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REPORT

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Condition of restored *Acropora palmata* fragments off Mona Island, Puerto Rico, 2 years after the *Fortuna Reefer* ship grounding

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Abstract *Acropora palmata* fragments generated by the *Fortuna Reefer* ship grounding (1997, Mona Island, Puerto Rico) were secured to reef substrate and to dead, standing *A. palmata* skeletons using stainless-steel wire ($n = 1{,}857$). The purpose of this study was to assess fragment survivorship and condition 2 years after the attachment of fragments. Surviving fragments (57%) were larger than dead fragments (26%) and 17% were missing, mostly from shallow water. Live fragments had tissue covering 52% of upper branch surfaces; 23% of the live fragments experienced little or no tissue loss; 27% exhibited proto-branches; 14% had fused to the substrate; and 16% had overgrown the wire. Mortality was greatest in deeper water, especially among fragments secured to *A. palmata* skeletons. Mortality was attributed to overgrowth by *Cliona* spp. and macroalgae, predation by *Coralliophila abbreviata* and *Hermodice carunculata*, disease, and *Stegastes planifrons* territories. Limitations associated with the restoration technique include a low ability of coral tissue to overgrow wire and wire corrosion and breakage. Low rates of natural fusion and continued wire failure may hinder long-term recovery as storms periodically detach and remove restored fragments.

Keywords Habitat restoration · Coral reef · *Acropora palmata* · Elkhorn coral · Ship grounding

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Introduction

On 24 July 1997, the *M/V Fortuna Reefer* ran aground on a coral reef located off the southeast coast of Mona Island, Puerto Rico. The 326-ft freighter remained aground in the *Acropora palmata* (elkhorn coral) zone for 8 days. Damage from the grounding and ship removal activities extended approximately 300 m in length by up to 30 m in width, with collateral injuries occurring over a wider area from cables dragged across reef surfaces. Large branches of *A. palmata* were sheared off and entire colonies were dislodged and fractured; brain corals (*Diploria strigosa*) were also shattered by the hull of the vessel and abraded by cables. Overall, damage from the grounding (0.8 ha) and the removal (1.9 ha) impacted a sizeable tract of coral reef (NOAA 1997a).

Physical disturbances caused by hurricanes and ship groundings have profound and long-lasting effects on regenerative processes of coral communities (Stoddart 1962; Woodley et al. 1981; Aronson and Swanson 1997). Destruction of *A. palmata* has resulted in a permanent reduction in the three-dimensional structural complexity of some reefs and has reduced the habitat available to associated organisms (Dennis and Bright 1988; Aronson and Swanson 1997; Lirman 1999). Recovery of elkhorn thickets may be delayed in severely damaged areas due to a loss of adult colonies, limited sexual recruitment and high mortality of fragments (Hughes et al. 1992). Thus, fragment stabilization may enhance survivorship and reduce the time required for the re-establishment of elkhorn thickets.

Acropora palmata is a fast-growing branching coral that typically formed monospecific stands or "thickets" on shallow exposed reefs (Goreau 1959; Almy and Carrion-Torres 1963; Bythell and Sheppard 1993). Although colonies are susceptible to dislodgement and breakage during hurricanes and tropical storms, they are generally adapted to high wave energy through modifications in colony morphology, such as branch orientation and thickness (Glynn et al. 1964; Woodley et al. 1981;

Gladfelter 1991; Lirman and Fong 1997a). The primary mode of propagation is by colony fragmentation, as this species exhibits low rates of sexual recruitment (Highsmith 1982). Moreover, fusion to the substrate and continued growth of fragments play a significant role in the recovery of damaged elkhorn thickets (Bak and Engel 1979; Highsmith 1982; Rylaarsdam 1983; Rosesmyth 1984; Lirman and Fong 1997b).

Survival, attachment, and continued growth of elkhorn fragments are limited by the substrate type where dislodged fragments land (Fong and Lirman 1995). Fragments deposited in sand are at risk of being abraded or smothered and have no solid substrate for attachment. Because of the heavy swells at the *Fortuna Reefer* grounding site and the large number of fragments that had accumulated in sand channels, NOAA restoration specialists suggested that timely stabilization of fragments could enhance coral survivorship and expedite natural recovery processes. Primary restoration began within 2 months of the incident and involved securing *A. palmata* branches to the reef substrate and to standing elkhorn skeletons using stainless-steel wire (Iliff et al. 1999). The emergency restoration conducted at Mona Island used an innovative technique never before attempted on this scale or with this species.

The purpose of this study was to assess the performance of the *Fortuna Reefer* restoration 2 years after it was completed. We examined the survivorship and growth of coral fragments and relationships among fragment size, orientation, and placement. The effectiveness of the restoration technique was evaluated by examining the percentage of fragments that were lost due to wire breakage, the ability of tissue to grow over the wire and differences in survival between two locations of attachment. This report provides information on the short-term success of a new method to reattach and stabilize elkhorn coral fragments to reef substrate and standing skeletons, which is of potential value when considering future restoration efforts involving *A. palmata*.

Materials and methods

Study site

The *Fortuna Reefer* restoration site (18°03′N; 67°52′W; Fig. 1) is located off Mona Island, 65 km from the west coast of Puerto Rico. The island forms the top of an underwater ridge separating the Atlantic Ocean from the Caribbean basin and is situated immediately due west of the deep-water Mona Passage. The restoration site ranges from 2–7 m in depth and is often affected by strong currents, heavy swell, and intense wave action from the Atlantic and Caribbean.

