Return to title

Survivorship of restored *Acropora palmata* fragments over six years at the M/V *Fortuna Reefer* ship grounding site, Mona Island, Puerto Rico

Andrew W. BRUCKNER* and Robin J. BRUCKNER

NOAA National Marine Fisheries Service, Office of Habitat Conservation, 1315 East West Highway, Silver Spring, MD 20910, USA
*Corresponding author: A. Bruckner
FAX: 301-713-1594, e-mail: andy.bruckner@noaa.gov

Abstract Patterns of survivorship of restored *Acropora palmata* fragments generated by the *Fortuna Reefer* ship grounding off Mona Island were examined over six years. Fragments (n=1857) were secured to the reef or dead standing colonies (skeletons) using wire within three months of the grounding. After six years, 20.3% (377) of the restored fragments were living, 56% died and 23.7% were detached and removed. Surviving fragments had live tissue covering an average of 60% of upper branch surfaces, although 30% had little partial mortality (<5%), 22% exhibited resheeting over previously exposed skeleton, and 30% had tissue that expanded onto the substrate or skeletons. Surviving fragments (58%) produced new branches (1-30 per fragment), with a mean length of 21 cm (maximum= 73 cm). The most important source of mortality was overgrowth by a boring sponge (*Cliona* spp., 20%). Partial tissue loss also resulted from wire abrasion (73%), predation by corallivorous gastropods, diseases, algal interactions, and damselfish algal lawns. Fragment size, depth and location of attachment were the most important factors affecting survival. Fragments that died were smaller (59 cm) than surviving fragments (79 cm). Fragments at 3-4 m depth, secured to the reef, and oriented upright had the highest survivorship, lowest amount of partial tissue loss and the greatest extent of new growth. Attaching fragments to skeletons may be beneficial in that it reduces time required to restore high relief habitat, but survivorship may be compromised in locations with bioeroding sponges, as these appear to preferentially colonize skeletons and consequently overgrow fragments.

Keywords *Acropora palmata*, coral restoration, ship grounding, elkhorn coral

Introduction

On July 24, 1997, the *M/V Fortuna Reefer* ran aground on a fringing reef located off the southeast coast of Mona Island, approximately 65 km off the west coast of Puerto Rico. The 326-foot vessel remained grounded within the island's the largest remaining *Acropora palmata* Lamarck 1816 (elkhorn coral) stand for eight days. Steel cables were attached between tugboats and the stern of the *Fortuna Reefer* to stabilize and extract the vessel. Removal of the vessel did not follow the collision path, and the steel cables expanded the injury as they dragged across the reef surface during salvage activities (NOAA 1997a).

The grounding and subsequent removal of the *Fortuna Reefer* impacted 6.8 acres of shallow fore reef habitat that was dominated by *A. palmata*. The reef substrate was crushed and fractured along the inbound and outbound track of the vessel, with near total coral destruction occurring in a path that extended up to 30 m wide and 300 m seaward. *A. palmata* sustained the largest losses, with *Diploria strigosa* Dana 1848 and other massive corals affected to a lesser degree. Entire colonies of *A. palmata* were crushed, dislodged and fractured, and the cables sheared off hundreds of additional *A. palmata* branches up to 6 m depth (Iliff et al. 1999).

A. palmata fragments were scattered across the reef and many had collected in sand channels. The surge continued to shift and overturn the fragments, abrading tissue and minimizing their likelihood of reattaching. Additionally, a high percentage of fragments were likely to die due to sand scouring and smothering by sediment, or be removed from the site during periods of high wave action. The Commonwealth of Puerto Rico and the National Oceanic and Atmospheric Administration (NOAA) Damage Assessment and Restoration Program (DARP) personnel determined that coral mortality could be reduced and the rate of recovery could be accelerated by securing coral fragments to the reef (NOAA 1997a).

