

Coral reef restoration

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Abstract

Coral reefs are widely recognized for concentration of biological activity, fisheries and tourism, coastal protection, geological processes, and aesthetic wonder. A principal cause of reef damage in Florida is ships running into reefs. The other major human impact on Florida's reefs is dredging for beach renourishment and channel maintenance. In response to chronic reef damage, federal and state agencies and consultants have developed techniques to restore, as best possible, reefs impacted by human disturbance. These efforts include salvaging sponges and corals, removing loose debris from the reef, rebuilding three-dimensional (3-D) structures onto leveled-scarified reef surfaces, and transplanting sponges and corals back on the cleared reef surfaces. This paper presents an overview of restoration approaches; a discussion on legal and administration to both damage and restoration of these essential fish habitats; a brief review of some case studies; and a discussion of restoration success criteria. Salvage of corals and sponges is critical to the success of any reef restoration effort. If a living surface is allowed to sit on the sand for a few days, that surface will die. Often the grounded vessel will have crushed the reef, excavating sediments and rubble that end up as a berm of material behind the ship's resting position. Dealing with massive amounts of rubble debris is challenging. The options include leaving it in place and stabilizing it with cements; moving it a long way from the site and dumping it in deep water; or reconfiguring it by moving it off reef and building piles where it can do no harm. After the debris is moved off the reef platform, corals and other sessile benthic organisms (salvaged resources) can be transplanted on the damaged area. Monitoring is important to determine the success of the restoration and to look for ways to improve future projects. Sampling sites for monitoring should include restored areas plus a reference area (undamaged habitat of a relatively similar nature that is in close proximity) for comparison. The following questions should be addressed for any reef restoration project: are the transplanted organisms still secured to the reef? Is the vitality (color, disease, algal competition) of the transplanted organisms equivalent to the organisms in the reference sites? Is recruitment (settlement of juvenile organisms) similar in the restored areas and the reference areas? Monitoring should be tied to decision making so corrections can be made. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Coral reefs are deterministic phenomena of sedentary organisms with high metabolism living in warm marine waters within the zone of strong illumination. They are constructional physiographic features of tropical seas consisting fundamentally of a rigid calcareous framework made up mainly of the interlocked and encrusting skeletons of reef building corals and calcareous red algae' (Wells, 1957). Coral reefs are found throughout the world in a band that is generally bounded by the Tropics of Cancer and Capricorn. Individual coral species grow at rates that range from about 1 to 10 cm annually. Overall, coral reef growth is slow, ranging from about 1 to 5 m per 1000 years.

Coral reefs are widely recognized as significant habitat providing structural heterogeneity and serve as refuge for a multitude of sessile and mobile organisms. Coral reefs have high gross primary productivity; however, net primary productivity is not great (Sournia, 1977; Gladfelter, 1985). Unlike most ecosystems, the primary producer is not a stand-alone autotroph; instead, a symbiotic complex of microscopic algae (zooxanthellae) living within the tissues of sponges and Cnidarians (corals, anemones, zooanthids) contribute a significant portion of the fixed carbon.

Reef structures are impressive natural breakwaters; they dissipate prodigious wave forces that strike their frontal masses. This protects low-lying coastal areas that would otherwise experience severe flooding during tropical cyclones or major frontal storms if the coral reef barrier were not present.

Coral reefs exhibit high biological diversity and concentrated biomass within the benthic communities. They are characterized as unpredictable communities (Slobodkin and Sanders, 1969; Connell, 1997), and their biological diversity is maintained by intermediate magnitude and frequency disturbance (Connell, 1978; Done, 1997). Coral reefs are often characterized as an underwater tropical rain forest: high biodiversity, rapid nutrient recycling, many forms of symbiosis, and layered structure of canopy, under-story, and surface (Hubbell, 1997). The upper reef layer is composed of large branching or massive corals that rise

above the reef framework; there is an intermediate layer of moderate-sized corals, sea fans, sea whips, and sponges; and at the sea floor level, algae and small sessile invertebrates dominate. Beneath the surface, there are caverns providing niches for cryptic organisms. As with the situation in an old growth forest, older corals are often partially deceased, and the non-living surface areas are covered with many different kinds of plants and animals. Coral skeletons are often excavated by algae, fungi, sponges, mollusks, and other organisms, generating a labyrinth of tunnels. Sponges also provide a refuge for smaller crustaceans, polychaetes, and even fish. Coral reefs have resident, semi-resident, and seasonally resident mobile species, especially fish.

In the last 20 years, the popularity of coral reef tourism has surpassed the economic benefit derived from coral reef fisheries, and the term 'eco-tourism' has been adopted to describe the activity of visiting unique natural areas to enjoy the setting and to observe the flora and fauna. Coral reefs are a major destination for ecotourists, especially Australia's Great Barrier Reef, Micronesia, French Polynesia, the Greater and Lesser Antilles, Central America, the Bahamas, and the Florida Keys. The opulent diversity in color, form, and texture on coral reefs has immense appeal to the viewers of natural history television programs. Dissemination of this information has resulted in greater social awareness of coral reef problems and conservation. 'The Year of the Reef' occurred in 1996 and conservation groups throughout the world focused attention on coral reefs and their problems. National and international coral reef initiatives have come into being to help conserve coral reef resources (McManus and Chua, 1990; Wilkinson et al., 1997).

2. Resource damage

The principal natural events that physically restructure coral reefs include tropical cyclones (hurricanes and typhoons), earthquakes, and lava flows. The magnitude of the change is proportional to the strength and duration of the event. A reef exposed to a class five hurricane may be



Fig. 1. R/V *Columbus Iselin* aground on Looe Key, August 10, 1994. Photo credit: G. Schmahl.

totally destroyed as a high profile coral reef, for example, Hurricane Hattie in Belize and Hurricane Allen in Jamaica wrought havoc and virtually destroyed reefs (Stoddart, 1962; Woodley et al., 1981). Smaller storms and large storms that do not linger are less destructive; for example, Hurricanes Donna and Betsy (1960 and 1964) damaged coral reefs off the Florida Keys; but reefs recovered within ten years (Springer and McErlean, 1962; Shinn, 1976). Winter frontal passages in high latitude reef systems can stress the biota by chilling waters to sub-lethal and lethal temperatures (about 14°C) (Davis, 1982; Porter et al., 1982; Roberts et al., 1982). Summer doldrums associated with ENSO phenomena stress flora and fauna because of elevated sea water temperatures (about 30–32°C) causing mass coral bleaching where the zooxanthellate organisms lose their algal symbionts and appear stark white (Jaap, 1979,

1985). Anthropogenic, physically destructive activity impacting coral reefs includes dredging channels and harbors, dredge mining sand for beach renourishment, vessel groundings, and anchoring on coral reefs. Any of these incidents may fundamentally change a reef or a portion of a reef.