Initial restoration

The Commonwealth of Puerto Rico and the National Oceanic and Atmospheric Administration (NOAA) Damage Assessment and Restoration Program (DARP) team conducted a natural resource damage assessment of the grounding site and expedited a settlement amounting to US $1.25 million for primary and compensatory restoration, which included $650,000 to conduct an emergency

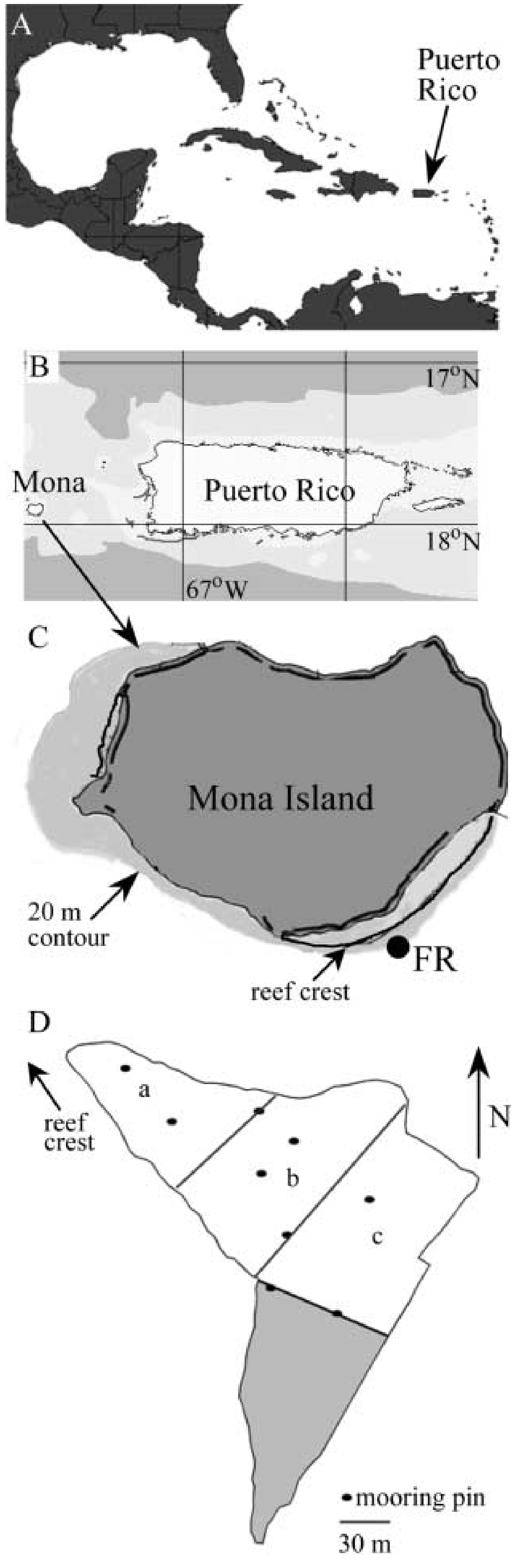

Fig. 1 Location of the *Fortuna Reefer* coral restoration site, Mona Island, Puerto Rico (**a**–**c**; 18°03′N; 67°52′W) and schematic diagram of the injured area (**d**). Mooring pins are indicated by *black dots* and were used to subdivide the site into smaller quadrants to ensure that fragments were not counted twice; in addition, the pins were used to delineate the site into three areas based on depth: *a* (< 3 m depth), *b* (3–4 m), and *c* (> 4 m). *Shaded area* furthest from the direct impact of the ship was not surveyed

restoration of coral resources injured as a result of the incident (NOAA 1997b). The objectives of the emergency restoration were to re-establish the structural relief of the coral reef community and reduce coral mortality by securing loose *A. palmata* branches to relict reef substrates and standing elkhorn coral skeletons (NOAA 1997a).

Between 24 September 1997 and 14 October 1997, a team of 19 divers including marine engineers and biologists stabilized 1,857 *A. palmata* coral fragments ranging in length from 15 cm to 3.4 m. Fragments were attached either to reef substrate or to dead, standing *A. palmata* skeletons. Stainless-steel wire was used to secure fragments to the reef; wire was extended across a fragment and then wrapped around stainless-steel nails that were cemented into holes drilled in the substrate. Plastic cable ties were used initially to secure smaller fragments to elkhorn coral skeletons, but wave surge loosened the cable ties and these fragments had to be further stabilized with wire (NOAA 1997a; Iliff et al. 1999). Additional fragments were attached to standing skeletons with stainless-steel wire alone. Fragments were reattached in either an upright or downward position (with respect to their original orientation) with the live, unbleached tissue facing upwards.

They were firmly attached so as to withstand normal surge and wave action typical of the conditions where this coral species thrives. Because of heavy swell encountered at the site, coral reattachment using concrete was deemed unfeasible (NOAA 1997a). The authors were not involved in the restoration.

Survey and analysis of restored fragment condition

Approximately 2 years after the injury and restoration we evaluated the condition of restored *A. palmata* fragments at the *Fortuna Reefer* restoration site. The survey involved an assessment of the number of fragments that remained attached and their condition, the number that had broken loose and were displaced, and the number that were missing. In addition to recorded data, photographic and video archives were made of the site and of specific fragments. Because of the extensive area of damage and the large number of fragments that were reattached, only a subset of reattached fragments (38%) were assessed in this study. Areas sustaining the greatest damage were surveyed first; the area farthest from the grounding (shaded area in Fig. 1d) was not examined due to time limitations.

