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Improving restoration approaches for *Acropora palmata*: Lessons from the Fortuna Reefer grounding in Puerto Rico

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Abstract. Detached *Acropora palmata* fragments (n=1857) generated by the *M/V Fortuna Reefer* grounding off Mona Island, Puerto Rico were secured to reef substrates or dead standing *A. palmata* skeletons using stainless steel wire. After 10 years, only 6% (n=104) of the fragments were alive, of which half (n=54) exhibited extensive branching (mean = 5 branches, 89 cm length), and a substantial increase in height (mean = 39 cm). Most surviving fragments were 20-100 cm (original length when first restored), secured to the reef and oriented upright. Fragments died or were lost in the first three years from wire breakage (23%), overgrowth by bioeroding clionid sponges (16%) and other factors (5%). Over the next 7 years, another 50% died due to gastropod predation, additional wire breakage and detachment during storms, and continued overgrowth by *Cliona*. Fragments attached to *A. palmata* skeletons initially grew rapidly and produced new branches, but most were subsequently dislodged due to bioerosion and breakage of the skeleton to which they were attached. Low fragment survival is attributed to 1) wire failure and inability of corals to overgrow wire, 2) limited fragment fusion, 3) attachment of fragments to inappropriate substrates, and 4) progressive mortality of large, older basal portions of detached colonies that failed to grow. Natural stressors unrelated to the restoration including diseases, predators, and bioeroding sponges have increased over time within and outside the grounding site and are also impacting fragment survival. Restoration may be a viable means to promote recovery of acroporid populations if the use of uncoated wire to attach fragments is avoided; fragments are placed on suitable substrates with live tissue in direct contact with the substrate to promote fusion, and efforts to mitigate disease and corallivory are undertaken.

Key words: *Acropora palmata*, Elkhorn coral, Restoration, Ship grounding, Coral disease.

Introduction

Since the listing of *Acropora palmata* on the U.S. Endangered Species Act in 2006, interest in recovering degraded and damaged populations of this species through restoration is increasing. Historically, most restoration efforts in the U.S. were conducted in response to ship groundings. Small scale restoration projects for *A. palmata* are now also being implemented after hurricanes and other catastrophic disturbances to minimize tumbling, scouring and loss of fragments associated with high wave energy and sand and rubble movement. Cement, epoxy, metal wire, cable ties, and/or molly bolts have all been used to reattach *A. palmata* fragments, with varying degrees of success (Precht 2006). Fragments have also been secured to artificial (cement) and natural (limestone rocks) structures, including reef crowns, rosettes, and limestone boulders, with further stabilization using molly bolts or other anchoring systems (Bruckner 2003). Fragments at the Fortuna Reefer site were attached to dead standing *A. palmata* skeletons to raise them off the substrate and to promote resheeting over dead skeletons (NOAA 1997; Iliff et al. 1999; Bruckner and Bruckner 2001).

The first major restoration effort for *A. palmata* in Puerto Rico was undertaken following the *M/V Fortuna Reefer* grounding on July 24, 1997. The grounding and removal of the vessel damaged shallow reef habitat dominated by *A. palmata* and *Diploria strigosa*. The reef substrate was crushed and fractured along the inbound and outbound tracks of the vessel, extending from the reef crest approximately 300 m seaward (2-4 m depth) and up to 30 m in width, with collateral damage to surrounding areas from cables used to extract the vessel (NOAA 1997).

An emergency restoration was completed within three months of the incident. The restoration focused on the reattachment of broken and dislodged *A. palmata* colonies and branches throughout the site of impact using stainless steel wire. Because of reports of frequent wire breakage and fragment loss, a mid-course correction using a stronger wire was undertaken in 2000 to prevent further fragment loss

(Bruckner and Bruckner 2001). This paper describes the fates of the fragments over 10 years, including patterns of survival, regrowth, and sources of mortality. The restoration techniques used at this site are evaluated and recommendations are presented on alternative approaches that may enhance the success of future restoration efforts for this species. Natural causes of mortality, unrelated to the grounding, are also discussed, along with options to mitigate these.