Dredging impacts typically involve a dredge cutter head running into the reef, ground tackle and pipes from the dredge damaging the reef, and dredge materials being dumped on the reef. In addition, dredging creates chronic high levels of turbidity which can destroy corals from lack of light and sediment smothering (Courtenay et al., 1974; Dodge and Vaisnys, 1977; Salvat, 1987; Rogers, 1990; Lindeman and Snyder, in press).

Ship groundings (Fig. 1) on coral reefs have occurred ever since humans first built boats and began going to sea. The ship's impact can dis-

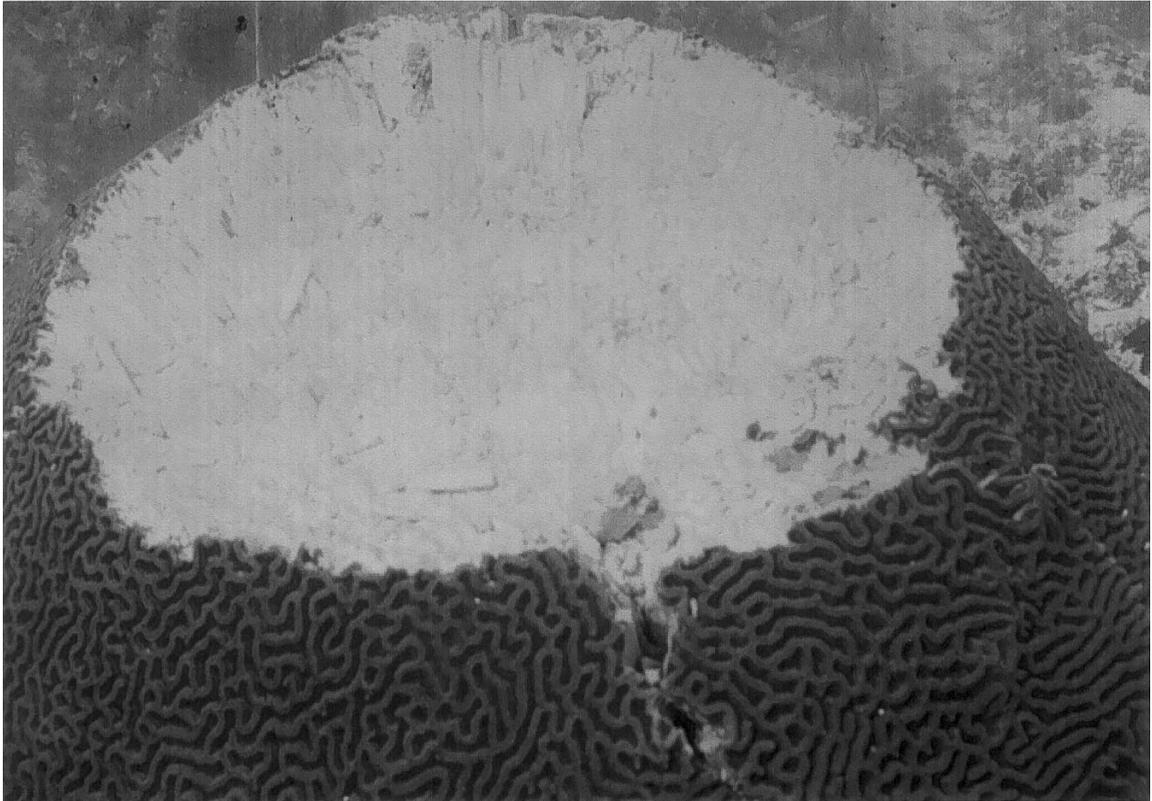


Fig. 2. Damaged coral, The hull of the Container Ship *Houston*, January, 1997, off Maryland Shoal, Florida Keys, cleaved the top off this boulder-brain coral, *Colpophyllia natans* (Houttyn). Photo credit: W. Jaap.

Table 1
Resource losses, Looe Key, *Columbus Iselin* grounding, survey, 21–23 September 1994^a

Sampling site:	East area	West area	Grounding scar
No. of Samples (one m ² quadrats)	36	29	34
No. of Cnidaria species	19	15	2
Mean species/m ² ($X \pm S$)	3.50 ± 1.36	3.62 ± 1.62	0.09 ± 0.37
No. of Cnidaria colonies	976	536	14
Mean colonies/m ² ($X \pm S$)	26.86 ± 26.03	18.48 ± 10.94	0.41 ± 2.20
Shannon Weiner, H'n, Cnidaria (log 2)	1.69	1.54	0.94
Evenness, J'n	0.40	0.54	0.94
Estimated loss of colonies			7977

^a Sampling included quadrat census the damage area and two reference sites in the adjacent area.

lodge and fracture corals (Fig. 2), pulverize coral skeletons into small debris-rubble, displace sediment deposits, and destroy or fracture the reef platform. Salvage operations often add damage due to inappropriate methods and poor control of

operations. In some cases, the ship's hull is ruptured and cargo and fuel are spilled on the reef.

Large ship groundings cause fundamental changes in community structure (Table 1). Small boat groundings (vessels < 100 ft [30 m] long) are



Fig. 3. Large ship anchor chain and coral damage, Tortugas Banks. Photo credit: G. Schmahl.

chronic in many areas. In the Florida Keys, \approx 500 small vessel groundings are reported annually; however, we estimate at least two to three times that number go unreported. Patch reefs in the Mosquito Banks area, Key Largo have experienced decline in coral cover as a result of numerous small boat groundings.

Anchor damages occur in many areas. The size of the anchor, weather, and frequency of anchoring are directly related to the magnitude of the damages. In most tourist areas, chronic anchor damage to coral reefs has been mitigated by installing special moorings that eliminate the need to anchor on the reef by allowing the dive boat to moor to a buoy (Halas, 1985, 1997). Fishing fleets that anchor in the same area for relief from adverse weather can cause major impact (Davis, 1977). In areas where large ships anchor on coral reefs, the damages are significant (Smith, 1988;

Fig. 3). Trawling or deploying other types of fishing gear can be harmful to coral reefs. The trawls can dislodge and abrade corals. Destructive fishing practices on coral reefs, in some parts of the world, include dynamite fishing and using toxic chemicals such as sodium hypochlorite and sodium cyanide to harvest fish and invertebrates (Alcala and Gomez, 1987; Eldredge, 1987).