For the attached fragments that had remained on the site since they were initially restored in 1997, data were collected in August 1999 on the size (maximum length), orientation (recorded as up, down, or sideways with respect to their orientation prior to fragmentation), location of attachment (reef substrate or standing skeleton), and condition. Each fragment was examined for the presence of new growth, including tissue growth over wire, and/or plastic cable ties, the presence of proto-branches, and natural cementation (fusion) to the substrate. In addition, we estimated the amount of partial or total mortality and recorded the cause of mortality. Partial or total mortality was attributed to overgrowth by *Cliona* spp. or macroalgae, predation by *Coralliophila abbreviata*, *Hermodice carunculata,* or *Sparisoma viride*, disease, presence of *Stegastes planifrons* territories, or was recorded as "unknown".

Estimates of remaining tissue and percent recent mortality were made by two divers (the authors) from a planar perspective. All fragments were assumed to initially have 100% of their upper surface covered with tissue. Remaining tissue area and amount of mortality are presented as the percent of the original tissue area remaining on the upper (exposed) surface of the branches and does not include loss of live tissue from the undersides of branches, or tissue associated with proto-branches. For each fragment, a 1-m bar divided into 5-cm increments was oriented along the center of the long axis of the fragment and used as a point of reference to estimate tissue survivorship and loss. For quality control we each measured 35 of the same fragments and compared tissue estimates prior to the actual survey to ensure that our values were consistent; in all cases, estimates for individual fragments differed by 0–5%.

The number of fragments that became detached and subsequently were removed from the site (missing fragments) was determined by tallying groupings of nails to which fragments were no longer attached (for fragments formerly secured to the reef) and counting remnant wire on elkhorn skeletons that was not associated with fragments (for fragments secured to standing skeletons).

Data analyses

Relationships among fragment size (maximum length), fragment orientation (up or down with respect to their original orientation on the colony prior to the ship grounding; sideways fragments were too few in number and are not included), location of attachment (reef substrate or standing skeleton), and depth (pooled into depths of <3, 3–4, and >4 m) were examined with respect to fragment survival and the amount of remaining tissue. Length measurements were log transformed and percentages of partial mortality were arcsine square root transformed prior to analyses as necessary. A Student's t-test was used to compare the mean length of living fragments with the mean length of dead fragments. Student's t-tests were also used to compare the mean percent of living tissue on fragments attached to the reef substrate with fragments attached to standing skeletons and the amount of tissue on fragments oriented upright versus fragments oriented downward. Correlation tests (Pearson's product-moment correlation coefficient) were used to examine relationships between fragment length and the numbers of surviving fragments in each 10-cm size class and the amount of partial mortality sustained by these fragments. A single-factor ANOVA was used to examine relationships between the amount of partial mortality and fragment size (fragments were pooled into 10-cm size classes) and also to determine whether fragment size differed among depths. Chi-square analyses of contingency tables were used to test the effects of orientation, location of attachment, and depth on fragment survival. Relationships between survivorship and orientation and survivorship and location of attachment were examined with 2×2 contingency tables; a 2×3 contingency table was used to examine relationships between fragment survival and depth. A two-factor ANOVA was used to examine the effect of depth and location of attachment and the interaction between these variables with respect to amount of tissue mortality.

Results

Condition of fragments

A total of 705 reattachment sites (38% of the original) were examined in August 1999. Of these, 57.5% ($n=405$) had fragments with some live tissue cover, 25.8% ($n=182$) had fragments that experienced total mortality, and fragments were missing at 16.7% ($n=118$) of the sites (Table 1). Most live fragments had lost some tissue during the 2 years since the restoration, although 23% of them ($n=90$) had tissue covering 90% or more of their upper surfaces. A number of fragments had developed vertical features (proto-branches), indicating upward growth. One or more small proto-branches (2–10 cm in height) were observed on 108 (19%) fragments. New upward growth occurred regardless of whether the fragment had fused naturally. Only 10% ($n=58$) had successfully fused to the substrate or the standing skeletons; 11% ($n=66$) had completely overgrown the wire; and 10.6% ($n=62$) had partially overgrown the wire. For 73% ($n=295$) of the surviving fragments, tissue mortality occurred in areas in direct

Table 1 Condition and size of *Acropora palmata* fragments 2 years after the *Fortuna Reefer* restoration, Mona Island, Puerto Rico. Fragments were attached in various orientations to the reef substrate or to dead, standing *A. palmata* skeletons. Percent of live fragments (% live) was calculated only from remaining fragments. Missing fragments are presented as number and percent of all fragments surveyed in that category

		Live		Dead		Length (cm)		Percent live tissue	Missing	
		No.	(%)	No.	(%)	Mean	SE		No.	(%)
Orientation	Up	267	71	109	29	65.6	2.0	54		
	Down	120	63	70	37	59.4	2.2	47		
	Side	18	86	3	14	87.4	7.6	48		
Location of attachment	Reef	232	73	86	27	77.4	2.8	52	99	(24)
	Skeleton	173	64	96	36	59.5	2.3	51	19	(6.6)
Depth										
< 3 m	Reef	58	74	20	26	77.2	4.5	56	47	(38)
	Skeleton	64	68	30	32	64.6	3.8	49	9	(9)
3–4 m	Reef	117	77	35	23	74.4	3.9	49	28	(16)
	Skeleton	71	70	30	30	56.3	3.8	60	3	(3)
> 4 m	Reef	59	66	30	34	77.8	4.8	56	24	(21)
	Skeleton	36	49	37	51	57.2	4.8	38	7	(9)
All fragments		405	69	182		64.3	1.5	52	118	(17)

contact with the wire (Fig. 2a). Some fragments had been attached to erect skeletons using plastic cable ties or a combination of cable ties and wire. Fragments appeared to be less negatively affected by the cable ties, as tissue readily overgrew them in 68% of these fragments ($n = 28$) (Fig. 2b). In a small percentage of remaining live fragments (8.9%, $n = 34$), the wire used to secure them was broken; these fragments remained in place, or had moved 0.5–2 m from the original site of attachment depending on their size.

