supervised by experts to ensure that the proposed work does not itself cause significant additional damage, during or after the repairs.

Criteria for conducting structural repairs should include design sufficient to withstand hurricane force conditions. Direct passage of a category 4 or 5 hurricane, moving slowly over a reef, will destroy almost everything in its path, especially in shallow water. And hurricanes can be expected to hit the Keys once every seven years. Repair structures must be over-designed to avoid breakage during storms.

Storms cause damage to coral reefs and are a natural part of the system. The potential for artificial structures or framework repairs to cause damage during storms is not a natural part of the system and should be avoided.

5.0 ECOLOGICAL RESTORATION

There is a general perception that coral reefs have degraded worldwide over the last ten to twenty years (Brown 1987, 1988, Williams et al. 1987, Allan 1992, Done 1992). Ship groundings can be viewed as one of many stresses that are responsible for damage to reefs. Stresses that are a natural part of the Florida reef tract ecosystem include seasonal extremes in water temperature, storms, decreased water quality emanating from Florida Bay, coral bleaching events, coral diseases, increased levels of ultraviolet radiation, and the mass mortality of the long-spined black sea urchin, *Diadema antillarum*. Restoration efforts must be conducted against this background of disturbance. Human-caused stresses (reviewed by Hatcher et al. 1989) such as declining water quality due to sewage and chemical pollution, increased sediment loading caused by coastal construction, and overfishing provide additional background that, on a site-by-site basis, might affect coral reef restoration efforts.

None of these stressors, natural or human-caused, are considered sufficiently threatening to Florida's offshore reefs to contraindicate substantial restoration efforts.

5.1 CORAL TRANSPLANTING

The high survival rate of corals transplanted into the *Wellwood* site (Hudson and Diaz 1988) further suggests that ambient conditions are favorable to support coral growth and restoration efforts. The rate of recovery of reefs damaged by ship groundings depends on the extent of damage, the type of damage, the species composition of the community and local environmental conditions (Pearson 1981). For example, an acroporid-dominated reef demolished by a hurricane can recover rapidly (Shinn 1976, Woodley 1992), but environmental changes can cause large stands to disappear (Davies 1982, Dustan and Halas 1987, Jaap et al. 1989). However, damage caused by large ship groundings is so devastating that several factors probably work together to slow recovery, including lack of suitable substrate for recruitment and lack of larval recruits because few adult colonies survive. Enhancement efforts are particularly relevant when recovery is recruitment limited, but few data are available on coral reproductive biology, larval dynamics or settlement in the Keys. Before ecological restoration is attempted,

Immediate replacement and recovery of dislodged or threatened corals and toppled reef fragments that survive grounding events ("victim rescue") should be accomplished. If time constraints prevent this, "survivors" should be recovered and set aside in coral "gardens" or "safe areas" until they can be reattached.

Every effort should be made to rescue damaged or toppled corals because there are few potential donor populations of large adult colonies available in the Keys for transplanting to grounding sites. Corals must be stabilized in their "gardens" as significant periods of time may pass before they are utilized in restoration efforts. Also, the methodology for accomplishing this procedure needs to be developed.

Programs that attempt to speed the recovery of damaged reefs by manipulating ecological processes usually include transplanting corals or enhancing three-dimensional structure, or both (Hudson et al. 1989).

Transplanting corals is considered a method to accelerate the early stages of natural recovery because: 1) natural rates of recruitment are slow for many species; 2) transplants may provide a source of larvae not locally available; and 3) recently settled corals grow slowly.

However, as stated above, populations of large slow growing corals that might act as donor populations are rare in the Keys, if they exist at all. This contrasts with sites in the Pacific where live pieces of coral are abundant and transplants can be used to increase the number of new colonies in damaged sites (see Maragos 1974, for Hawaii; Birkeland et al. 1979, for Guam; Harriott and Fisk 1987, 1988 for Australia; and Guzman 1991, for Costa Rica).

5.2 THREE DIMENSIONAL RELIEF

In addition to transplants of live material, construction of artificial structures to increase habitat complexity should be considered when restoring large areas of damaged reef. Increasing three dimensional structure is thought to make the habitat more suitable to coral recruitment and growth by providing microhabitats that facilitate the natural recovery process, in addition to providing habitat for other reef organisms. Specially constructed modules that provide a variety of microhabitat types will attract a large diversity of organisms and may facilitate recruitment of corals to the structure and adjacent reef. Grazing fishes and sea urchins that find shelter in the artificial structures may reduce algal cover that can limit coral recruitment. The structures, if properly constructed and secured to the reef, provide long-lasting habitat configurations that can also add to the aesthetic value of a badly damaged grounding site. Furthermore, construction and placement of the artificial structures, when done within the framework of a research monitoring program, is likely to result in significant increases in knowledge about natural recovery and restoration.

To determine the success of coral transplanting or placements of artificial structures in enhancing recovery, it is important to also assess natural variation in species distributions, reproductive biology and recruitment success in areas outside the grounding sites. This level of monitoring requires multiple reference sites to encompass the range of natural variation in the system. Programs that modify the habitat by adding corals or structure will require detailed long-term monitoring to determine which methods are best suited to enhance recovery in the Keys. Additionally, construction of artificial structures should include design criteria sufficient to withstand hurricane force conditions. As with structural repair considerations, steps taken to improve three dimensional relief should not pose a threat to adjacent areas or within grounding sites due to dislodgment during storms.