Under the Oil Pollution Act of 1990, NOAA expedited a settlement with the responsible party amounting to US $1.25 million for primary and compensatory restoration, including $650,000 to conduct an emergency restoration of coral resources (NOAA 1997b). A team of 19 marine engineers and biologists completed the restoration within 3

Return to title

months of the incident (9/24-10/14/97). A total of 1857 *A. palmata* fragments and detached colonies were secured to either relict reef substrates (reef) or to dead standing *A. palmata* colonies (skeletons) using stainless steel wire. For fragments secured to the reef, wire was extended across each branch in one or more places and wrapped around pairs of stainless steel nails that were cemented into holes drilled in the substrate. Fragments were also attached to skeletons with cable ties, and further reinforced with wire after cable ties began to loosen from surge (Iliff et al. 1999).

The objectives of this study were to characterize the effectiveness of the restoration approach at enhancing retention of corals and identify factors contributing to the survival and mortality of restored fragments. This study provides information on the relationships between fragment size, orientation, and attachment substrate on the extent of fragment survival and growth, as well as the effects of wire and other biotic agents on these processes. Future restorations involving *A. palmata* may be enhanced through application of lessons learned from this study.

Materials and Methods

The *Fortuna Reefer* grounding site is on the southeast coast of Mona Island (18°03'N; 67°52'W; Fig. 1), due west of the deep-water Mona passage and 65 km from the west coast of Puerto Rico. Mona Island forms the top of an underwater ridge separating the Atlantic Ocean from the Caribbean basin. The site is routinely exposed to high wave action, strong currents,

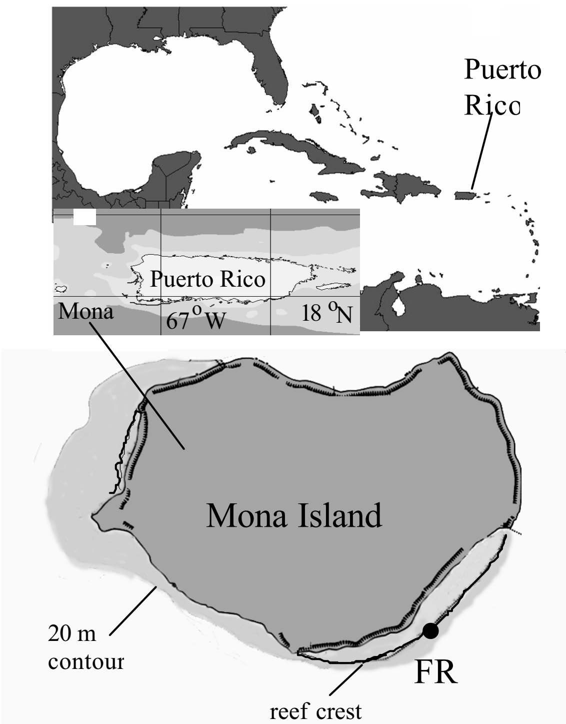

Fig. 1. Location of the *Fortuna Reefer* (FR) restoration.

and heavy swells, and has been hit by several recent storms from the Atlantic and Caribbean, including Hurricane Georges in 1998. The grounding occurred on the shallow fore reef, immediately seaward of the reef crest within a well-developed *A. palmata* stand, with damage extending from 2-6 m in depth.

Fragment survival and patterns of coral recovery were evaluated in August 1999, approximately two years after the grounding, and in May and August 2000, 2001 and 2003. The surveys involved an assessment of the number and condition of attached fragments, and counts of fragments that had broken loose and were missing. All dead fragments were marked with a numbered tag when first identified, to avoid counting these on subsequent surveys. The number of missing fragments was estimated from groups of paired nails no longer associated with fragments, remnants of wire attached to skeletons, and detached fragments within the grounding site that had embedded wire.

For each remaining fragment, measurements were made of 1) the maximum length, using a one meter bar divided into 1 cm increments; 2) orientation, recorded as up, down or sideways with respect to the orientation on a colony prior to breakage; 3) location of attachment (reef or skeleton); and 4) status (live or dead). Live fragments were also examined for tissue growth over wire or exposed skeleton, the number and size of proto-branches, natural cementation (fusion) to the substrate, and growth onto the reef or skeletons. The amount of partial tissue mortality on upper branch surfaces was recorded for all live fragments, which was estimated using the one meter bar and recorded as a percentage of the total fragment length. Partial or total mortality was attributed to wire abrasion, disease, predation by parrotfish, gastropods or fireworms, competition with algae, overgrowth by encrusting invertebrates (especially the brown boring sponge, *Cliona* spp.), and damselfish algal lawns. All fragments were assumed to have live tissue on 100% of their upper surface when first restored, determined from a review of video archives of the restoration taken in 1997.