The only identifiable cause of total mortality was overgrowth by the boring sponge *Cliona* species complex (9% of all restored fragments surveyed, $n = 51$; Fig. 2c). Partial mortality was associated with *Cliona* spp. (5% of the living fragments, $n = 20$), predation by *Coralliophila abbreviata* gastropods (4%, $n = 15$), overgrowth by *Dictyota* spp., other macroalgae, and/or unidentified cyanobacterial mats (3%, $n = 11$), *Hermodice carunculata* (fireworm) predation ($n = 7$), white-band-type diseases ($n = 6$), and *Stegastes planifrons* (damselfish) algal lawns ($n = 3$).

Length-related survivorship

Restored fragments identified during this survey ranged in length from 15 to 340 cm. The mean length of fragments was 64 cm (SE = 1.5; median length = 55 cm) and 73% of the fragments ranged from 30–90 cm. Of the original 1,857 fragments reattached during the restoration in 1997, 653 were 15–50 cm in length (estimated to be 50% of the fragments in this size class created during the incident), 869 were 50–100 cm (80% of the total in this size class), and 335 were more than 1 m (all fragments in this size class) (NOAA 1997a). There were no significant differences between the size classes of the fragments in the population restored in 1997 and the restored fragments examined in 1999 (pooled into three size classes, G-test of goodness of fit, $G = 4.67$, $p = 0.1$), indicating that the size classes of the fragments examined in 1999 were a representative sample of the fragments reattached in 1997.

Surviving fragments examined in August 1999 were significantly larger (mean = 69.8 cm) than dead fragments (mean = 52.2 cm; $t = 6.3$, $df = 476$, $p < 0.001$). Figure 3 shows the number of fragments in each size class that were alive and the number that had died. More than 75% of the fragments larger than 50 cm survived, while only 46% of those smaller than 50 cm survived, and the number of surviving fragments was correlated with fragment size ($r^2 = 0.42$, $p = 0.001$; 95% confidence limits, $0.26 \leq \rho \leq 0.84$). In addition, the amount of partial mortality differed between size classes (single-factor ANOVA, $F = 2.5$, $df = 586$, $p < 0.001$). There was a positive relationship between fragment size and percent tissue remaining ($r^2 = 0.42$, $p < 0.002$); however, there was a high degree of variability within larger size classes (Fig. 4).

Effect of fragment orientation and location of attachment

Differences in fragment orientation (up or down) and location of fragment attachment (reef substrate or standing skeletons) had minor effects on survivorship and the amount of remaining tissue (Table 1). Approximately 65% of all fragments examined were attached right side up (the original orientation before being dislodged from the parent colony, $n = 376$), but there was no difference in fragment length with respect to orientation ($t = 1.33$, $df = 564$, $p = 0.183$). No significant difference was observed in fragment survival with respect to orientation (chi-square analysis of a 2×2 contingency table, $\chi^2 = 3.25$, $df = 1$, $p = 0.072$), but there were differences in the amount of tissue remaining on surviving fragments ($t = 1.65$, $df = 385$, $p = 0.035$), with fragments attached right side up having a greater percentage of live