5.3 INNOVATIVE TECHNIQUES FOR ENHANCING RESTORATION

Novel techniques of enhancing regeneration of reefs with respect to corals should be considered. For example, introduction of *Diadema antillarum* (a previously common sea urchin), which is understood to be a key component in determining community structure of coral reefs. (Sammarco 1980, 1982a,b), might help reduce the percent cover of benthic algae that can compete with corals for space on the reef. Sea urchins might also reduce algal cover that limits coral growth and recruitment; however little is known of this process in the Keys. Additionally, the possible introduction of newly released coral larvae (possibly collected during spawning events) coupled with special techniques to help insure settlement might enhance recovery processes by several-fold. The use of innovative experimentation in these areas should not be underestimated.

6.0 MONITORING AND RESTORATION PRIORITIES

The three goals of the workshop were to make recommendations: 1) about the appropriateness of various methods to restore reefs damaged by ship groundings (ecological and structural considerations); 2) to develop methods to evaluate restoration techniques (monitoring); and 3) to identify projects to advance knowledge about coral reef restoration ecology. Existing technology and methodologies are considered sufficient to monitor the results of restoration activity. However, long-term baseline studies of processes that affect coral reef structure and health are not common, and studies are generally designed to detect change after-the-fact - when it is too late. In addition to conventional descriptive parameters (e.g., percent live coral cover, species richness and diversity, distribution and abundance of diseases), monitoring efforts should attempt to assess sublethal stresses at an early stage of surveillance (Brown 1988). Early detection will help distinguish natural from anthropogenic influences on the reef.

As described by Brown (1988), a combination of monitoring techniques at several spatial and temporal scales is needed, and should include, but is not limited to: 1) studies at the community level, 2) the use of indicator species, 3) coral recruitment patterns, 4) sclerochronology and related measurements, 5) metabolic measurements, 6) zooxanthellae loss/stress, and 7) reproductive biology.

Ultimately, resource management suffers unless scientists can explain how community rates and processes differ between damaged and undamaged reefs.

The best way to ensure that restoration projects of highest scientific merit are supported is to solicit proposals in open competition that are then peer-reviewed by an independent panel of experts.

Restoration proposals must include a long-term monitoring component. This will require a long-term (measured in decades) financial commitment from State and federal agencies. The Sanctuary program should maintain in-house expertise and collaborations with academic institutions to ensure adequate data management and timely evaluation of results.

The Sanctuary program will not be able to evaluate the increasing number of groundings that occur each year and restore sites that incur substantial damage without additional staff.

A restoration and monitoring "manager/scientist" and at least one assistant should be hired to help implement the workshop recommendations.

Implementation of the recommendations that follow depend upon funding and staffing commitments unprecedented in the history of coral reef studies in the Florida Keys.

For each grounding site, recovery enhancement efforts should include a balanced multi-faceted approach that optimizes community recovery while at the same time manipulating selected species is likely to achieve success. Parameters such as large positive changes in percent live coral cover, increases in species richness, natural recruitment equivalent to or higher than rates in undamaged areas, similarity to original conditions (as measured quantitatively by similarity indices), increased three-dimensionality (Dahl 1973: surface index) and increasing measures of colony height (Johannes 1975) should be considered measures of success.

Each grounding site will require a specific restoration plan, and the goal of these activities should be defined for each site prior to the start of restoration activity.

6.1 RESULTS OF PREVIOUS RESTORATION ACTIVITIES

Few reports are available that describe major coral reef restoration projects. In Florida, Hudson et al. (1989), S. Blair, (pers. comm.) and W. Jaap (pers. comm.) have initiated restoration programs. A large coral reef restoration project is underway in the Maldives (Edwards and Clark, 1992), and substantial scientific literature exists that helps define a body of theory that can be applied to restoration efforts (Appendix C). Further, an extensive literature is available related to artificial reefs, regarding materials usage, ability to attract species, design considerations and stability.

A previous workshop addressed rehabilitating coral reefs degraded by human activities (Woodley and Clark, 1989). The recommendations of Woodley and Clark (1989) emphasized impact mitigation (e.g., reducing a source of pollution) followed by natural recovery, which they called "passive rehabilitation." In the case of vessel groundings, impact mitigation is not feasible, except in the case of "victim rescue (see Section 5.1)." In terms of "active rehabilitation," defined as manipulation of reef organisms to facilitate recovery of value, Woodley and Clark (1989) considered the efforts required to restore reefs too expensive, except for reefs with a high value per unit area, such as in marine parks. Recommendations for active

rehabilitation fell under four general headings: 1) increase coral populations; 2) reduce algal populations; 3) increase fish populations; and 4) increase other beneficial species (mariculture). All of the recommendations included research components. However, because the workshop addressed all factors that degrade reefs, not just vessel groundings, the scope of the report did not provide detail about how to restore sites damaged by ships.

Clark and Edwards (in press) and Edwards and Clark (in press) worked to restore reefs "mined" for building materials in the Maldives. Reefs mined over 20 years ago remain essentially unchanged, with no recovery observed. The defined goals of the Maldives restoration effort were to restore the capacity of reefs to absorb wave energy and to re-establish exploitable fish populations. The approach used by Edwards and Clark (1992) involved use of artificial concrete structures to: 1) stabilize unconsolidated bottom components left behind by mining operations; 2) provide suitable shelters to attract fish; and 3) promote growth of corals where they would not otherwise grow.

Experimental concrete structures were constructed with different three dimensional relief and with different stabilizing effects on the bottom. At each of three replicate sites, fifty cubic meter hollow blocks were used in a 10 x 5 array to cover a total area of 150 m², flexible concrete "mattresses" (with and without coral transplants) were used to cover approximately 288 m², and chain-link fencing was anchored to the bottom to cover 150 m². The area selected for rehabilitation by Edwards and Clark was large (4 ha) and shallow (0.5 to 1.8 m deep), and consisted mostly of sand and coral rubble. The results of this study are considered encouraging, with increased fish populations nearly comparable to control sites and faster than expected coral colonization rates. However, none of the concrete structures were totally effective at stabilizing sand and rubble.