Material and Methods

Between September and October 1997, restoration experts stabilized detached *A. palmata* colonies and branches (n=1857) throughout the grounding site (2-6 m depth) off the southeast coast of Mona Island (18°02'N; 67°51'W; Fig. 1). Coral fragments (15-340 cm in length) were secured to the reef by wrapping stainless steel wire over coral fragments and around stainless steel nails that were inserted into pre-drilled pilot holes. Additional fragments were attached to dead standing *A. palmata* skeletons using wire and/or cable ties (NOAA 1997).

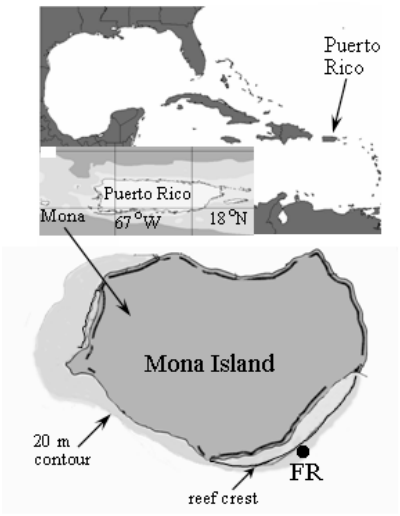

Figure 1: Location of the Fortuna Reefer (FR) restoration site.

We first examined the site in February 1998, and subsequently monitored changes to fragments and unmanipulated colonies and fragments in surrounding areas 1-3 times per year through February 2008. The initial survey involved an assessment of the number, size, and condition of fragments that remained attached, and the number of fragments that were detached and displaced or missing. Detached and missing fragments were identified from 1) groupings of nails within the reef without attached fragments; 2) remnant wire on skeletons that was not associated with fragments; and 3) unsecured fragments with remnants of attached wire that accumulated in sand channels or were scattered throughout adjacent fore and back reef habitats.

For each remaining fragment, measurements of the size (maximum length to nearest cm), orientation (up, down or sideways with respect to their orientation prior to breakage), origin (branch end, middle, or base of colony), location of attachment (reef or skeleton), and condition (live or dead) were recorded. Live fragments were also evaluated for tissue growth over the wire, presence and size of proto-branches, natural cementation (fusion) to the substrate, and resheeting over *A. palmata* skeleton. Estimates of size (length, width, height), percent remaining tissue, and old vs. recent mortality were made from a planar perspective using a 1 m bar (marked in 1 cm increments) oriented along the long axis of the fragment. Partial mortality was recorded as the percent loss from the upper surface of the reattached branches, and does not include the undersides of branches. All fragments were presumed to have 100% of their upper surface covered with tissue when first reattached in 1997.

Causes of partial or total mortality were identified as disease [white band disease (WBD), Caribbean ciliate infections, white patch (pox) disease, or growth anomalies], overgrowth by boring sponges (*Cliona* spp.), predation by snails (*Coralliophila abbreviata)*, polychaete worms (*Hermodice carunculata),* parrotfish *(Sparisoma viride*), macroalgal competition, or three-spot damselfish *(Stegastes planifrons*) territories. If the cause of mortality could not be determined, it was recorded as unknown.

Results

A total of 1857 fragments were reattached in 1997. Most surviving fragments (n=104; 5.6%) identified in February 2008 were attached to the reef (n=78; 75%) or dead *A. palmata* skeletons (n=26; 25%) and oriented upright (92%). A number of additional fragments that were originally attached to dead skeletons (n=28) had become detached due to wire failure and breakage of the underlying branches, and had accumulated in sand channels (Fig. 2). Over half (63%) of the surviving fragments had living tissue on most of their upper branch surfaces (>80%) and numerous branches (3-23 branches, 15-70 cm length); these had increased in height (20-80 cm) and width (15-150 cm). Other surviving fragments (37%, n=38) consisted of large (>80 cm length) middle and basal portions of broken colonies. These exhibited minimal signs of new growth over 10 years and a lack of fusion as the fragments were progressively losing tissue (mean=37% live tissue). Few fragments firmly fused to the reef substrate or coral skeletons (12%), and none of the fragments attached to dead skeletons successfully grew tissue over the underlying skeletal surfaces to which they were attached.