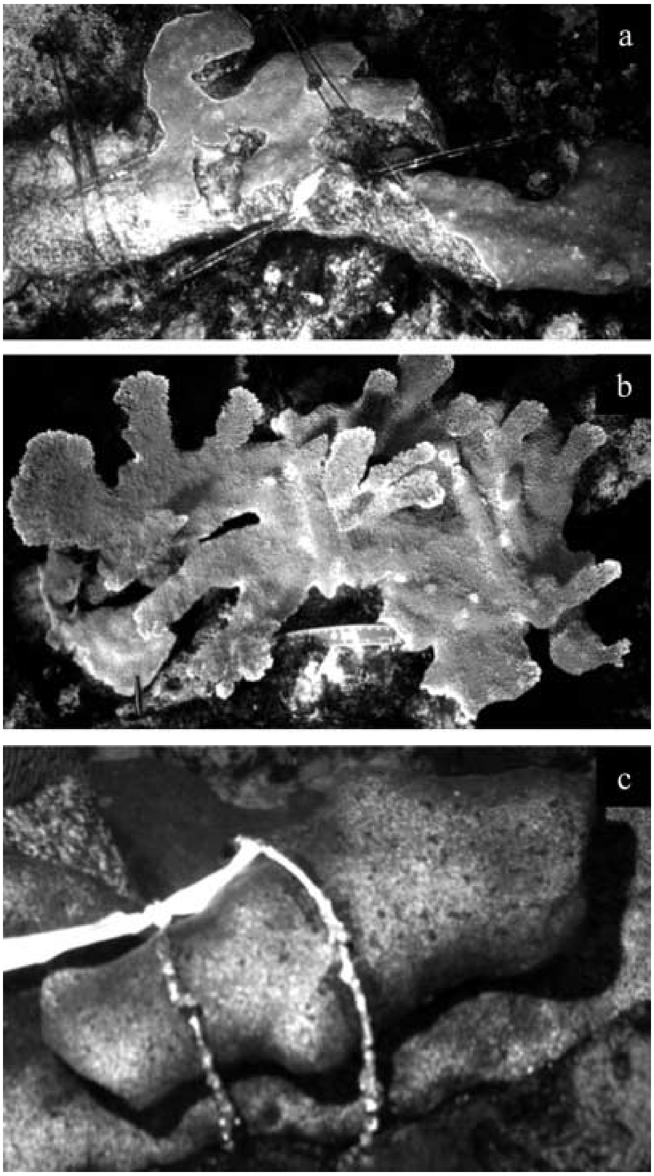

Fig. 2a–c Examples of restored *Acropora palmata* fragments at the *Fortuna Reefer* coral restoration site photographed in August 1999, approximately 2 years after restoration. **a** Fragment attached to the substrate, illustrating wiring technique used to stabilize it. Partial mortality occurred where tissue was in contact with the wire. Fragment is 104 cm in length. **b** Fragment reattached to an erect *A. palmata* colony using cable ties. This fragment exhibited fusion, growth over cable ties and well-developed proto-branches. Fragment is 82 cm in length. **c** Fragment attached to standing elkhorn skeleton that was colonized by *Cliona* species complex; fragment was subsequently overgrown by the sponge. Fragment is 26 cm in length

tissue (mean = 54%; 95% confidence interval = 50–58%) than those attached upside down (mean = 47%; 95% confidence interval = 40–52%). There was also a significant difference in fragment survival between the two attachment locations (chi-square analysis of a 2×2 contingency table, $\chi^2 = 6.2$, df = 1, $p = 0.013$), with a higher proportion of the living fragments found attached to the reef substrate. However, there was no difference in the amount of tissue remaining on live fragments with respect to attachment location (mean = 52%; t = 0.47, df = 401, $p = 0.64$; Table 1).

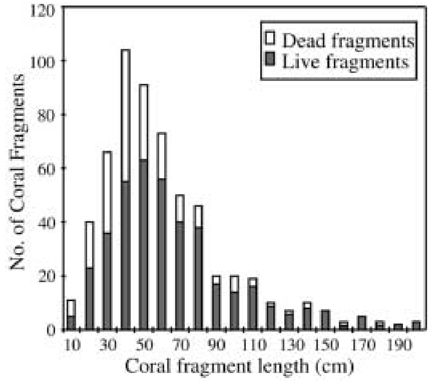

Fig. 3 Size frequency distribution of restored *Acropora palmata* fragments at the *Fortuna Reefer* coral restoration site. Number of fragments in each size class are shown as *stacked bars*

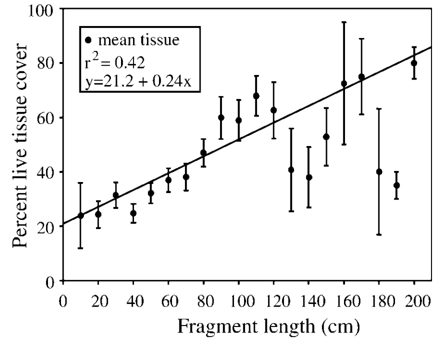

Fig. 4 Mean percent of live tissue (± SE) on upper branch surfaces for surviving *Acropora palmata* fragments at the *Fortuna Reefer* coral restoration site. Data are pooled into twenty 10-cm size classes

Effect of depth on fragment retention

Restored fragments were located from 2–7 m depth and were pooled into shallow (2–3 m), intermediate (3–4 m) and deep (> 4 m or deeper) categories (Table 1). The greatest number of lost fragments were identified in shallow water (25% of the total sample examined in shallow water), followed by those in deep water (16%); fewer fragments from intermediate depths were missing (11%). The number of fragments missing also differed between attachment locations, with 84% of all missing fragments originally attached to the substrate. This may be an artifact of the data, however, as the tallied number of fragments attached to standing colonies and subsequently lost may be an underestimate. Since nails were not used when securing fragments to elkhorn skeletons, the only indication that a fragment previously existed there was the presence of remnant wire.

Effect of depth and location of attachment on fragment condition

The condition of remaining fragments, measured as the percent of surviving fragments and the amount of live tissue, was compared among depths and attachment locations. The length frequency distributions from the three depths did not differ significantly (pooled orientation and attachment location; single-factor ANOVA, F = 1.37, df = 589, $p = 0.25$). Differences in survivorship were noted among depths (chi-square analysis of a 2×3 contingency table, $\chi^2 = 11.76$, df = 2, $p = 0.003$). More than 70% of the remaining fragments from shallow and intermediate depths survived, while only 59% of the deep fragments had survived. In addition, differences in the number of fragments that died were noted among depths for fragments attached to standing elkhorn skeletons (chi-square test, $\chi^2 = 9.26$, df = 2, $p = 0.01$), but not for fragments attached to the reef substrate (chi-square test, $\chi^2 = 3.33$, df = 2, $p = 0.19$). More than 50% of the fragments reattached to skeletons in deep water had died (Table 1). A two-factor ANOVA comparing the condition of the remaining live fragments with depth and attachment location indicates that no differences exist among depths for the percentage of tissue loss (F = 1.81, df = 2, $p = 0.165$; Table 2). In addition, the amount of partial mortality on surviving fragments was not significantly different between attachment locations (F = 0.94, df = 1, $p = 0.333$). In contrast, there was a significant interaction between attachment location and depth (F = 4.94, df = 2, $p = 0.008$), with the greatest amount of tissue loss (62%) occurring in fragments attached to standing skeletons in deep water.