Results

Fragments attached to the reef ranged in length from 10-340 cm and included all fragments generated by the grounding that were 1 m or longer, 80% of fragments were between 50-100 cm and 50% of fragments were less than 50 cm in length (Bruckner and Bruckner 2001). Fragments were secured to two substrate types, reef and standing *A. palmata* skeletons. The position of attachment was determined by the condition of fragments and their orientation after the grounding, such that the least damaged or abraded surface was positioned upright. This resulted in approximately 65% of the branches being oriented in an upright position, 35% oriented upside down with respect to their original orientation, and a small proportion (<2%) attached sideways. In addition, the largest fragments were secured primarily to the reef, due to difficulties in stabilizing fragments over 100 cm in length on skeletons. A comparison of all restored fragments did not reveal differences between fragment length and orientation (t-test,

Return to title

p=0.02; sideways fragments were excluded from analysis due to the low number of fragments with this orientation). In contrast, significant differences were observed between substrate types, with more small fragments attached to skeletons and the largest fragments secured primarily to the reef (t-test, p<0.001).

Six years after the grounding, 20.3% (377) of the restored fragments were living, while the remainder had died (56%) or were detached and removed from the site (23.7%). Dead fragments were observed during every survey, although a higher proportion of fragments died in the first four years (20-38% per year) and fewer fragments died between August 2001-August 2003 (5.4%) (Fig 2).

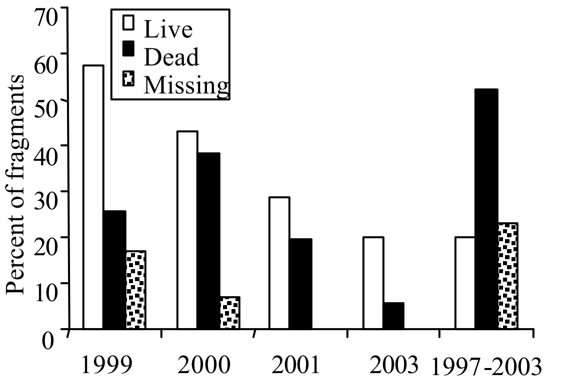

Fig. 2. The fates of *A. palmata* fragments over 6 years. The white bars refer to the percent of the fragments that are still living, the black bars are those that died, and the shaded bars are fragments that were detached and removed.

Fragments that died (56%) were significantly smaller (mean=59 cm) than surviving fragments (mean=79 cm [Fig. 3]). Overall, about 50% of the small fragments (<50 cm) died in the first two years while only 10-20% of the fragments >50 cm died. A greater proportion of large fragments died between 2001 and 2003 than observed in the first four years (t-test, p<0.01), but the overall mean size of fragments that died was smaller than the original size of remaining live fragments (Table 1). There was no apparent relationship between orientation and length for fragments that died, although the remaining live fragments that were oriented upright and attached to the reef were significantly larger than all other live fragments (ANOVA, p=0.067). Fragments attached to the reef and oriented upright exhibited the highest rate of survival (33.7%), while fragments attached to skeletons and oriented down had the highest rate of mortality (85%).

Wire corrosion and breakage and a low rate of natural fusion were important factors that resulted in the detachment and loss of 25.3% of fragments between October 1997 and May 2000. By May 2000, only 10% of the live fragments had successfully fused

Substrate	Reef		Skeleton	
Position	up	down	up	down
No. Live	134	55	149	34
Size Live	93 (3.5)	80 (5.0)	65 (3.2)	62 (4.9)
% partial mortality	36 (2.9)	40 (3.9)	41 (2.3)	49 (6.0)
% with proto	66	49	59	38
No. proto	4.9 (0.4)	3.8 (0.4)	4.3 (0.4)	3.5 (0.6)
Proto Size	24 (1.6)	19 (2.2)	20 (1.4)	18 (0.6)
% Dead	66.3	74.8	70.0	85.0
Size Dead	68 (1.9)	68 (2.5)	49 (1.4)	48 (1.5)

Table 1. Condition of restored *A. palmata* fragments in August, 2003. Differences in survival (live) and mortality (dead) for fragments attached to the reef or standing *A. palmata* skeletons and oriented upright or down are shown. The total number, size (mean length, cm), amount of partial mortality (%), and extent of new growth in the form of protobranches (% of fragments with proto, number of proto per fragment and mean length in cm of protobranches) is shown for live fragments, followed by the percent of dead fragments and their length (cm). Standard error is in parenthesis.