A restoration effort in Florida known as "The Sunny Isles Reef Restoration Project" came about as the result of injury, caused by dredging, to the nearshore reef tracts off Dade County (S. Blair, pers. comm.). Injury was caused by dredge suction heads (weighing approximately 8 tons) that were dragged across the reef. All epibenthic growth was removed and three dimensional habitat complexity was greatly reduced. The goal of the project was to restore the three dimensional structure of the injured areas in a manner that would provide complex and diverse benthic habitats similar to the surrounding noninjured reef. Four experimental concrete modular unit designs were used to provide three dimensional relief, diverse habitat (open, restricted and cryptic) and suitable surfaces for attachment and penetration by organisms (carbonate rock and concrete). A total of eighty structures (fifty domes 4 ft wide x 4 ft long x 2.5 ft high, see Figure 7; twenty reef replacement modules 4 ft wide x 8 ft long x 3 ft high, and ten "M" modules 5 ft wide x 8 ft long x 5.5 ft high, see Figure 8) were placed on two sites, within approximately 2.5 acres of injured reef. The structures were designed to attract epibenthic and cryptic communities, which in turn, would support and attract fishes and motile invertebrates. The structures also provided refuges and breeding sites for the associated communities. Monitoring suggests that areas with the artificial structures are enhanced compared to injured areas without the structures. Furthermore, not all modules are equally effective in providing a broad range of habitat types to attract fish and benthic organisms. For example, the dome modules appear to provide suitable structure for epibenthic organisms but they do not attract fish.

The success of the Maldives and Dade County (Sunny Isle Beach Restoration) efforts suggest that large scale implementation of artificial concrete structures is an effective approach for enhancing coral reef restoration.

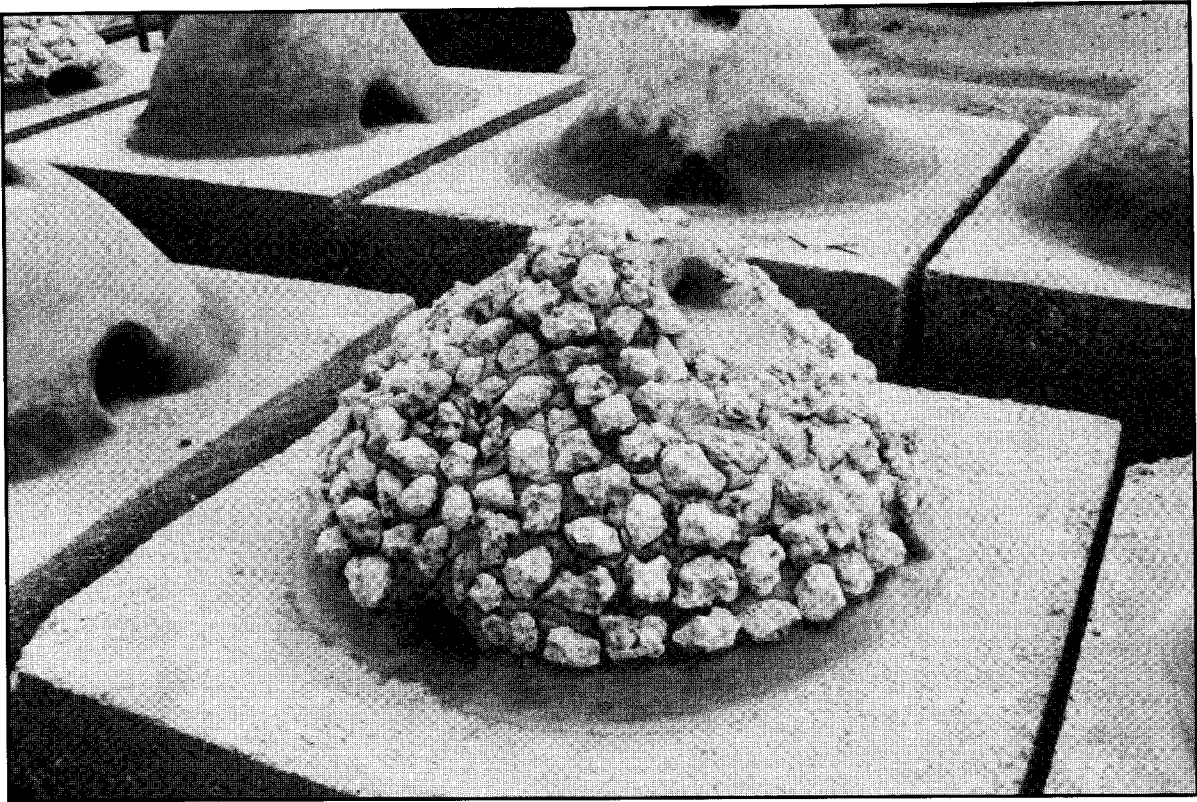


Figure 7. Rocky dome used in Sunny Isles Reef Restoration Project, with limestone rocks grouted onto domes. Structure is 4 ft wide x 4 ft long x 2.5 ft high.