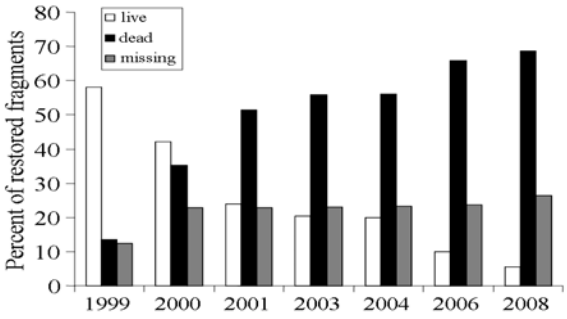

Figure 2: Changes over 10 years in the proportion of restored fragments (total=1857) that were still alive (white bars), dead (black bars) and detached and/or missing (grey bars).

Original fragment length, orientation (up or down), position on the source colony (e.g., branch end or middle) attachment location, and depth were important factors in the long-term survival of restored fragments (Fig. 3). The highest survival was recorded from 1.5-4 m depth, especially medium sized fragments (20-100 cm length) that were oriented upright and were attached to reef substrates. Small and medium-sized fragments attached to dead skeletons initially exhibited high rates of growth, but most were directed upward by production of new branches with only limited resheeting onto the dead coral substrates.

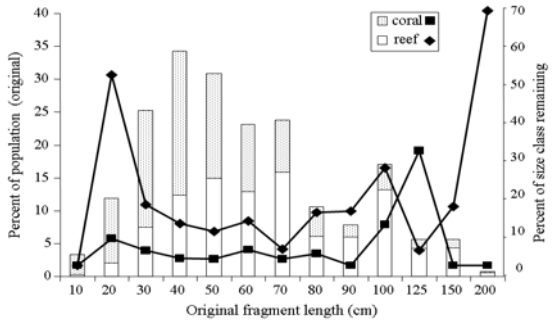

Figure 3: Percent of live fragments in each size class when initially restored (stacked bars) divided into fragments attached to the reef (white bars) and dead skeletons (grey bars), and the percent within each size class that was still alive after 10 years (line graph), attached to the reef (diamond) or to dead *A. palmata* skeleton (square).

Wire failure resulted in the loss of 23% (n=427) of the restored fragments in the first three years (prior to the mid-course correction). An additional 7% (n=55) of the fragments that were rewired in 2000 were lost during years 8-10, primarily due to breakage of underlying *A. palmata* skeletons as the fragments increased in size and branching complexity. Overgrowth by the boring sponge (*Cliona* spp.) was responsible for 22% total loss with 5% of the survivors currently affected by *Cliona* (Fig. 4). Mortality from *Cliona* was attributed to placement of fragments on or near substrates colonized by this sponge. Coral diseases identified throughout the site included WBD (7.3% of all fragments affected over 10 years), ciliate infections (3.2%), white patch disease (0.3%), and growth anomalies (1.3%). Numerous fragments died from WBD (5.8%), and the prevalence of WBD steadily increased from 2003-2008 (Fig. 4), while other diseases caused minimal partial mortality. Corallivorous gastropods (*C. abbreviata*) increased in abundance (maximum = 286 snails/survey) and density over time, affecting 17% (n=315) of all fragments over 10 years. These gastropods were found on fragments and colonies with WBD, as well as healthy corals, but they formed larger aggregations on stressed corals (6-40 snails per coral vs. 1-5 on "healthy" fragments), especially fragments that were dislodged and deposited in the sand. Damselfish algal lawns (1.1%), parrotfish predation (0.1%), and algal overgrowth (0.2%) were rare. The site was invaded by a crustose coralline algae (*Peyssonnelia* spp.) in 2006, which is rapidly spreading and has recently begun overgrowing corals. No bleaching was observed among *A. palmata* colonies or fragments during the 1998 and 2005 mass bleaching events or other years.