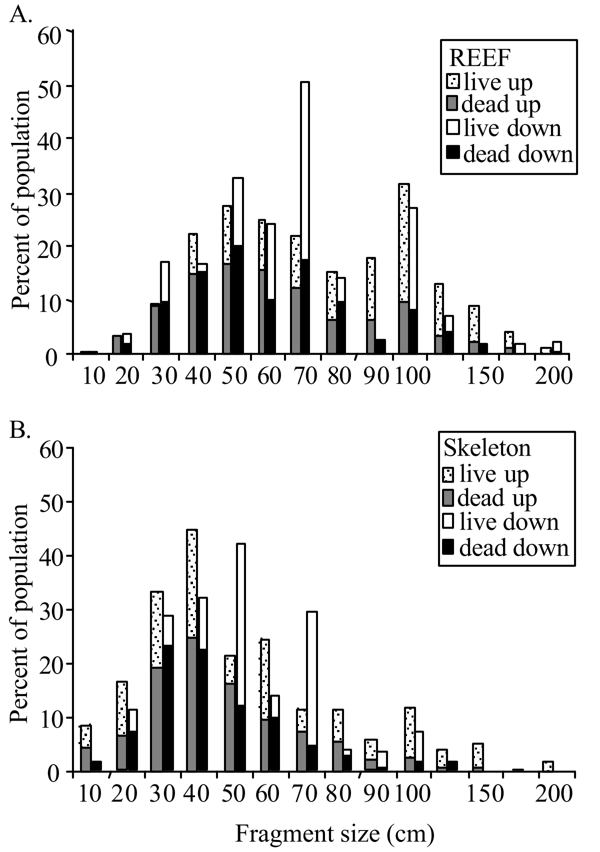

Fig. 3. Size frequency distribution of dead and live fragments oriented up (white bars) and down (black bars). A. Length of fragments (cm) attached to the reef. B. Length of fragments (cm) attached to skeletons.

Return to title

to the reef (10%) or to skeletons (7%), and continued wire breakage was noted throughout the site. A mid-course correction conducted in July 2000 using a less corrosive and stronger wire (Monel 400) was effective at retaining fragments; an additional loss of 0.5% was recorded over the following three years.

Most fragments lost tissue on the upper branch surface at some point during the study due to biotic factors (e.g., predation, disease and competition). The percent of live tissue remaining on fragments increased with increasing fragment size in 1999 (r^2=0.42, p<0.001), but by 2003 all remaining live fragments had the same amount of tissue on the upper branch surface regardless of size (r^2=0.08, p=0.2; Fig 4). In 1999, live fragments had tissue on about half of their upper surfaces, and 23% exhibited little or no mortality. Small fragments were missing about 70% of the tissue on their upper branch surfaces, while larger fragments had 20-50% partial tissue mortality. By 2003, both small and large fragments were missing about 40% of their tissue, although 30% had little or no morality. No differences in partial mortality were observed in 2003 among size classes when attachment sites and orientation are pooled. However, fragments oriented upright and attached to the reef had the lowest amount of partial mortality (36.4%), while fragments attached to skeletons and oriented downward had the highest percentage partial mortality (48.6%).

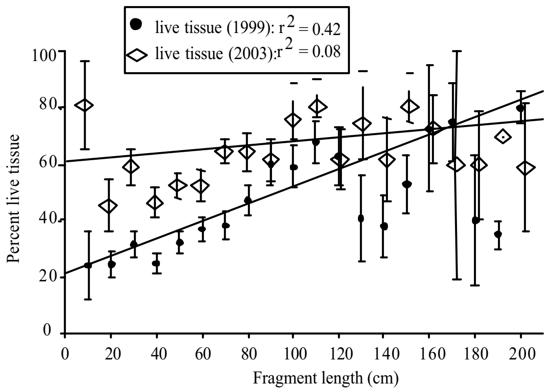

Fig. 4. Relationship between length and amount of partial tissue mortality in 1999 (solid circle) and in 2003 (open diamond).