Table 2 Two-factor ANOVA examining the condition of surviving fragments from three depths attached either to relict reef substrates or to standing elkhorn skeletons. Condition was determined from amount of tissue remaining, using arcsine transformed percentages. *SS* Sum of squares; *MS* mean square

Source of variation	df	SS	MS	F	*p*
Depth	2	2,236	1,118	1.81	0.165
Attachment location	1	580	580	0.94	0.333
Interaction	2	6,095	3,047	4.94	0.008
Error	399	243,144			
Total	404	252,055			

Discussion

Primary restoration at the *Fortuna Reefer* site was undertaken within 2 months of the grounding incident under the assumption that without rapid reattachment, a high percentage of fragments might die due to sand scouring and other factors, or be removed from the site during periods of high wave action (NOAA 1997a). To maximize the potential for reef recovery, the aim was to restore injured corals to the greatest extent possible. Few unrestored fragments (<2%) were tagged for controls (i.e., fragments created by the incident that were not reattached), because settlement monies from ship groundings and oil and hazardous materials releases may not be used to design and test hypotheses. The absence of data on the survivorship of control fragments provides an incomplete picture of the benefits gained by the considerable investment to secure the fragments. Nevertheless, a broad-scale census of the status of the wired fragments, as gauged by the extent of survivorship and regrowth, provides valuable information on the relative utility of the technique used to secure fragments, the relationships among survivorship and size, orientation, depth, and substrate, as well as information on potential sources of mortality. This information can be used to enhance future restoration efforts for this coral species and may assist in determining the need for subsequent corrective actions to enhance fragment survivorship.

To become successful recruits, *A. palmata* fragments must fuse to the substrate to prevent removal by wave action. The wiring technique used to stabilize fragments at the *Fortuna Reefer* grounding site was developed with the intent to enhance natural processes of fragment stabilization. It was used as an alternative to cement or epoxy due to the high wave exposure typical at this site and the amount of time required for these materials to harden. In August 1999, both living and dead fragments that were securely attached with wire were observed throughout the restoration site. Broken wire was also common; wire had loosened on some fragments and others had broken free and were carried away. Overall, 17% of the fragments that were restored originally were identified as missing. Fragment loss was greatest in shallow water, as evidenced by the number of nails, and/or wire without associated fragments. It is likely that more fragments were removed that could not be identified, however. Nails were not used to secure fragments to *A. palmata* skeletons and fragments and wire may have been removed completely, rendering the reattachment site undetectable.

Although wire failure appears to be a significant cause of transplant loss, these losses were relatively low considering that this reef is routinely exposed to severe weather and the site was directly impacted by Hurricane Georges in 1998. Studies that have followed the natural fate of hurricane-generated fragments have reported large losses in the months following the disturbance. In Florida, during an 11-month period in which no additional storms occurred, 57% of the fragments were removed from a hard-bottom substrate (Lirman and Fong 1997b). Similarly, over a 4-year period in Puerto Rico, a tropical storm and two hurricanes removed greater than 96% of *A. palmata* fragments that were generated on an offshore patch reef by a previous storm (Bruckner, unpublished data).

In many cases, the wiring technique appeared to hamper the growth of coral tissue, as evidenced by the absence of tissue directly in contact with the wire. Wire often separated two or more patches of tissue on fragments that otherwise exhibited little or no tissue mortality away from the wire. The wiring technique did not inhibit tissue growth on all *A. palmata* fragments, however, since 16% of the fragments had tissue growing over the wire. Tissue mortality associated with the wire might have been reduced by using plastic-coated stainless-steel wire.

Previous observations of the restoration site indicated that the wire was colonized by filamentous algae and macroalgae and algae were killing tissue in places (E. Weil, personal communication, April 1998); this was less common 3 months later, however (M. Miller, personal communication). During the present survey, algae (primarily filamentous green algae, *Dictyota* spp., and cyanobacterial mats) were observed on the wire associated with a relatively small proportion of the living fragments (3%). The presence of algae did not appear to be selectively affecting the wired fragments during this study, since dense macroalgae also occurred away from the wire and along the margins of unrestored *A. palmata* fragments.

The extent of survival and potential for regrowth may be affected by fragment size. Modular organisms are known to allocate different proportions of their energy and resources to reproduction, with larger colonies of some species investing more energy in reproduction than in growth (Jackson and Hughes 1985). If this is the case for *A. palmata*, smaller fragments potentially have a better chance of survival because they may concentrate their resources on growth, increasing their ability to reattach rapidly. The effect of size on survivorship of *A. palmata* fragments has been studied previously with conflicting results, however. Highsmith et al. (1980) observed a positive correlation between fragment size and survivorship, while Rogers et al. (1982) noted that fragments that survived were smaller overall than those that died. Lirman and Fong (1997b) did not observe any relationship between fragment size and survivorship, possibly because the majority of the fragments were small. In the present study, the mean size of fragments that died was significantly smaller than that of the live fragments, with the highest rate of mortality observed among fragments under 50 cm in length.

Reef-building corals are affected by partial colony mortality due to various factors. Tunnicliffe (1981) noted that Caribbean acroporids exhibit the fastest growth at the distal edges of the colonies and older, basal regions sustained higher rates of mortality. Lirman and Fong (1997b) observed tissue loss in many (73%) of their tagged fragments; fragments lost 61% of their original tissue area over an 11-month period, but surviving fragments had begun to develop vertical growth features. In the present study, surviving fragments had tissue on approximately half of their upper branch surfaces after 2 years. Although reattached fragments on the *Fortuna Reefer* site appear to have fared better than unrestored fragments in Florida and elsewhere in Puerto Rico, differences may be related to specific environmental parameters that vary among locations. In addition, the amount of tissue remaining on the branch surface may be less important for long-term survivorship than the ability of fragments to reattach and develop new vertical branches. In both studies, fragments had lost a considerable portion of their living tissue, but many were developing proto-branches, indicating that continued growth was occurring.