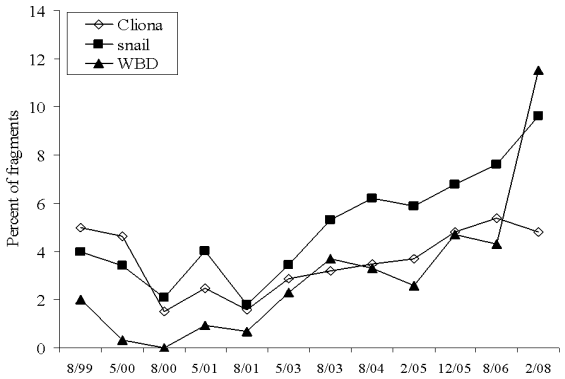

Figure 4: Major causes of partial and whole fragment mortality. A total of 22% of all fragments were overgrown by *Cliona* spp. (open diamonds), 5.8% were killed by WBD (triangles), and 17% were preyed on by *C. abbreviata* gastropods (square).

Discussion

Ten years after completion of the *M/V Fortuna Reefer* restoration, only about 6% of the fragments remain alive. About half of these have continued to grow and have produced numerous branches, recreating the structural complexity of an *A. palmata* reef. Other survivors, primarily the largest basal and middle portions of the colonies, failed to produce protobranches and are continuing to lose living tissue. A significant proportion of the fragments died from natural stressors unlikely to have resulted from the grounding or restoration. This includes pervasive and increasing predation pressure by *C. abbreviata* and an

outbreak of WBD that began five years after the grounding. Substantial loss in the first 2 years and over the longer term was also directly related to the restoration techniques used to secure the fragments, substrates selected for attachment, orientation of fragments, and attachment of larger, older basal parts of the colony with a lower likelihood of survival.

Attachment methods

"Traditional" methods to reattach coral fragments, including cement, epoxy, and cable ties were first attempted at the *M/V Fortuna Reefer* site. Cement offered the most efficient, natural, and cost-effective approach to secure fragments, but it was difficult to use due to the long setting time required and the heavy surge at the time of the restoration. A quick setting 2-part epoxy was also impractical because it was neutrally buoyant and larger fragments failed to properly adhere to substrates if algae, sediment, and sessile invertebrates were not thoroughly removed. Fragments secured initially to *A. palmata* skeletons with plastic cable ties were reported to loosen under surge conditions; thus, stainless steel wire was used (NOAA 1997; Iliff et al. 1999).

Over 10 years, wire proved to have numerous drawbacks. Considerable time was spent inserting stainless steel nails into reef substrates to provide a holdfast for the wire. This necessitated use of a hydraulic drill and a compressor to drill holes and cement to secure the nails. Another limitation of wire was the difficulty in securely attaching fragments to the reef to dampen wave surge effects. The slight, continuous movement of the fragments hampered their ability to fuse naturally and wire abraded the coral tissue, resulting in extensive partial fragment mortality (Bruckner and Bruckner 2001). Stainless steel wire used at the site also became pitted and broke, necessitating a mid-course correction after three years. Fragments were rewired using a stronger Monel nickel/copper alloy wire, but this also began to break after 4-5 years contributing to further fragment loss. Both types of wire also provided a substrate for accumulation of macroalgae and attachment of *Millepora alcicornis*, further compromising fragment health (Bruckner and Bruckner 2006b).

Cable ties are the optimal choice for reattachment of *A. palmata* on shallow exposed reefs, as coral tissue and skeleton is rapidly accreted over the plastic, and cable ties can be firmly tightened, although multiple ties may be required to prevent loosening. As a pilot experiment, we secured fragments removed from colonies with WBD to *A. palmata* skeletons using cable ties (n=23) and underwater two part epoxy. After four years only a single branch attached with cable ties was detached while all fragments attached with epoxy were lost; all other fragments secured with cable ties (94%) fused to the skeletons and overgrew the plastic (Bruckner and Borneman unpub. data). During the mid-course correction, a small number of fragments in shallow water were reattached to the reef substrate with cement. While several of these have died, none have become detached. Over the long-term, cement or some of the newer, commercial underwater epoxies like Allfix and Z-Spar may prove to be the most successful, cost-effective, and rapid method to reattach fragments, especially if the fragments are temporarily secured with plastic-coated wire or cable ties to allow time for cement to set. Plastic coated wire is likely to facilitate tissue overgrowth and reduce the likelihood of wire breakage but still must be monitored frequently to avoid loss of fragments due to storms.