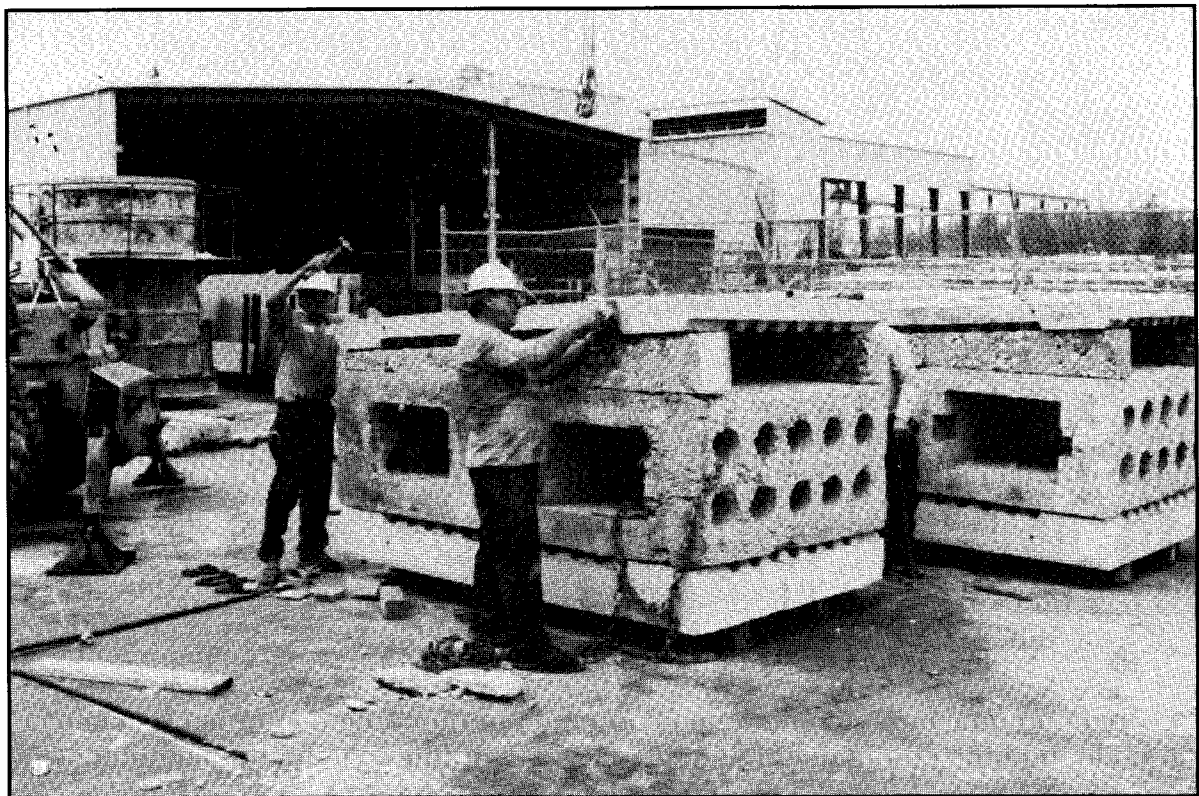


Figure 8. "M" modules used in Sunny Isles Reef Restoration Project. Structure is 5 ft wide x 8 ft long x 5.5 ft high.

6.2 SPECIFIC RECOMMENDATIONS FOR GROUNDING SITES IN THE KEYS

Injury at the *Wellwood*, *Maitland* and *Elpis* grounding sites is well described in a series of reports (Bright and Andryszak 1984, Curtis 1985, Gittings 1991a, Gittings 1991b). Recommendations for restoring specific grounding sites in the Keys include the following:

1. A detailed quantitative re-evaluation of natural recovery at the *Wellwood* site is needed. Also, the status of coral transplants attached after the grounding should be assessed to determine whether or not the transplants accelerated natural recruitment processes or provided sufficient habitat complexity to enhance other aspects of community recovery.
2. The use of artificial structures (that mimic coral formations) at the *Wellwood* grounding site is an obvious course of action, especially since the bottom is stable and secondary damage is no longer a threat. The structures must be part of an artificial reef experiment.
3. The nine-year-old *Wellwood* site is extremely valuable as a reference site for evaluating natural rates of recovery. The nine-year record should be carefully evaluated before any restoration activity begins at the site.
4. Further, at least half the *Wellwood* site should be left alone to continue long-term monitoring of natural recovery rates.
5. Restoration activity at the *Alec Owen Maitland* and *Elpis* grounding sites should be directed to stabilize the bottom to prevent secondary damage at the sites.
6. All these activities should begin as soon as possible after detailed prerestoration monitoring efforts are completed, both inside the injured sites and in reference areas.

6.3 MONITORING AND AND OTHER STUDIES

Five major topic headings are presented in Table 2 that each contain several specific project titles related to coral reef restoration; each project is rated from high to low according to whether or not expected results will increase knowledge about coral reef ecosystem function that is considered important to advance restoration efforts. Estimates are also provided of startup costs for each project heading.

6.3.1 MONITORING

As described above, monitoring efforts are of highest priority, and should occur before groundings occur (e.g., photogrammetry) and after the damaging events. Monitoring that includes the entire reef tract was viewed as a longer-term objective that will develop as individual local monitoring and restoration efforts get underway throughout the Keys. In addition to biological monitoring,

Physical oceanographic monitoring should be conducted at grounding sites to help detect episodic events that might facilitate or hinder recovery and restoration efforts.

Monitoring of temperature, current speed and direction, and salinity at grounding sites throughout the Keys is recommended. The parameters do not need to be measured at every grounding site. Rather, stations should be located to encompass the different water masses that affect the upper, middle and lower Keys. Several meteorological and oceanographic monitoring stations are already established along the reef track, as part of NOAA's C-Man buoy system and Florida Institute of Oceanography's SEAKEYS program, that might be used as bases to collect additional physical oceanographic information, particularly related to current speed and direction. Physical oceanographic data will provide information about: 1) mesoscale processes related to factors affecting larval dispersal; 2) factors that correlate with coral bleaching; 3) episodic effects of major storms; and 4) long-term variability that is unknown for the region.