3. Natural recovery processes

Following a major disturbance on a coral reef, natural recovery originates with algae recruitment into the scarified areas. Typically brown, cyanobacteria (bluegreen), and some green algae are the initial colonizers. Clarke and Edwards (1994) reported that concrete structures deployed on degraded reef flats in the Maldives recruited

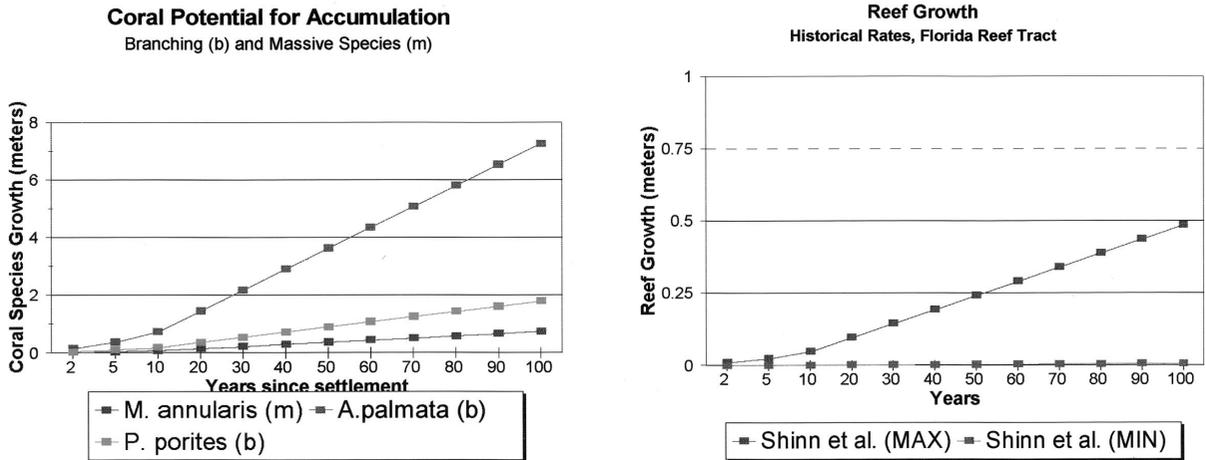


Fig. 4. Coral and reef growth, Florida Keys reefs. Reef growth based on (Shinn et al. (1977)), coral growth based on Vaughan (1916), Hoffmeister and Multer (1964), Jaap (1974), Shinn (1976), and Hudson (1981). In the coral growth rate, the assumptions include constant growth, no predation, no competition, and no disturbance.

green algae in 7 days, barnacles in 14 days, and stony corals in 6.5 months. The local setting will have significant influence on the rate of recovery. After 1 or 2 years, crustose coralline algae, sponges, octocorals, zooanthids, and pioneering stony corals begin to settle and exploit the open space. Pioneering corals such as the Octocoral genus *Pseudopterogorgia* and the stony coral *Favia fragum* recruit and start to grow. After 8 to 10 years an area will have a high density of sponges and octocorals with a moderate density of pioneering stony corals: *Agaricia agaricites*, *Porites porites*, *Porites astreoides*, *Favia fragum*, and *Colpophyllia natans*. Because octocorals recruit and grow at a relatively rapid rate, they may recover to pre-disturbance population densities in 10–15 years. Stony corals recruit and grow at a much slower rate than the octocorals, and their recovery may require several decades to a century.

Two corals (*Acropora palmata* and *Montastraea annularis*) have been documented as the principal reef framework builders in the Florida and many parts of the Caribbean (Shinn et al., 1977). In Florida, *Acropora palmata* has an average annual growth rate of 72.5 mm, while *M. annularis* has an annual growth rate of 7.3 mm (Figs. 4 and 5). Coral reef growth rate in the Florida Keys reefs is 0.65–4.85 m per 1000 years (Shinn et al., 1977).

Because reef recovery and growth rate is slow even under optimal conditions, restoration actions that will enhance recovery are beneficial.

An unstable substrate and associated poor water quality will retard recovery. The rubble is dynamic; it will move as a result of storms and strong currents, and fine fraction sediments will be re-suspended during storms. This reduces water clarity and creates stress for autotrophic organisms (Hubbard, 1973). Initial coral settlement may occur but survival is poor. Juvenile corals can be buried or turned over, leaving them in an unfavorable situation. Predator pressure may be concentrated on the few surviving adults and juveniles (Knowlton et al., 1981). It is impossible to precisely predict the time required for population and community recovery to the pre-disturbance condition. Most evaluations have documented at least a decade for recovery following moderate disturbance events (Pearson, 1981; Sheppard, 1982; Connell et al., 1997).

4. Restoration actions

The single most important action in coral reef restoration is the rescue of damaged resources as rapidly as possible by placing them in a safe



Fig. 5. Lift bag, moving large boulders, *Maasdam* restoration, Soto's Reef, George Town, Grand Cayman, British West Indies. Photo credit: T. Fulton.

location until there is an opportunity to transplant them back on the reef. After a ship runs aground on a reef, it may remain there for days until it is pulled from the reef. During this time, the major effort on the part of the trustee [government agency(ies) that has jurisdiction] is to conduct a preliminary damage survey and to provide a triage for damaged benthic resources. This includes righting overturned corals and salvaging broken

pieces of coral and caching them into safe areas for temporary storage. For large formations, lift bags (Fig. 8) and portable winches have proven to be an effective means to move large boulders. Plastic milk crates work well for temporary storage of smaller coral pieces and can be moved by two divers. This work is labor-intensive, and, in a large grounding, it might require 2000–3000 h of labor to sort through the debris field.

Once the vessel is moved off the reef, the triage salvage continues, while a restoration plan is developed. If the responsible party [ship owner(s) and insurance company(ies)] agrees to accept responsibility, a contractor may be hired to execute the restoration.

5. Removing and/or stabilizing loose debris

Initially, the biggest challenge is determining an expedient way to manage loose debris. Solutions include removing it, stabilizing it with mortar, or capping it with boulders or cement structures. Barging the material off-site is expensive and requires state and federal permits. Divers can transport the material from the site, deposit the material in an area that is sand or rubble bottom, and build artificial reefs with piles of debris. Rubble is often concentrated in piles or berms on the reef and it can be maintained in that configuration, using cement to hold the mass together. Hudson and Diaz (1988) used Portland cement to stabilize an area at Molasses Reef following the *Wellwood* grounding in 1984.

Limestone boulders, 3–4 ft in diameter, can be barged to the site and lowered to the rubble field with a crane. These boulders, which can be placed either in piles or in a layer to cover the area, will help stabilize the rubble surface and keep it from moving. The boulders provide 3-D structural replacement, and gaps between them provide refuge sites for mobile fauna. Additionally, the boulders recruit algae, sponges, octocorals, and stony corals.

A method infrequently used to stabilize loose rubble is an articulated concrete mat that was originally designed to reduce soil erosion along the interstate highway system. The mats are constructed in an open web of cement blocks connected with mylar cables. They were first deployed to stabilize rubble on a reef flat in the Maldives (Brown and Dunne, 1988; Clarke and Edwards, 1994) and subsequently were deployed at the *Houston* grounding site (1998) off Maryland Shoal in the Florida Keys. Mat survivability in hurricanes is moderate. We found some movement and cable fracture following Hurricane Georges passage at the *Houston* site.