A critical factor affecting the ability of a fragment to successfully recruit is the substrate type where the fragment is deposited (Lirman and Fong 1997b). Bak and Criens (1981) found that *A. palmata* fragments fuse to other, living elkhorn fragments faster than to any other type of substrate. In Florida, elkhorn fragments landing on rubble substrate had a higher survivorship and a lower percent tissue loss than those deposited on relict reef substrate (Lirman and Fong 1997b). At the *Fortuna Reefer* grounding site, fragments were secured to the relict reef substrate or to dead, standing elkhorn skeletons. Those fragments attached to skeletons were expected to exhibit enhanced survivorship associated with a reduction in scouring, improved water circulation, increased light exposure, and possibly a reduced exposure to benthic predators and pathogens. Contrary to this hypothesis, fragments secured to the reef substrate had a higher survivorship than those attached to elkhorn skeletons. Although fragments on the reef substrate were larger, the percentage of tissue remaining after 2 years on survivors did not differ between the two attachment locations. The differences in survivorship are likely to have resulted from a higher rate of mortality experienced by those fragments placed in contact with the invasive sponge *Cliona* spp., which was found commonly overgrowing elkhorn skeletons and less frequently on the substrate.

It is important to note that elkhorn populations have undergone a regional decline over the last two decades (Gladfelter 1982; Bythell and Sheppard 1993). Large-scale catastrophic losses have been associated with physical disturbance from hurricanes, but a widespread, white-band disease (WBD) epizootic is a contributing factor that has certainly accelerated the decline and continues to afflict elkhorn colonies throughout the region (Gladfelter 1991; Aronson and Precht 2001). Chronic partial mortality from natural stressors like WBD, predation, and other factors not associated with the restoration may be largely responsible for the inability of fragments to successfully fuse to their attachment sites. For instance, the undersides of branches on intact colonies such as those previously affected by WBD often lack live tissue. Should they become fragmented, they may be unable to reattach without tissue in direct contact with the substrate (Bruckner, unpublished data).

In this study, recent signs of mortality including WBD were observed on a small proportion of the restored fragments, as well as on several surrounding *A. palmata* colonies that were unaffected by the ship grounding. Given a widespread occurrence and a presumed increase in the prevalence of coral disease, predators, and other stressors affecting acroporids in Puerto Rico (Bruckner et al. 1997; Williams et al. 1999), it is unlikely that mortality of restored fragments is exclusively related to the restoration. It is possible that stabilization of *A. palmata* fragments may be an activity that has only slowed an inevitable monotonic mortality process. Nonetheless, studies in Puerto Rico and Florida have shown that unrestored fragments continue to grow, but even sizeable fragments in good condition are lost during periods of high wave energy if they do not have a secure connection to the substrate (Lirman and Fong 1997b; Bruckner, unpublished data). Results to date from the *Fortuna Reefer* site emphasize the importance of a timely restoration. Without intervention, this site might have mirrored other locations in Puerto Rico, where almost complete removal of fragments occurred during subsequent storms due to low levels of natural fusion (Bruckner, unpublished data).

Adaptive management may be particularly valuable as this coral species has been declining throughout its range since the late 1970s, and innovative techniques that enhance survivorship may be critical in promoting localized recovery of elkhorn populations. In anticipation of the continued degradation of the stainless-steel wire which begins to corrode at points of crimping and twisting and given the large number of fragments that were unable to fuse to the substrate, corrective action to maintain the remaining fragments on the site may increase the overall effectiveness of initial restoration efforts. Recommendations for altering the original technique include the use of Portland cement or two-part marine epoxy (Hudson and Diaz 1988; Gittings et al. 1994), in conjunction with heavy-gauge monofilament line, nylon or Teflon-coated wire, or plastic cable ties for short-term fragment stabilization while the adhesive sets. It is imperative that those fragments exhibiting high rates of growth and fusion should not be included in corrective restoration efforts. Corrective action for the remainder will continue to maintain restored fragments on site, providing additional time for recovery and enhancing the long-term success of the initial restoration. This technique would benefit from the coordinated efforts of a multi-task team to remove the wire from loose fragments, scrape and clean the undersides of fragments and the reattachment sites to remove algae and other encrusting organisms, apply the cement or epoxy, and temporarily secure the fragments to allow the adhesive to set. Furthermore, a portion of the fragments restored in 1997 should be left unmanipulated in order to allow an assessment of the benefits gained by a mid-course correction and the potential value of future restoration efforts.

Restoration is a relatively new science that soon may need to be applied on a larger scale to mitigate effects of hurricanes, bleaching events, and disease outbreaks (Precht 1998). Current research is focusing on methods to enhance coral recruitment, restore the natural balance of herbivores and maintain coral nurseries to rescue and rehabilitate fragments generated by physical disturbances, for use as transplants for degraded areas. The application of new technologies like those used in the *Fortuna Reefer* restoration can continue to advance the science. Emphasis must be placed on scientifically based approaches needed to assess the outcome of restoration efforts and improve techniques to restore, rehabilitate, and replace damaged corals.