Coral Reef Restoration Projects	Priority	Exp Results (yrs)	Est Cost/Yr. (x \$1000)
Biological Monitoring			
Local	High	1-10	150/75
Photogrammetry	High	1	50
Effect of Grazing	High	2-5	50
Physical Oceanographic Monitoring			
Local (temperature)	High	1-5	15/5
Historical Grounding Study	High	2-5	25
Local (hydrodynamics, salinity)	Medium-High	1-5	100/20
Nutrients (site specific)	Low-High	1-5	100/25
Bioassays of Iron/Sulfur	Low-Medium	1-5	25
Temperature Tolerance of Corals	Low-Medium	1-5	100
Geology			
Success of Repair	High	1-10	10
Monitoring Wells	Medium	1-5	100/25
Net Reef Growth/Bioerosion	Medium	1-10	50
Natural Cementation	Medium	3-10	25
Recruitment			
Substrate Selectivity	High	1-10	50
Natural Recruitment Rates	High	1-10	50
Size-Frequency Distributions (demography)	High	1-3	50
Relationship Between Settlement and Recruitment	High	3-10	50
Habitat Requirements to Facilitate Fish Recruitment	High	1-10	50
Community Development Trends	High	5-10	50
Larval Availability	High	3-5	50
Reproductive Potential of Corals	High	3-5	75
Transplant Studies			
Sources of Mortality	High	1-3	50
Survival of Damaged/Undamaged Fragments	High	1-3	50
Effect on Sites Where Corals are Removed	High	1-3	50
Mariculture (cloning, larval rearing, fragments)	Medium-High	2-10	100/50

Table 2. Coral reef restoration projects. When two costs are provided (e.g. 150/75), the first includes setup expenses and the second is the long-term annual amount.

Restoration projects that do not include a monitoring component miss a valuable opportunity to advance knowledge about how coral reefs function. This is particularly relevant in Florida because several different physiographic regimes affect the reef tract (reefs in the Keys span two degrees of latitude and are at their extreme northern limit of distribution), and results obtained at one site may not be applicable elsewhere.

As noted above, offshore waters that bathe the reef tract are considered of sufficient quality to maintain natural rates of reef growth. However, the potential for water quality to be negatively affected by human activity is recognized as increasing in the Keys, and warrants careful monitoring.

6.3.2 GEOLOGICAL STUDIES

The project of highest priority in the geology category relates to monitoring the success of structural repairs to the reef. For example, cement repairs must be evaluated to determine whether or not cracks and crevices are expanding, or if secondary sand and rubble production was successfully arrested. Long-term evaluation of artificial concrete structures is also included in this category. Few studies have been conducted that measure bioerosion rates and processes in healthy or damaged reefs. Restoration efforts will also have to be measured against natural reef growth rates or declines. High rates of bioerosion can result when coral mortality rates are high, but no measurements have been made for reefs damaged by ship groundings. When the living veneer is removed from the reef by a vessel grounding the endolithic communities are likely to undergo major changes in community structure that should also be monitored.

Little is known about groundwater movement beneath the Keys and reef track. Ground water monitoring wells for nutrients and possibly hydrogen sulfide might help explain naturally low rates of coral recruitment (Shinn, pers. comm.). Nutrient pollution can reduce recruitment by enhancing algal cover and toxic amounts of hydrogen sulfide might keep coral larvae away from otherwise suitable substrate. Monitoring wells are already in place at many locations and the geological interpretation of cores taken from the wells might help explain patterns of historical and recent reef development.

6.3.3 CORAL REPRODUCTION STUDIES

Most studies related to coral reproduction are considered high priority because knowledge about coral reproductive biology, including dispersal and recruitment, are essential for understanding the distribution and abundance of coral populations and communities. Although Table 3 summarizes data about coral reproductive biology in the Caribbean, few studies have been conducted in the Keys. Coral reproduction has largely been studied in conjunction with the mass spawning events that occur on the Great Barrier Reef in Australia. While synchronous spawning occurs for some corals in the Keys, the reproductive output is strikingly less than occurs on the Great Barrier Reef and appears to be significantly less than occurs elsewhere in the Caribbean (A. Szmant, pers. comm.). It is unknown if coral populations in the Keys are recruitment limited, or whether or not mortality of recently settled larvae is high; growth rates of recently settled corals are unknown in Florida.

Harrison and Wallace (1990) summarized current knowledge of coral reproduction, dispersal and recruitment and they highlighted several topics that require further work, such as: patterns of sexual reproduction (hermaphroditic vs. gonochoric: brooders vs. broadcasters); interactions between growth (resource allocation) and reproduction (fecundity); regional comparisons of coral community reproductive patterns; spawning and factors that affect fertilization; timing and modes of larval development; larval dispersal settlement behavior and substrate preferences; growth rates and effects of other organisms. Furthermore, size frequency distributions (demographics) of adult coral populations are unknown in the Keys.