If the debris is in an area with strong currents and wave surge, it may be advisable to remove the material and take it to an area where it can cause no harm (upland or in deep water).

6. Structural reconstruction

Damages that destroy 3-D relief or severely crack open the reef platform should be repaired and/or replacement modules should be installed. When large formations are dislodged or turned upside down, consideration should be given to recover these resources and move them back to their approximate, former location. Caution must be exercised to avoid human injury and further reef damage. Large structures can be manipulated with multiple lift bags and secured by cement and steel reinforcement rods.

If the damage pulverized 3-D relief, new structures can be fabricated from limestone and/or cement. The types employed in Florida include molded cement structures, large limestone boulders, and cement materials in combination with natural rock. Hudson et al. (1989) tested a concrete hemisphere, the size and shape of which mimicked moderate-sized boulder and brain corals ($\approx 2\text{--}3$ ft [0.6–0.9 m] in diameter) with a hollow interior designed as refuge habitat for mobile organisms. The hemispheres were first deployed off Elliott Key, Biscayne National Park, in 1977, where they have remained in place and recruited an impressive sessile community. In 1989 the census enumerated: 89 octocoral colonies (15 species) and 45 stony coral colonies (7 species). Recent improvements to this design include additional openings for improved internal water circulation and limestone rock embedded in the concrete to add rough texture.

Limestone boulders 3–4 ft (0.9–1 m) in diameter and built up in two to three layers on a concrete base, and held together with cement and steel have been successfully deployed off Sunny Isles, Dade County, Florida (Selby and Associates, 1992). These modules were barged to the dredge damage site and installed with a crane, and have remained stable through a major hurricane, Andrew. They provide relief that is natural look-

ing as well as refuge areas for large and small mobile organisms. Another method employed off Dade County was the use of large-diameter concrete culvert pipe. The pipe's outer surface was covered with cement and limestone rocks and holes were struck through the culvert to provide better circulation and egress.

At Looe Key, a spur was reconstructed using cement and limestone rock. Steel and cement will be used to strengthen the reef platform that was severely cracked from the grounding of the nuclear submarine *Memphis*.

7. Transplanting sponges and corals

Transplanting should be considered in coral reef restoration to benefit recruitment, accelerate recovery, and improve the visual perspective. Barren areas have low natural recruitment (personal observation). Experiments done on the *Mavro Vetric*, Pulaski Shoal, Dry Tortugas grounding site imply that recruitment of stony corals into barren zones is very low. Recruitment is, for the most part, from local populations, and large barren areas do not have a local population to produce progeny, and chemical signals that trigger larval settlement may be missing in the barren area.

Transplanting has received little systematic evaluating until recently. Harriott and Fisk (1988) summarized the results of five transplanting studies dating from 1974 to 1988; survival of the transplanted corals ranged from 0 to 100%. Success or failure was dependent upon the species, environmental conditions, type and shape of transplants, and if the transplants were attached to the substrate or not.

Those sponges, corals, and coral fragments that were salvaged and set aside should be the first candidates for transplanting following debris cleanup. Transplant methods include throwing (sowing) bits and pieces into the damaged area or securing individual pieces or whole organisms to the reef platform with cement, epoxy, hardware (such as stainless threaded rod), or cable ties. Sponges and octocorals (sea fans, sea grounding site whips, and sea plumes) should be trans-

planted intact with a portion of rock to which they are attached.

At the turn of the century, Vaughan (1916) used cement to attach stony corals to small pillars at Dry Tortugas, Florida, and Goulding Cay, Bahamas, for growth rate experiments. The method had minimal impact on the individual corals, and Vaughan's growth rate results are frequently referenced. A method used to cement corals back on a reef starts with one to four liters of Portland type II mortar mix (Neeley, 1988). The mixed mortar is put in a watertight container (plastic bag, a bowl with a sealed top, or a length of sealed PVC pipe). A diver swims the cement to the work site, or it can be sent to the bottom on a line. The surface area is cleaned, all or part of the mortar is used to build a mound of cement on the reef platform, the coral, sponge or octocoral is inserted into the cement mound, and the diver works the cement around the edges of the transplanted organism (Fig. 6). If the area experiences currents and wave surge, soft dive weights or a sand bag can be placed around the base of the organisms to stabilize the transplant while the cement hardens. Adding moulding plaster to the cement during the mixing will speed the cement curing time. However, care must be exercised, since the plaster is chemically reactive and causes the cement mixture to become hot. The mixer and diver should wear rubber gloves to protect their hands. Commercial products such as Water Plug™ will also set up rapidly. Cement will dissolve underwater, leaving grey silt on the bottom. Placing soft dive weights around the base of the cemented organisms and fanning the area removes residue from the sea floor.

Marine epoxy works well to reattach small to medium-sized organisms back on the reef platform. Liquid Rock 500 epoxy and hardener are dispensed from twin tubes placed in an applicator with a nozzle containing internal mixing spirals (Fig. 7). The surface must be cleaned with a wire brush. If the organism is going to be transplanted on a vertical surface, a small hole is drilled into the reef surface, the back of the coral, and a small brass or stainless rod is fitted into the hole in the coral. Epoxy is applied to back of the coral and the rod. The coral and rod are placed on the reef