Substrates for attachment

Fragments were attached to branches of dead standing *A. palmata* colonies with the expectation that they would attach to the dead branches and resheet over the skeleton, thereby restoring the three dimensional topographic relief much more rapidly (NOAA 1997; Iliff et al. 1999). Few fragments accreted tissue and skeletal material onto adjacent branches, and none grew back down the colony. Instead, most growth was directed upward in the form of new branches. These continued to increase in size and weight, creating more wave resistance until the underlying skeleton broke. The fragments were subsequently dispersed, overturned and deposited in sand flats, or removed from the site. Placement of fragments above the substrate had minimal benefits at reducing disease prevalence or corallivore abundance; and overgrowth by *Cliona* was actually higher than that observed in fragments attached to the reef (Bruckner and Bruckner 2006a), possibly because *Cliona* colonizes dead corals more frequently than the reef substrate. Fragments secured in an upright position to the base of colonies may have a better chance of fusion and resheeting as they grow upward.

Branch size and origin

Restored fragments ranged in length from 15-340 cm and included branch ends, as well as older colony bases and middle. Branch ends up to ~100 cm exhibited the highest rates of survival and growth, and greatest ability for natural fusion. Many of the largest basal and middle portions survived over 10 years, but they were affected to a greater degree by disease and corallivory, and very few developed new branches. In fact, most failed to grow at all, and instead slowly lost living tissue over 10 years. These fragments also often lacked tissue on their undersides when first restored, reducing their ability to fuse. Due to their large size, stabilizations and attachment is more labor

intensive, while small to medium sized branch ends can be relocated and secured more rapidly with cable ties, cement, or epoxy. Larger fragments could be positioned (but not attached) onto hard substrates to reduce scouring and smothering by sediment, and their weight and structural complexity alone may be sufficient to minimize movement. The time required to secure these could be better invested into attaching a greater number of smaller branch ends.

Enhancing natural fusion

Only a limited number of fragments, primarily smaller branch ends with live tissue on the upper surfaces and undersides when first attached, accreted tissue and skeleton onto the underlying substrate over 10 years. Other branches were unable to reattach, mainly because the branches were not positioned such that living tissue was directly in contact with the substrate, and fragments exhibited slight back and forth movement during wave surge. Fusion may be enhanced by placing fragments at a slight angle such that a portion of the living surface of the branch was in contact with exposed, algal-free substrate. Ensuring contact of living tissue with a hard substrate free of algae may provide adequate time for natural fusion, thereby minimizing losses at a later stage when the wire breaks.

Controlling natural stressors

The gastropod *Coralliophila abbreviata* is a significant predator of *A. palmata* and may also be a vector for disease (Bruckner et al. 1997; Williams and Miller 2005). If snails occur within the restoration site, these should be removed while the restoration is underway, with additional removal as needed during annual monitoring to minimize tissue loss. Collection of *C. abbreviata* into sealable plastic bags for disposal on land is recommended due to their brooding life history strategy. We conducted a snail removal experiment from this site in Aug 2006. After 1.5 years, a large number of snails recolonized the area, but far fewer than before (Bruckner and Borneman unpubl. data). Although the causative agent of WBD remains elusive, and few attempts to treat WBD-affected corals have been undertaken, branch ends removed from colonies with WBD and attached to surrounding substrates exhibited high rates of survival, while the source colonies completely died (Bruckner and Borneman unpubl. data). One other stressor, the bioeroding sponge *Cliona*, readily overgrew fragments placed on or next to it. *Cliona* also spread to new areas, increasing in cover over the duration of this study. Placement of fragments away from competitive species (such as, *Cliona* and *Palythoa*), minimizes the likelihood of overgrowth, and may allow ample time for fusion and growth of fragments.

Success of future restoration efforts directed at this species may be enhanced by taking into consideration the environmental conditions affecting the site and suitability of the site for restoration including physical factors such as wave exposure, condition of reef substrates (e.g., cover of macroalgae and bioeroding sponges), and presence of disease and corallivores. Specific restoration techniques including the use of materials that do not negatively affect living tissue, placement of fragments on suitable (cleaned) substrates, orienting fragments such that live tissue contacts the substrate, and selection of small to medium sized branch ends can enhance survival and possibly speed up ecological recovery of the site.

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