Stony Corals in the Keys	Size	Growth Rate	Growth Form	Sex	Recolonization Potential	Transplant Potential
<i>Acropora cervicornis</i>	S-L	H	branch	Hp	Low-Medium	Medium-High
<i>A. palmata</i>	S-L	H	branch	Hp, SG/B	Low-Medium	Medium
<i>Agaricia agaricites</i>	S-M	M-F	plate	M, GB	High	Medium-High
<i>A. lamarcki</i>	S-L	S	plate			High
<i>A. fragilis</i>	S	S	plate		Low	Low
<i>Colpophyllia natans</i>	S-L	S	head			Medium-High
<i>Dendrogyra cylindrus</i>	M-L	S	head/col	Gp	Low	Low
<i>D. stokesii</i>	S-M	S-M	head		High	High
<i>Diploria clivosa</i>	S-L	S	head		Low	Medium-High
<i>D. labyrinthiformis</i>	S-L	S	head		Low	Medium-High
<i>D. strigosa</i>	S-L	S	head	Hp, SG/B	Low	Medium-High
<i>Eusmilia fastigiata</i>	S-M		branch		Low	Low-Medium
<i>Favia fragum</i>	S	M-F	head	Hs, B	High	Low
<i>Leptoseris cucullata</i>	S		plate		Medium	Low
<i>Madracis mirabilis</i>	S-M	F	branch			High
<i>M. decactis</i>	S-M	S	branch			High
<i>Manicina areolata</i>	S-M		head	B/SG	Medium	High
<i>Meandrina meandrites</i>	S-L		head		Low	Medium-High
<i>Millepora alcicornis</i>	S-M	F	branch		Low	High
<i>M. complanata</i>	S-L	M	blade		Low	High
<i>Montastraea annularis</i>	S-L	S	head	Hp	Low	High
<i>M. cavernosa</i>	S-L	S	head	Gp	Low	High
<i>Mussa angulosa</i>	S	S	lg polyps		Low	High
<i>Mycetophyllia aliciae</i>	S-M		plate			Low
<i>M. ferox</i>	S-L		plate	Hp		Low
<i>M. lamarckiana</i>	S-M		plate			Medium-High
<i>Oculina diffusa</i>	S-M	S-M	branch		Low	Low-Medium
<i>P. porites</i>	S-M	M-F	branch	G	High	High
<i>P. astreoides</i>	S-M	S-M	head	Hs	High	High
<i>P. furcata</i>	S-M	M	head		Medium	High
<i>P. divaricata</i>	S		branch		Medium	High
<i>Scolymia spp.</i>	S	S	one polyp		Low	Low
<i>Siderastrea radians</i>	S	S-M	head	G	Medium-High	Low
<i>S. siderea</i>	S	S-M	head	G	Low-Medium	High
<i>Solenastrea bournoni</i>	M					
<i>Stephanocoenia michelinii</i>	S-L		head		Low	High

Table 3. Coral growth forms and reproductive biology in Florida. Sex data were compiled from Harrison and Wallace (1990), Szmant (1986), Fadlallah (1983), Sammarco (1980, 1982). Additional data from S. Blair, R. Aronson, R. Smith and P. Edwards (all pers. comm.). Transplant potential refers only to ability of adults to survive transplanting, not whether or not sufficient adult populations exist to reseed damaged areas. Codes: S=Small, M=Medium, L=Large; F=Fast; H=hermaphroditic, S=slow, or spawn gametes, G=gonochoric, B=brood planulae, M=mixed, p=protogynous, s=simultaneous. Blank boxes=data not available.

Smith (1992) used data from ship grounding sites and other published results to demonstrate the importance of life history (brooders versus broadcast spawners) on the recovery process. Most significant was the low rate of recruitment by broadcasters but high rates of juvenile survival. These results further justify the need to salvage coral fragments after injury by vessel groundings, particularly *Diploria* and *Montastrea* spp, as they do not recruit frequently but the transplanted fragments persist (Hudson and Diaz, 1988). Successful restoration techniques may also depend on active intervention at several points in the life history of corals. For example, certain types of substrates or artificial structures might facilitate settlement of larvae, or some corals might be seeded by collecting larvae and transporting them to sites they would otherwise never reach. Corals might be raised (mariculture) to some critical size if high mortality or slow growth rates prevent sites from naturally re-establishing adult populations.

NOAA should undertake research to better understand coral reproductive biology that will contribute valuable insights and ultimately methodologies to help scientists and resource managers better plan restoration projects.

6.3.4 CORAL TRANSPLANT STUDIES

The right-hand column in Table 3 addresses coral transplant studies. A large body of literature exists related to transplanting corals, most of which was done in the Pacific (Maragos 1974, Birkeland et al. 1979, Harriott and Fisk 1987, 1988), but some information is available for Florida (Hudson and Diaz 1988, Hudson et al. 1989).

In general, coral transplantation in the Keys is not considered a viable way to restore sites damaged by ship groundings for two reasons; 1) grounding sites are large and 2) donor populations are rare or absent.

Transplants generally survive, but there is not a ready supply of individuals from donor populations in the Keys. However, as described below, transplants might be used under certain conditions. Recommendations for selection of corals for transplantation are presented in Table 4.

If transplant studies are conducted they must include an experimental framework that evaluates survival, growth and sources of mortality. In general, slow growing corals that do not recruit well should be targeted in recovery enhancement efforts. In addition, if assessments of recovery within grounding sites determine that fast growing corals that recruit well in damaged areas are also poorly represented, then these too should be included in transplant efforts. This might suggest that recruitment is dependent on a local source of larvae not available to the grounding site. Fast growing adults that produce local recruits will quickly increase habitat complexity and may ultimately generate conditions favorable for other species to recruit, including fish. Fast growing "weedy" species are (by definition) relatively abundant and common and represent a better "donor" population than the slower growing head corals. Corals that recruit poorly, but are long-lived once they achieve a critical size, might be good candidates for culture. Coral larvae collected during mass spawning events might provide sufficient material for culture studies and in situ recruitment studies.

Fast growing species such as acroporid corals might be used to "jump-start" the system by quickly increasing live percent coral coverage and spatial heterogeneity. Growth of acroporids can exceed 10 cm in linear length per year, they branch at least seasonally and they reproduce both by fragmentation and through sexual propagules. In general, grafts (or pieces) are easily obtained when adult populations are common, and are less damaging to the donor population than using the whole colonies (however, the donor population should also be monitored). Pieces can be easily attached at the grounding site by wedging them into cracks, with cement or by attaching them to frames or other anchoring structures. One potential problem with acroporids is that these corals have been in general decline during the last ten to fifteen years, and while a high percentage of fragments do well, diseases and other factors can affect survivorship (Bak and Criens, 1981).