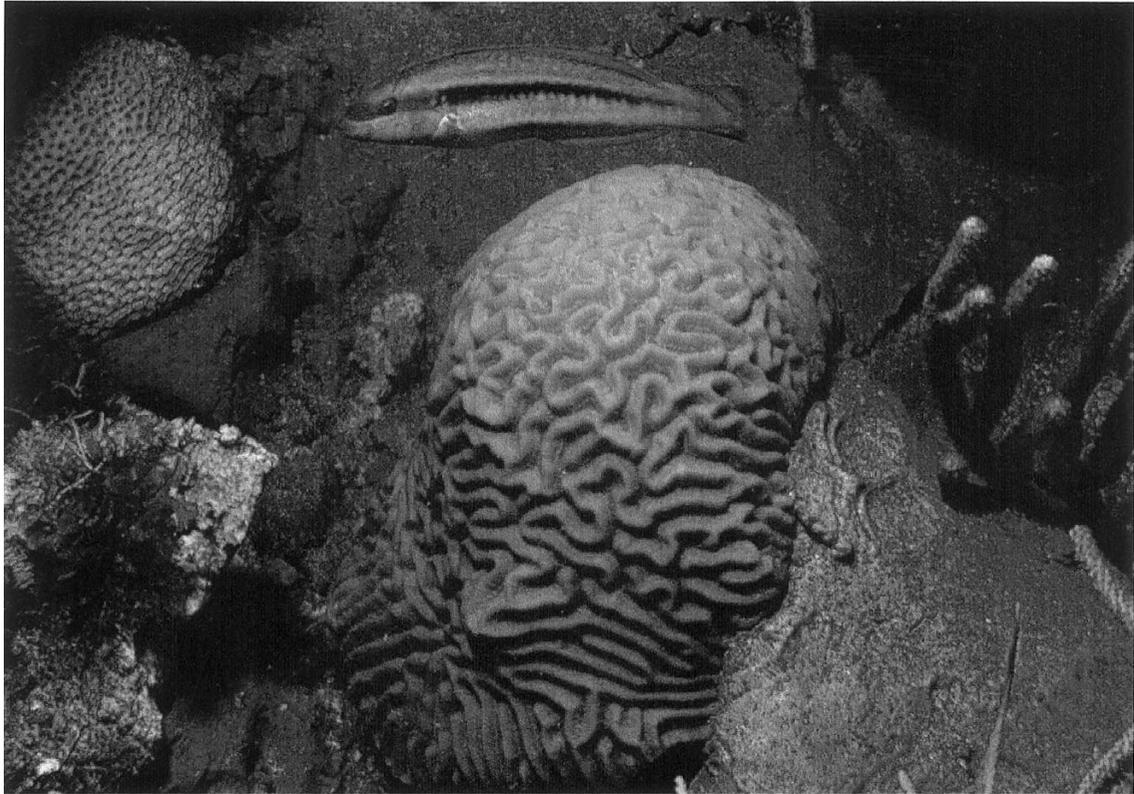


Fig. 6. Corals cemented to reef platform following the M/V *Mavro Vetranic* accident, Pulaski Shoal, Dry Tortugas, Florida, October, 1989. A mass of mortar was laid down and the corals were set into it. Photo credit: W. Jaap.

surface with special care so that the rod is inserted into the holes.

Organization is important to ensure efficiency. Transplant candidates should be transported from their storage cache and placed near where they will be transplanted. The work team should understand their tasks and should have a set of communication signals. A rope and buoy can be used to signal topside when to send cement to the bottom. The transport of the cement from the boat to the sea-floor can be done with a rope to avoid risk (multiple ascents and descents) to divers. Branching corals grow faster and weigh less than equivalent sized massive corals and frequently recruit by fragments that break, become lodged in the reef, fuse to the reef surface, and may grow into mature corals. Cement, epoxy, corrosion-resistant hardware, and plastic cable ties have been used to secure coral branches on

reefs. Loose branch fragments may fuse to the reef without securing them.

Sponges, octocorals, and other sessile benthic organisms should be transplanted by transplanting the rock to which they are attached. Because demosponges, the most common type of sponge found on shallow-water coral reefs, are soft bodied, they cannot be directly transplanted. Octocorals are flexible and some species (*Eunicea* spp) are quite sensitive to Portland cement.

8. Recent technological advances

The process of repopulating an area with organisms is time-consuming and expensive. At the present time, growing stocks of sponges and corals for restoring damaged habitat is in its infancy. There has been limited success growing

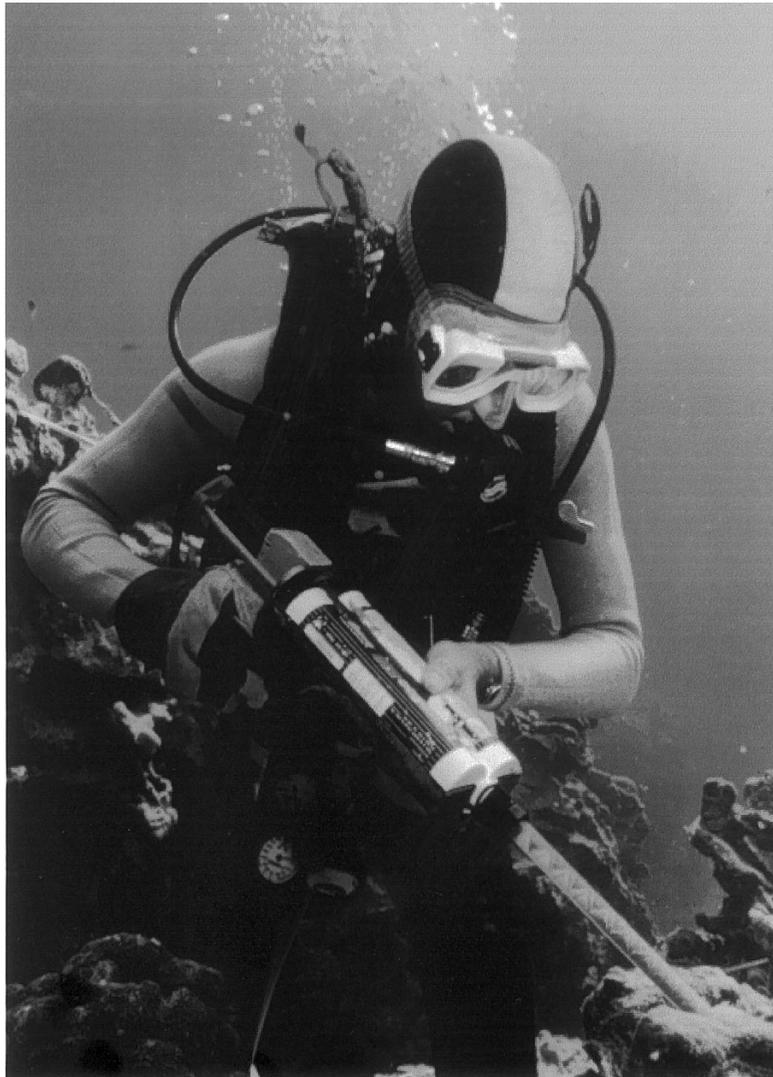


Fig. 7. Using epoxy to attach corals back on the reef platform, *Maasdam* restoration, Soto's Reef, Grand Cayman, British West Indies, February, 1996. The epoxy is Liquid Rock 500™, the diver is dispensing a small mass of epoxy, a moderate size coral is then inserted into the mass. Photo credit: T. Foulton.

corals in closed systems, proving that it can be feasible to rescue small fragments of corals and sponges and transfer them to closed or open system aquaria or a protected ocean area to grow and be available for restoration projects and experiments. Currently, the donor stocks are harvested from a nearby site and used to rehabilitate a damaged site. In several cases federal and state agencies have rescued corals from areas about to

be impacted by dredging and moved the corals to safe offshore areas (Bouchon et al., 1981).