Partial and total mortality of fragments was attributed to numerous biotic agents, including overgrowth by a boring sponge (*Cliona* spp.), gastropod predation (*Coralliophila abbreviata* Lamarck), white-band disease (WBD), algal competition, damselfish (*Stegastes planifrons*) algal lawns, neoplasia, parrotfish predation, and fireworm predation (*Hermodice carunculata* Pallas). Tissue abrasion associated with wire and/or fragment movement was noted under and adjacent to the wire in 73% of the live fragments during surveys in 1999. The most significant identifiable cause of total mortality was overgrowth by *Cliona* spp. sponges (20%), which primarily affected fragments attached to standing skeletons. Boring sponges continue to impact fragments, with 5% affected in 2003. Macroalgae (primarily *Dictyota* spp.) colonized the wire and the sides of fragments adjacent to the substrate, but were not observed to overgrow live fragments. Diseases were observed at a low frequency throughout the site during every survey. An outbreak of WBD was documented in May and August 2003, which primarily affected standing colonies within and adjacent to the grounding site (15% of the colonies were affected), although a small number of restored fragments (4%) were also affected (Fig. 5). The number of fragments with *C. abbreviata* has remained fairly constant (12-15 per survey), although the percentage has increased (3-6%) due to a concentration of predators on a declining number of live corals.

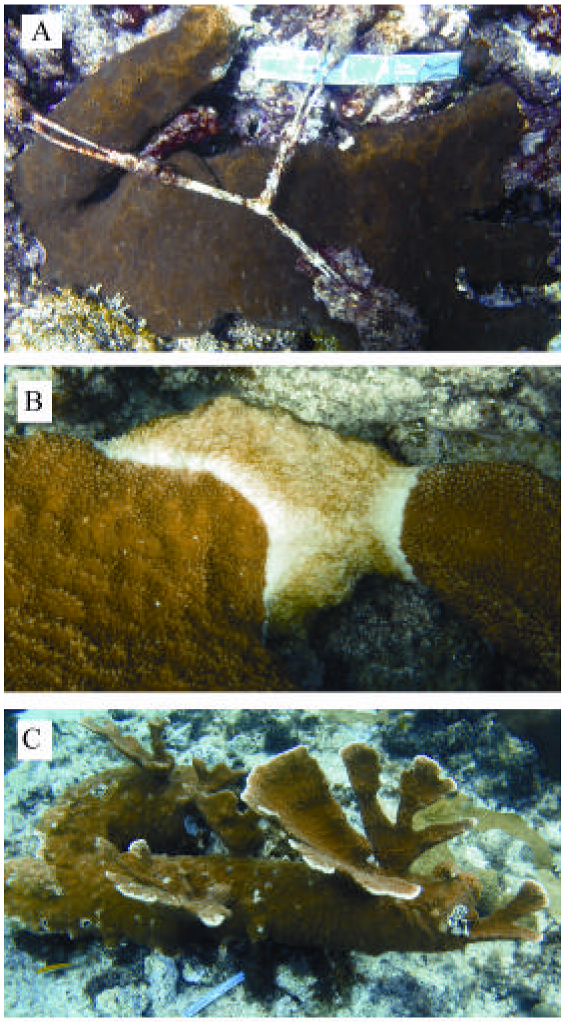

Fig. 5. Examples of restored fragments six years after the Fortuna Reefer grounding. A. Fragment that was overgrown by the boring sponge *Cliona* spp. B. Fragment affected by coral disease (WBD). C. Healthy fragment that has fused to the substrate and produced new branches.

Return to title

Many of the surviving fragments in August 2003 (58%, n=218) have developed branching patterns that are characteristic of standing colonies. On average, fragments had four protobranches (maximum of 30) each, ranging in size from a mean of 21 cm to a maximum of 73 cm. As fragments increase in size they show a trend of increasing protobranch size (r^2 = 0.60, p<0.01); larger fragments also had a greater number of protobranches (r^2 =0.58, p=0.01). By August 2003, fragments also exhibited resheeting over previously denuded exposed skeleton and the wire (22%), and many had fused to their attachment substrate (30%) and were expanding onto the reef or skeletons (18%).