-
1. Corals should be collected from a habitat similar to where they will be transplanted, with respect to depth, turbidity, water movement and sediment load.
-
2. For a rapid increase in coral cover, species with a fast growth rate should be selected. This will include mainly branching colonies, rather than massive or encrusting colonies. In the Keys, acroporids and plating corals such as *Agaricia* are good candidates.
-
3. Damage to colonies during collection should be minimized, so colonies with dead or weak bases are preferable to colonies attached by a large base or living tissue. Corals should be collected nearby to minimize travel time. Storage in air or water is species specific.
-
4. Collecting efforts can be used to secure a large number of small colonies, or a small number of large colonies. Many small colonies can be spread over a large area. Mortality of large colonies is usually low, but there will be fewer of them.
-
5. Sexually mature colonies may provide a source of new recruits for the reef. If few corals are present, species that are hermaphrodites may have a greater chance of having their eggs fertilized. Species whose planulae settle quickly, or are brooded, are more likely to recruit to the same reef as their parents.
-
6. For reseedling with coral fragments, select species that are known to recruit from fragments naturally. Three dimensional branching colonies are ideal since the colonies can be buried or wedged into sediment or rock, and the living part of the coral that is raised may survive and grow.
-
7. Species that are likely to appear naturally after a short period usually will not require transplantation. Monitoring recovery in damaged areas will confirm whether or not typical patterns develop.
-
8. Corals that are slow to recruit and are also slow growing are good candidates for transplanting, especially if donor populations are readily available.
-

Table 4. Guidelines for transplanting corals in the Florida Keys (after Harriott and Fisk 1984, 1987).

6.3.5 OTHER STUDIES

Several additional projects should be considered that will help to understand factors that affect restoration efforts.

Assessments of older grounding sites could provide an opportunity to evaluate natural recovery in a variety of different communities.

The evaluation of older grounding sites should occur in several stages, each of which provides successively more detail. For example, detailed aerial surveys would follow after a search of historical (and recent) records. If grounding sites are identified from the air, the next step would be to select several sites for detailed characterization, both at the grounding site and within adjacent undamaged areas. Criteria used to select sites for this survey should include: accuracy and detail of historical information, size of the grounding site, and location relative to recent grounding sites. In addition to historical grounding sites, artificial structures of known age might be used to evaluate recruitment rates and growth rates of corals, information relevant to natural recovery at grounding sites.

Photogrammetry, mentioned above in the context of identifying historical ship grounding sites, is valuable in its own right as a way to obtain significant baseline information about reef structure over a wide geographic range. NOAA, the Environmental Protection Agency and FDNR are in the process of mapping the entire reef tract, Florida Bay and the adjacent coastal areas. The photography is complete and ground truth work is underway. This baseline information can be used during the damage assessment phase at grounding sites by providing a pregrounding "snapshot" of the resource before it was damaged. Efforts should be made to determine whether or not these projects captured images that are useful to Sanctuary personnel for their damage assessment responsibilities.

If existing photographs do not adequately cover areas at high risk for groundings, then it should be considered a high priority to acquire images at the required resolution and geographic scale.

7.0 CONCLUDING STATEMENT

A balanced approach to coral reef restoration that is site specific will achieve the most success. Parameters for measuring success must be defined before restoration begins at each site. Success is likely to be measured differently at each site, but criteria that include increasing percent live coral abundance and species richness, increased number and diversity of fishes, and general increases in habitat complexity are sure to be a common thread among most sites. While corals are the dominant organism in terms of reef structure, monitoring efforts must not neglect other community components, such as soft corals, sponges, mobile invertebrates and algae. Artificial concrete structures that increase three-dimensional structure are a quick way to restore both aesthetic value (if they mimic pre-existing formations) and ecosystem function to a damaged site. Long-term evaluation of the site should be conducted on a multidecadal scale. Monitoring should be directed to evaluate the mode and pace of community development within sites damaged by vessel groundings and adjacent healthy reference reefs.

Scientists were challenged at the workshop to apply their scientific experience and knowledge of coral reefs, to the applied problem of restoring ecosystem function to damaged reefs in a timely manner. The consensus of the group was that active intervention to restore reefs can be accomplished within a framework that also advances knowledge about how the system functions. Basic knowledge about the system is what allowed workshop participants to make the first recommendations about how best to enhance recovery. A long-term commitment to coral reef restoration by the Florida Keys National Marine Sanctuary will additionally yield unprecedented data that will help resource planners and managers better protect all coral reef resources in the Keys.

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APPENDIX A

Meeting Agenda

MONDAY, APRIL 12, 1993

7:00 - 9:00 PM RECEPTION; Key Largo Sheraton, Ballroom Terrace

TUESDAY, APRIL 13, 1993

7:30 - 8:00 AM CONTINENTAL BREAKFAST; (Meeting room)

8:00 - 8:20 INTRODUCTORY REMARKS, WORKSHOP ORGANIZATION

Dr. Steven Miller, NURC/UNCW

Dr. Charles Wahle, NOAA/OCRM/PCD

8:20 - 9:00 DESCRIPTION OF M/V WELLWOOD GROUNDING SITE

9:00 - 1:30 PM FIELD TRIP TO MOLASSES REEF, KLNMS

2:00 - 2:45 DESCRIPTION OF M/V ALEC OWEN MAITLAND GROUNDING SITE

2:45 - 3:30 DESCRIPTION OF THE M/V ELPIS GROUNDING SITE

3:30 - 3:45 COFFEE

3:45 - 4:00 OVERVIEW OF DAMAGE ASSESSMENT AND RESTORATION PROGRAM

Ms. Darlene Finch, NOAA/OCRM/SRD

4:00 - 5:00 INJURY ASSESSMENT

5:00 DAY ONE ENDS

WEDNESDAY, APRIL 14, 1993

7:30 - 8:00 AM CONTINENTAL BREAKFAST; (Meeting room)