Researchers at the University of Guam collected gravid corals from a nearby reef, brought the corals into their laboratory, and maintained the individuals under nominal environmental conditions until they spawned (Richmond, 1995). Larvae were nurtured in the laboratory until they matured and were ready to settle. The larvae were

Table 2
Coral reef trustee jurisdictional responsibilities

Area	State of Florida Department of Environment and Protection	Department of Interior	NOAA — National Marine Sanctuary	NOAA — NMFS Magnuson Act
State waters	XXX			
Federal parks	XXX	XXX		
Fed. wildlife refuges		XXX		
Federal waters				XXX
Fla. Keys National Marine Sanctuary	XXX		XXX	

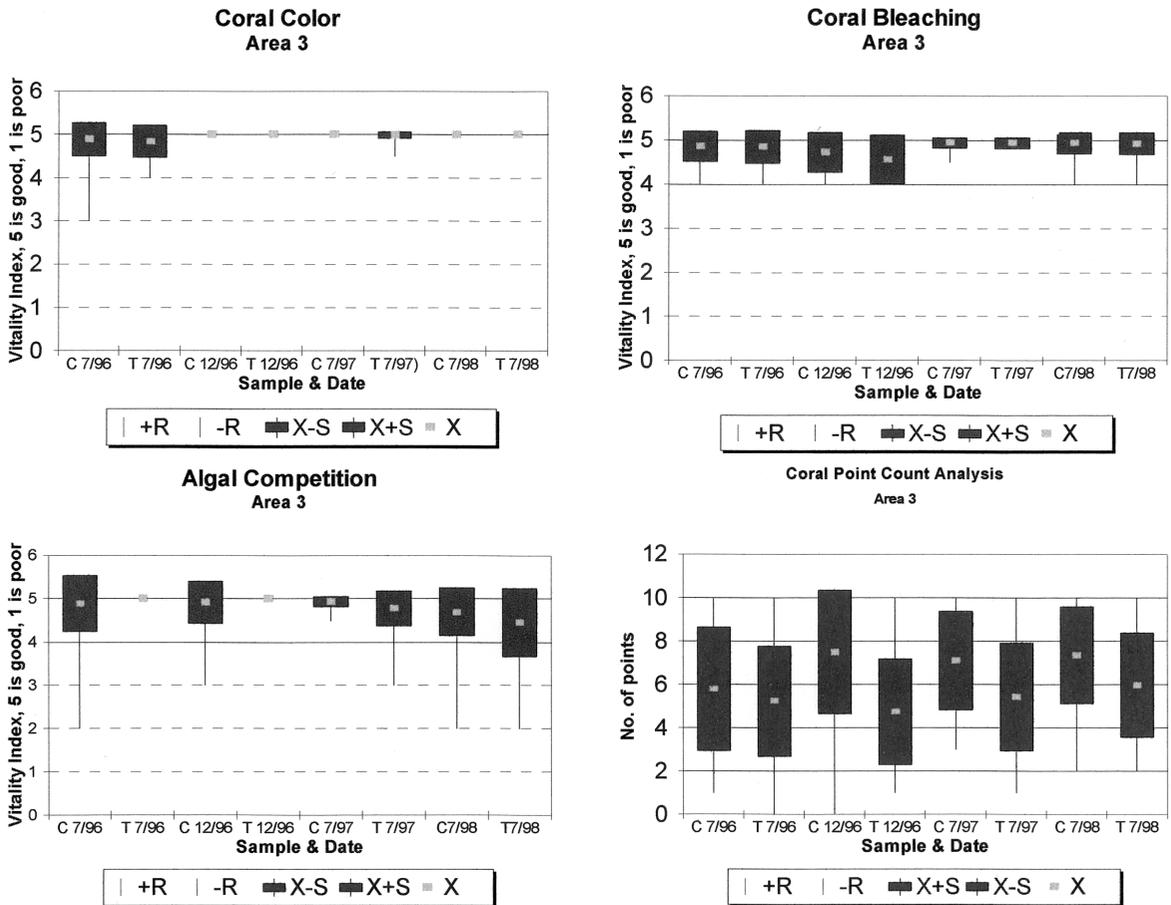


Fig. 8. Monitoring results, *Maasdam* restoration, Soto’s Reef, Grand Cayman, British West Indies. Coral color, bleaching, and algal competition evaluations were qualitatively scored, coral cover is quantitative based on point count ($n = 36$ photos at each reference, and restored site). The abbreviations are: C: control, T: transplants.

Coral cover, photo quadrats Soto's Reef

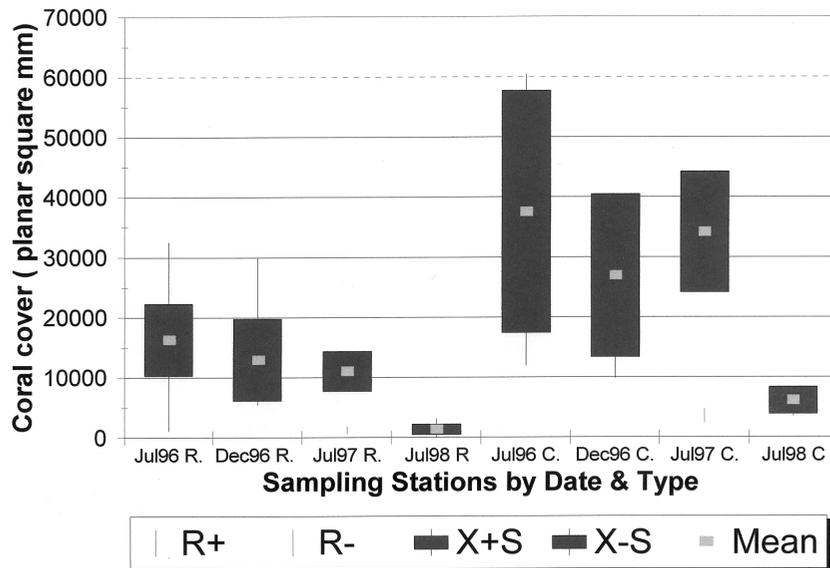


Fig. 9. Planimetric analytical evaluation of coral cover, *Maasdam* restoration, Soto's Reef, Grand Cayman, British West Indies. Data based on ten restored (14 m²) and five reference (7 m²) photo quadrats. Abbreviation: R = restored, C = reference.

taken to a reef that had suffered typhoon damage and released. The experiment concluded that many larvae settled and grew. Retention structures can be temporarily placed on the reef and the larvae are placed within the structures to maximize settlement.