Discussion

Over six years nearly 80% of the fragments that were reattached to the reef or standing elkhorn coral skeletons died or were removed during periods of high wave action. While this appears to be a substantial loss, it is comparable to or less than that observed in studies following the survival of unrestored storm-generated fragments. Other studies following the fates of storm-generated fragments report high rates of early mortality and near total loss when sites are affected by subsequent storms. For instance, Highsmith et al. (1980) observed 50% mortality after four months in Belize, while 35-65% of the fragments in two locations in USVI died within 11 months (Rogers et al 1982). In Florida, 57% of the storm-generated fragments landing on hard bottom substrates were removed within 11 months, and all remaining fragments were removed after 3 years (Lirman 2000). In Puerto Rico, mortality of close to 90% of storm-generated fragments was observed within two years of Tropical Storm Debby, primarily due to a disease outbreak. Fragments generated during a subsequent storm (Hurricane Hortens) exhibited higher rates of survival, however over 97% were removed from the site two years later during Hurricane Georges (Bruckner unpubl Data).

The survivorship of fragments at the *Fortuna Reefer* site was dependent on fragment size, depth, location of attachment, and ability to fuse and expand onto the substrate. Fragments at intermediate depths (3-4 m) that were secured to the reef and oriented upright had the highest survivorship overall. Deeper areas (5-6 m) had the highest rates of mortality and shallow areas (2 m) had the highest losses due to detachment and wire breakage. Surviving fragments were also larger than fragments that died. Highsmith et al. (1980) observed a similar relationship between fragment size and survivorship, while Rogers et al. (1982) reported lower survivorship among larger fragments. In Florida, fragment size did not appear to effect survival of either hurricane-generated fragments or transplanted fragments, although waves and currents removed smaller fragments more frequently than large fragments (Lirman 2000).

The use of wire appears to be effective over the short term for securing coral fragments to the reef and was successful at retaining fragments during storm events. In areas that routinely experience high surge and wave action, wire may be more efficient than cement or epoxy, because it does not require time to adhere and can be used in areas with algae or sediment without any surface preparation. One of the main drawbacks is that the wire frequently abraded the tissue, dividing living tissue on a fragment into two or more separate patches. Only a small proportion of fragments (22%) were able to completely or partially overgrow the wire after two years. Mortality associated with wire abrasion may be reduced by ensuring that fragments are firmly anchored and do not move under surge conditions, and could be avoided altogether by using wire that is coated in plastic. Plastic cable ties were also used to secure fragments to skeletons; tissue readily grew over the plastic, however cable ties stretched and loosened relatively quickly and proved to be inadequate in a high surge environment.

The wire also was observed to corrode and break, resulting in substantial losses (17%) after two years. These losses are less than expected if fragments had not been secured, as the site was impacted by a category 3 hurricane and nearly all unrestored fragments in neighboring sites were removed. However, losses may have been less if a greater proportion of fragments had fused to the substrate. The low rate of fusion may be attributed to orientation of fragments, as few fragments were positioned such that the edge of live tissue was in direct contact with the substrate. Use of a less corrosive and more durable wire, such as the wire used during the midcourse correction, may also minimize wire breakage.

Although fragments attached to skeletons were predicted to show enhanced survivorship (Iliff et al. 1999), the opposite was observed. While this may be partially related to the smaller size of fragments attached to skeletons, a high number of fragments were attached to skeletons colonized by the boring sponge, *Cliona* spp. and were subsequently killed by this sponge. Although *Cliona* spp. was the most important factor contributing to partial and total mortality of fragments, it may be avoidable by better fragment placement. Other biotic factors, such as predation by corallivorous gastropods and WBD were unrelated to the restoration approach and are factors that have contributed to the regional decline of these corals (Bruckner et al. 1997; Aronson and Precht 2001; Bruckner 2003). While losses from these factors are largely uncontrollable, their occurrence within a proposed restoration site should be one of the factors used to determine whether the restoration should occur and is likely to recover degraded populations. It may be possible to control *C. abbreviata* populations through removal (Miller 2001). Because we do not know the causative agents of WBD and other diseases, it is not currently possible to avoid diseases or mitigate disease impacts.