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References

Almy CC, Carrion-Torres C (1963) Shallow-water stony corals of Puerto Rico. Caribb J Sci 3:133–162

Aronson RB, Precht WF (2001) Evolutionary paleoecology of Caribbean reef corals. In: Allmon WD, Bottjer DJ (eds) Evolutionary paleoecology: the ecological context of macroevolu tionary change. Columbia University Press, New York, pp 171–233

Aronson RB, Swanson DW (1997) Disturbance and recovery from ship groundings in the Florida Keys National Marine Sanctuary. Dauphin Island Sea Lab Tech Rep 97–002, National Undersea Research Center–University of North Carolina, Wilmington

Bak RPM, Criens SR (1981) Survival after fragmentation of the colonies of *Madracis mirabilis*, *Acropora palmata* and *A. cervicornis* (Scleractinia) and the subsequent impact of a coral disease. Proc 4th Int Coral Reef Symp 2:221–228

Bak RPM, Engel MS (1979) Distribution, abundance and survival of juvenile corals (Scleractinia) and the importance of life history strategies in the parent coral community. Mar Biol 54:341–352

Bruckner RJ, Bruckner AW, Williams EH Jr (1997) Life history strategies of *Coralliophila abbreviata* Lamarck (Gastropoda:Coralliophilidae) on the southwest coast of Puerto Rico. Proc 8th Int Coral Reef Symp 1:627–632

Bythell J, Sheppard C (1993) Mass mortality of Caribbean shallow corals. Mar Pollut Bull 26:296–297

Dennis GD, Bright TJ (1988) The impact of a ship grounding on the reef fish assemblage at Molasses Reef, Key Largo National Marine Sanctuary, Florida. Proc 6th Int Coral Reef Symp 2:213–218

Fong P, Lirman D (1995) Hurricanes cause population expansion of the branching coral *Acropora palmata* (Scleractinia): wound healing and growth patterns of asexual recruits. Mar Ecol 16:317–335

Gittings SR, Bright TJ, Hagman DK (1994) The *M/V Wellwood* and other large vessel groundings: coral reef damage and recovery. In: Ginsburg RN (comp) Proc Colloq Global Aspects of Coral Reefs: Health, Hazards and History, Rosenstiel School of Marine and Atmospheric Science, Miami, pp 174–180

Gladfelter WB (1982) White-band disease in *Acropora palmata*: implications for the structure and growth of shallow reefs. Bull Mar Sci 32:639–643

Gladfelter WB (1991) Population structure of *Acropora palmata* on the windward fore reef, Buck Island National Monument, St. Croix, US Virgin Islands. US Department of the Interior, National Park Service, US Virgin Islands

Glynn P, Almodovar LR, Gonzalez J (1964) Effects of Hurricane Edith on marine life in La Parguera, Puerto Rico. Caribb J Sci 4:335–345

Goreau TF (1959) The ecology of Jamaican coral reefs. I. Species composition and zonation. Ecology 40:67–90

Highsmith RC (1982) Reproduction by fragmentation in corals. Mar Ecol Prog Ser 7:207–226

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

Hudson J, Diaz R (1988) Damage survey and restoration of the *M/V Wellwood* grounding site, Molasses Reef, Key Largo National Marine Sanctuary, Florida. Proc 6th Int Coral Reef Symp 2:231–236

Hughes TP, Ayre D, Connell JH (1992) The evolutionary ecology of corals. Trends Ecol Evol 7:292–295

Iliff JW, Goodwin WB, Hudson JH, Miller MW, Timber J (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, Abstracts, National Coral Reef Institute, Florida, p 110

Jackson JBC, Hughes TP (1985) Adaptive strategies of coral-reef invertebrates. Am Sci 73:265–273

Lirman D (1999) Reef fish communities associated with *Acropora palmata*: relationships to benthic attributes. Bull Mar Sci 65:235–252

Lirman D, Fong P (1997a) Susceptibility of coral communities to storm intensity, duration and frequency. Proc 8th Int Coral Reef Symp 1:561–566

Lirman D, Fong P (1997b) Patterns of damage to the branching coral *Acropora palmata* following Hurricane Andrew: damage and survivorship of hurricane-generated asexual recruits. J Coast Res 13:67–72

NOAA (1997a) National Oceanic and Atmospheric Administration Damage Assessment and Restoration Program web site. http://www.darp.noaa.gov/seregion/fr.htm. Updated 30 April 1998

NOAA (1997b) *Fortuna Reefer* settlement agreement (9/11/97). http://www.darcnw.noaa.gov/fort-cd.pdf

Precht WF (1998) The art and science of reef restoration. Geotimes 43:16–19

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

Rosesmyth MC (1984) Growth and survival of sexually produced *Acropora* recruits: a post-hurricane study at Discovery Bay, Jamaica. In: Proc Joint Meeting International Society for Reef Studies and Atlantic Reef Committee and University of Miami, Advances in Reef Science, 26–28 Oct, pp 105–106

Rylaarsdam KW (1983) Life histories and abundance patterns of colonial corals on Jamaican reefs. Mar Ecol Prog Ser 13:249–260

Stoddart DR (1962) Catastrophic storm effects on the British Honduras reefs and cays. Nature 196:512–515

Tunnicliffe V (1981) Breakage and propagation of the stony coral *Acropora cervicornis*. Proc Natl Acad Sci USA 78:2427–2431

Williams EH Jr, Bartels PJ, Bunkley-Williams L (1999) Predicted disappearance of coral-reef ramparts: a direct result of major ecological disturbances. Global Change Biol 5:839–845

Woodley JD, Chornesky EA, Clifford PA, Jackson JBC, Kaufman LS, Knowlton N, Land JC, Pearson MP, Porter JW, Rooney MC, Rylaarsdam KW, Tunnicliffe VJ, Wahle CM, Wulff JL, Curtis ASC, Dallmeyer MD, Jupp BP, Koehl MAR, Niegel J, Sides EM (1981) Hurricane Allen's impact on Jamaican coral reefs. Science 214:749–755