Morse et al. (1994) and Morse and Morse (1996) isolated the chemical glycosaminoglycan (a sulfated polysaccharide) from a coralline algae (*Hydrolithon boergesenii*) that signals *Agaricia agaricites hummlis* larvae to settle. The synthesized material, called 'coral flypaper,' has proved effective for attracting larvae. Presumably chemical signals for other species can be isolated and synthesized to develop other larval settlement stimulators. Littler and Littler (1995) demonstrated that the Caribbean coralline alga *Porolithon pachydermum* had accelerated growth when grazed upon by the chiton *Choneplax lata*. The chiton also grazes on the macro-benthic algae. Experiments should be undertaken to see if seeding a disturbed area with *C. lata* would reduce macro frondose algae, stimulate coralline

algae growth, and enhance coral settlement. If so, this is another method to speed recovery.

Moderate to dense cover of fleshy-benthic algae is a deterrent to coral recruitment. The major grazing animal on the reef was the black, spiny sea urchin (*Diadema antillarum*); however an epidemic resulted in a population collapse in 1983 (Lessios et al., 1984). A damaged reef could be rejuvenated by culturing *Diadema*, putting them on the damaged site, and allowing them to graze the algae away (Sammarco, 1980). A pilot study to look at rearing *Diadema* is underway. Although the technique has merit, it requires complex timing and coordination.

9. Mitigation

In some incidents, it may be virtually impossible to execute restoration on-site, because the accident occurred in an area that is virtually inaccessible, the wave surge is always present and impossible to work in, or the depths are so deep

Coral Recruitment, Soto's Reef Recruits less than 3 cm in diameter

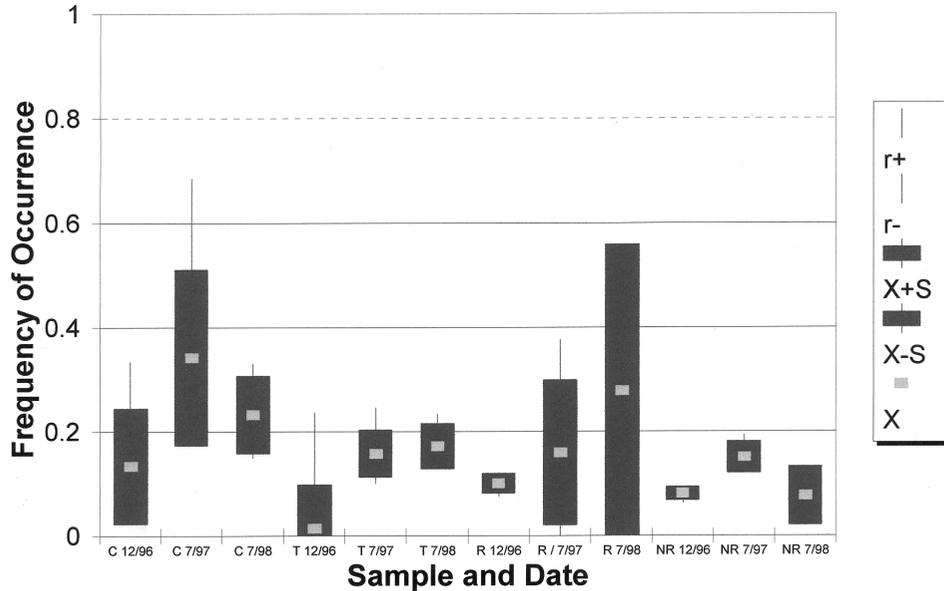


Fig. 10. Coral recruitment at the *Maasdam* restoration, Soto's Reef, Grand Cayman, British West Indies. The abbreviations are: C: Control, T: Transplant, R: Rubble piles, NR: a remote reef, several miles from Soto's Reef.

that it is impossible to conduct safe diving operations. Appropriate alternatives to restoration include improving aids to navigation, public education programs, and restoration on orphan sites (an area where an accident occurred and the responsible party had no assets to make restitution) in the adjacent area and research in restoration and monitoring.

10. Administrative and legal issues

In state waters, the Florida Department of Environmental Protection (FDEP) is the designated trustee. Southwest of Miami, jurisdiction is complicated (Table 2) by federal parks, wildlife refuges, state parks, aquatic preserves, and the Florida Keys National Marine Sanctuary (FKNMS). For example, in Dry Tortugas National Park, the seafloor jurisdiction is totally retained by Florida, while in Biscayne National Park, the jurisdiction is totally under federal authority. The largest reef area (FKNMS) is under

joint federal and state jurisdiction.

Until recently, the typical large-ship grounding in FKNMS was pursued legally. The vessel was impounded and a bond was received. An injury survey with accompanying damages based on economic models (market value, lost use, or habitat equivalency) was generated for litigation. Little effort was put into triage or emergency restoration. The legal process was an exercise in which the trustees and the responsible party played brinkmanship: holding out until the court appearance was immanent then, at the last minute, reaching a settlement. Only one (USA) coral reef grounding case has been settled in court: the *Windspirit*, 130 m-long sailing cruise ship that anchored on coral, Francis Bay, Virgin Islands National Park in 1990. Judge T.K. Moore ordered the cruise ship owner to pay \$300 000 in 1995 (Caroline Rogers, USGS, BRD, Personal Communication). Large monetary settlements in vessel grounding incidents have resulted in a significant change in attitude. The insurance companies have been more willing to consider taking

proactive tactics (offering to take responsibility for the injuries and restoration).

11. Recent restoration projects

The groundings that occurred in the Florida Keys between 1984 and 1989, with one exception, did not receive immediate restoration. Recovery on these sites was poor (Gittings et al., 1988; Hudson and Diaz, 1988; Hanisak et al., 1989; Gittings and Bright, 1990; Gittings, 1991a,b,c,d). Five recent incidents have occurred (three in Florida, one in the Cayman Islands, and one at St. John, USVI) where the responsible party has taken a proactive stance. In each case, a large ship caused injuries ranging from a few toppled corals to massive reef damage. The responsible party (RP) accepted responsibility, hired contractors to execute restoration, and funded a monitoring program. This process reduced protracted legal debate and expedited recovery. The RP paying for the restoration operation is usually more efficient than the government's since it eliminates the bureaucratic contractual procedures (requests for proposals, formal bidding, writing contracts, and other time consuming, and non-productive elements) mandated by law for a government agency to hire a contractor. The RP and the trustee technical staff develop a restoration plan, hire the contractor with the advise of the trustee, the work commences, and the trustee monitors performance. If performance does not meet standards, the trustee may elect to stop operations and consider either continuing restoration after corrections are made or moving toward legal proceedings. For the RP, the costs are less because the time scale is reduced, divers and biologists do not command the same salaries as lawyers and accountants, and the principal efforts are focused on restoring the reef.

12. Case histories

12.1. *Firat*

The *Firat* ran across a reef and beached, follow-

ing passage of Tropical Storm Gordon, near Port Everglades in Broward County, Florida, 15 November 1995. The insurance company quickly hired a contractor to salvage the ship and tow it offshore without doing additional reef damage and hired a contractor to conduct a reef injury survey. The survey included bottom mapping with differential GPS and diving to locate dislodged corals. Within 6 weeks, 600 corals were transplanted, mapped, and identified. The responsible party and trustee technical staff instituted a monitoring plan, which included a five-year program to evaluate the success of the work (Continental Shelf Associates, 1999).