Most of the surviving fragments at the *Fortuna Reefer* site now resemble adult colonies. Fragments have produced new branches, are fused with the substrate, are resheeting over previously exposed skeletal surfaces, and are expanding onto the surrounding substrate. Given the dire state of most remaining Caribbean acroporid populations, along with a low probability of recovery through sexual recruitment and frequent removal of unrestored fragments from similar high wave energy habitats, 20% survival of restored fragments over six years can be considered a success. However, future restorations involving this species should be undertaken only after careful evaluation of existing conditions at the proposed restoration site to determine whether biotic or abiotic factors are present that will reduce survivorship and whether impacts from these can be mitigated to maximize success. In addition, the materials used to secure fragments should minimize negative interactions with live tissue, and fragments should be placed on the appropriate bottom type and positioned to capitalize on the potential for fusion and continued growth.

Acknowledgements

Funds for these surveys were provided by Earthwatch Institute, the NOAA Coral Reef Conservation Program and the NOAA Restoration Center. Special thanks to the captain and crew of Mona Aquatics, Earthwatch Volunteers and University of Puerto Rico graduate students. We are grateful for the field assistance provided by Ron Hill, Michelle Sharer and Michael Nemeth. Technical review by Liz Fairey and Tom Hourigan is greatly appreciated. We would like to thank the anonymous reviewers, whose helpful comments improved the manuscript. The opinions and views expressed in this document are those of the authors and do not necessarily reflect those of the National Marine Fisheries Service, National Oceanic and Atmospheric Administration, or the U.S. Government.

References

Aronson RB, Precht WF (2001) Evolutionary paleoecology of Caribbean coral reefs. In: Allmon WD, Bottjer DL (eds) Evolutionary paleoecology: the ecological context of macroevolutionary change. Columbia University Press, New York, pp 171-233

Bruckner AW, Bruckner RJ (2001) Condition of Restored *Acropora palmata* Fragments off Mona Island, Puerto Rico, Two Years after the *Fortuna Reefer* Ship Grounding. Coral Reefs 20: 235-243

Bruckner AW (2003) Proceedings of the Caribbean *Acropora* workshop: potential application of the Endangered Species Act as a conservation strategy. NOAA Technical Memorandum. NMFS-OPR-24 January 2003, 199 pp

Bruckner RJ, Williams Jr. EH, Bruckner AW (1997) Life history strategies of *Coralliophila abbreviata* Lamarck (Gastropoda: Coralliophilidae) in Southwest Puerto Rico. Proc 8th Intl Coral Reef Symp, Panama 1: 627-632

Highsmith RC, Riggs AC, D'Antonio CM (1980) Survival of hurricane-generated coral fragments and a disturbance model of reef calcification/growth rates. Oecologia 46: 322-329

Iliff JW, Goodwin WB, Hudson JH, Miller MW (1999) Emergency stabilization of *Acropora palmata* with stainless steel wire and nails: impressions, lessons learned, and recommendations from Mona Island, Puerto Rico. Int Conf on Scientific Aspects of Coral Reef Assessment, Monitoring, and Restoration. National Coral Reef Institute, Florida, p 110

Lirman D (2000) Fragmentation in the branching coral *Acropora palmata* (Lamarck): growth, survivorship, and reproduction of colonies and fragments. J Exp Mar Biol Ecol 251: 41-57

Miller MW (2001) Corallivorous snail removal: evaluation of impact on *Acropora palmata*. Coral Reefs 19: 293-295

NOAA (1997a) National Oceanic and Atmospheric Administration Damage Assessment and Restoration Program (DARP) Web Site: http: // www.darp.noaa.gov/southeast/fortuna/restore.html updated: 2005

NOAA (1997b) Fortuna Reefer Settlement Agreement http://www.darp.noaa.gov/southeast/fortuna/pdf/fort-cd.pdf

Rogers CS, Suchanek TH, Pecora FA (1982) Effects of Hurricanes Davis and Frederic (1979) on shallow *Acropora palmata* reef communities: St. Croix, USVI. Bull Mar Sci 32: 532-548

.