8:00 - 8:15 INTRODUCTION

8:15 - 10:15 STRUCTURAL RESTORATION OF DAMAGED REEFS

10:15 - 10:30 COFFEE

10:30 - 12:00 STRUCTURAL RESTORATION OF DAMAGED REEFS

12:00 - 1:00 PM LUNCH, Cafe Key Largo at the Sheraton

1:15 - 3:15 ECOLOGICAL RESTORATION OF DAMAGED REEFS

3:15 - 3:30 COFFEE

3:30 - 5:00 ECOLOGICAL RESTORATION OF DAMAGED REEFS

THURSDAY, APRIL 15, 1993

7:30 - 8:00 AM CONTINENTAL BREAKFAST; (Meeting room)

8:00 - 9:00 MONITORING REEFS

9:00 - 10:15 RESEARCH PRIORITIES

10:15 - 10:30 COFFEE

10:30 - 12:00 RECOMMENDATIONS FOR FUTURE ACTION BY NOAA

12:00 - 1:00 LUNCH

1:00 - 3:00 RECOMMENDATIONS FOR FUTURE ACTION BY NOAA

3:00 MEETING ADJOURNS

APPENDIX B

Workshop Participants

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Appendix C: References

Dispersal, Recruitment and Settlement of Corals

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Appendix D

Summary of Panel Recommendations

- 1) Within the constraints of the salvage operation and damage assessment needs, action should be taken to save, right or stabilize dislodged coral heads and surviving coral fragments resulting from the grounding.
- 2) NOAA should hire additional staff and develop a quick-response capability to meet the needs of injury assessment, mitigation and restoration.
- 3) High resolution aerial photographs should be taken of reefs subject to damage by ship groundings, such as shallow or emergent reefs identified as Sanctuary Preservation Areas in the FKNMS management plan.
- 4) When the threat of secondary damage is high, rubble and sand that are produced by the grounding or from damaged framework should be monitored to document the amount of material produced and its fate.
- 5) A consensus definition developed by the group defined coral reef restoration as a proactive program designed to speed the recovery of a damaged reef to an endpoint that has aesthetic value and is functional as a coral reef ecosystem.
- 6) Framework damage that periodically produces rubble and sand causing widespread secondary damage should be repaired.
- 7) Structural repair to minimize or eliminate the potential for secondary damage must be completed before other restoration activity begins.
- 8) Excavations (e.g., caused by propeller wash) that continually produce silt or rubble should be stabilized, either by re-establishing the crust or by repairing the sides and bottom without filling the hole.
- 9) Framework destruction, such as major fissures, fractures and large dislodged boulders should be repaired or reattached, especially if associated with secondary damage or if the possibility exists that the hardened overlying crust will be undermined and collapse.
- 10) Action to restore or mitigate damage to the reef framework must be sufficiently evaluated and supervised by experts to ensure that the proposed work does not itself cause significant additional damage, during or after the repairs.
- 11) Storms cause damage to coral reefs and are a natural part of the system. The potential for artificial structures or framework repairs to cause damage during storms is not a natural part of the system and should be avoided.
- 12) None of these stressors, natural or human-caused, are considered sufficiently threatening to Florida's offshore reefs to contraindicate substantial restoration efforts.
- 13) Immediate replacement and recovery of dislodged or threatened corals and toppled reef fragments that survive grounding events ("victim rescue") should be accomplished. If time constraints prevent this, "survivors" should be recovered and set aside in coral "gardens" or "safe areas" until they can be reattached.
- 14) Transplanting corals is considered a method to accelerate the early stages of natural recovery because: 1) natural rates of recruitment are slow for many species; 2) transplants may provide a source of larvae not locally available; and 3) recently settled corals grow slowly.
- 15) As described by Brown (1988), a combination of monitoring techniques at several spatial and temporal scales is needed, and should include, but is not limited to: 1) studies at the community level, 2) the use of indicator species, 3) coral recruitment patterns, 4) sclerochronology and related measurements, 5) metabolic measurements, 6) zooxanthellae loss/stress, and 7) reproductive biology.

- 16) The best way to ensure that restoration projects of highest scientific merit are supported is to solicit proposals in open competition that are then peer-reviewed by an independent panel of experts.
- 17) A restoration and monitoring "manager/scientist" and at least one assistant should be hired to help implement the workshop recommendations.
- 18) Each grounding site will require a specific restoration plan, and the goal of these activities should be defined for each site prior to the start of restoration activity.
- 19) The success of the Maldives and Dade County (Sunny Isle Beach Restoration) efforts suggest that large scale implementation of artificial concrete structures is an effective approach for enhancing coral reef restoration.
- 20) Physical oceanographic monitoring should be conducted at grounding sites to help detect episodic events that might facilitate or hinder recovery and restoration efforts.
- 21) Restoration projects that do not include a monitoring component miss a valuable opportunity to advance knowledge about how coral reefs function. This is particularly relevant in Florida because several different physiographic regimes affect the reef tract (reefs in the Keys span two degrees of latitude and are at their extreme northern limit of distribution), and results obtained at one site may not be applicable elsewhere.
- 22) NOAA should undertake research to better understand coral reproductive biology that will contribute valuable insights and ultimately methodologies to help scientists and resource managers better plan restoration projects.
- 23) In general, coral transplantation in the Keys is not considered a viable way to restore sites damaged by ship groundings for two reasons; 1) grounding sites are large and 2) donor populations are rare or absent.
- 24) Assessments of older grounding sites could provide an opportunity to evaluate natural recovery in a variety of different communities.
- 25) If existing photographs do not adequately cover areas at high risk for groundings, then it should be considered a high priority to acquire images at the required resolution and geographic scale.