12.2. *Maasdam*

January 12, 1996, the cruise ship *Maasdam* struck (but was not aground) Soto's Reef, George Town, Grand Cayman Islands, British West Indies. The damaged area was determined by the Cayman Island Department of the Environment to be $\approx 1000 \text{ m}^2$ of reef (planar area), including anchor scaring, crushed coral formations, and large chunks of reef platform that were broken and toppled onto a sand bed adjacent to the reef. The RP accepted responsibility and worked with the Cayman Island DOE staff to develop a restoration plan, including a monitoring. Work commenced in late January 1996 and was completed in April 1996 after an estimated 9000 h of underwater work: sorting coral and rubble, taking rubble off site, moving large boulders back atop the reef, and reattaching ≈ 3000 individual corals. Monitoring of the project included a baseline (Jaap and Morelock, 1996), 6 months (Jaap and Morelock, 1997a), 1 year (Jaap and Morelock, 1997b), and 2 years (Jaap and Morelock, 1998).

12.3. *Ryndam*

In January 1997 the cruise ship *Ryndam* dropped an anchor within the no-anchor zone in the Virgin Islands National Park, St. John, USVI. The National Park Service determined that damage occurred to reef resources. The vessel owner dispatched a consultant to independently verify the injuries. The anchor and ground tackle had

dislodged several corals and cut a shallow trench through a sedimentary-algal community. The toppled corals were set upright, and a fine was paid for anchoring in the no-anchor zone.

12.4. *Houston*

In February 1992 the container ship *Houston* ran aground because of a navigating error near Maryland Shoal in the lower Florida Keys. The ship was successfully removed with minimal collateral damage. The vessel operator and insurance companies agreed to assume responsibility, hired contractors and responded with multifaceted restoration. The initial work entailed defining the damages, salvaging corals, and reattaching corals to the reef platform. In the second phase, large rubble berms were stabilized with epoxy cement. Large limestone boulders and articulated concrete mats were used to cover or buffer loose rubble fields on the site. The RP also agreed to install six radar response transmitters (Raycon beacons) on navigational aids that are situated between Dry Tortugas and Fowey Rocks to provide additional warning to vessels plying the Straits of Florida. Hurricane Georges damaged some of the restoration and the RP agreed to take remedial action to correct the problems.

12.5. *Memphis*

The *Memphis*, a Los Angeles-class attack submarine, ran aground on a reef off Dania, Florida, 25 February 1993. The Navy and Department of Justice were unwilling to take responsibilities and contested the reef damages. After three years of legal maneuvering, the case was settled for \$750 000.

These examples illustrate, working with the responsible party to initiate restoration quickly is a policy that can be beneficial. The goals of coral reef restoration should be to maximize resource recovery as soon as possible. The goal should not be this is a source of funds to support government programs and infrastructure.

13. Restoration success criteria

The monitoring of a site should have a time scale relative to the potential for full recovery. For example, if the site is expected to recover within 10 years, monitoring should be for that time span, with more intensive sampling at the onset and reduced effort toward the end (Table 3). Monitoring is the only way to determine success of the restoration, observe status and trends, and correct problems (Gomez and Yap, 1984; Likens, 1988; Connell et al., 1997). If a project is worthy of executing a restoration, it is worthy of monitoring the progress of the recovery.

13.1. *Stability*

The reconstructed elements should be stable enough to withstand nominal waves and currents. If 20%¹ or more of the structures have moved, broken up, deteriorated, or caused collateral damage, remedial action should occur. If there is high risk of human injury, the repair or remedial action should be taken as soon as possible.

13.2. *Toxicity*

If there is an obvious zone around the structure where plants and animals are dead or showing signs of stress because of materials leaching from the structure, it will be necessary to re-evaluate the structure and the need to remove it.

13.3. *Aesthetics*

Where feasible, it is recommended that the reconstruction should match the natural habitat characteristics. Limestone rock is a better replacement than steel or concrete. Ships, airplanes, and other waste materials should not be used as replacement structures for restoring a shallow-water coral reef.

¹ The 20% threshold has been a figure that the trustees and responsible parties have agreed to in several recent cases in Florida.

13.4. Rubble stability

If 20% of a rubble berm or loose materials have moved, remedial action should be executed.

13.5. Transplanting organisms

Inspecting the status and condition of transplanted organisms requires visual observations, photography, and video. During transplanting operations, a map of transplanted organism sites with installed reference markers and GPS coordinates should be compiled. The status of attachment/adhesion is important. If 20% or more of the reattached organisms are dislodged, remedial action is called for. Equally important is the vitality of the transplanted organisms. Assessment should include color, bleaching, competition with benthic algae, disease, and percentage of cover by functional groups (stony coral, sponge, octocoral, benthic algae, rock). The sampling must include sampling sites and corals (same taxa) from an adjacent undamaged area to provide a reference sample for vitality. If the condition of transplanted organisms has deteriorated compared to the reference organisms, causes for the deterioration should be investigated.

Coral condition from the *Maasdam* restoration monitoring, 2 years after the restoration was finished, is presented in Fig. 8. Data were collected using 35 mm photographs. Each photograph was scored for color, bleaching, and algal competition, and the amount of cover present in the photograph was evaluated using point count analysis (Curtis, 1968). The fate of individual coral colonies following transplanting used planimetric analysis. The individual corals were evaluated at baseline (about 1 month), 6 months, 1, and 2 years following restoration. There appears to be moderate fluctuations about the central tendency (Fig. 9). The restored stations were consistently lower in coral cover because transplanting did not attempt to restore to pre-accident status. In other studies, the success of transplanting corals to rehabilitate degraded reefs range from moderate to high success. Guzman (1991) reported 79–83% success for 110 fragments of

Pocillopora transplanted on a reef off the Pacific coast of Costa Rica.

13.6. Coral recruitment

Defined as: settlement of sessile benthic organisms, resulting in spatial occupation of the damaged areas. Visual observations, photographs, video, and experiments are typically employed to evaluate this. The damaged area is compared to an undamaged reference site(s) to judge progress. Fig. 10 presents data collected six months, one year, and two years after completion of restoration at the *Maasdam*, Soto's Reef site. There is good indication that coral recruitment on the restored areas is quite similar to the reference sites.

The Soto's Reef project had a short monitoring component that documented the restoration actions was relatively successful, did not cause harm, and functioned as intended. Ideally, we would have preferred that the monitoring be continued for at least 10 years (sampling to include a baseline, 6 months, 1, 2, 4, 6, 8, and 10 years) considering the magnitude of the damage.

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