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Coral transplants as rubble stabilizers: a technique to rehabilitate damaged reefs

P.T. Rojas Jr.[1], L.J. Raymundo[1,2*], R.L. Myers[1]

1) University of Guam Marine Laboratory, UOG Station, Mangilao, Guam 96923
2) Department of Ecology and Evolutionary Biology, Cornell University, Ithaca NY 14850, USA
[*]Corresponding author: ljraymundo@gmail.com

Abstract. Developing practical techniques to mitigate the effects of coastal development, ship groundings and destructive fishing has challenged reef managers for 30 yr. Coral communities reduced to rubble do not support recruits due to their instability; such areas have slim chances of recovering naturally. We relocated "corals of opportunity" to a 50-year-old rubble bed and tested the efficacy of using two species of corals with contrasting morphologies as rubble consolidators. We hypothesized that *Porites rus,* which forms upright columns and extensive basal plates, would be a superior consolidator to *Porites cylindrica,* which has a dendritic growth form without basal plates. After 18 months, growth and survival varied significantly between species. The majority of *P. rus* transplants survived (93.3%), while only 23.3% *P. cylindrica* transplants did. Mean basal growth was 0.8 mm mo^{-1} for *P. rus* and 0.07 mm mo^{-1} for *P. cylindrica,* with *P. rus* overgrowing rubble within 6 mo. The plate-forming morphology enhanced survival by stabilizing fragments as they grew. In contrast, none of the *P. cylindrica* transplants consolidated onto rubble during the course of our study.

Key words: rehabilitation, *Porites,* rubble stabilization, Guam.

Introduction

Guam reefs have traditionally been heavily used for food and recreation (Amesbury and Myers 1982; Zeller et al. 2006) and fish stocks have declined steadily over the past 50 yr. The Guam Visitors Bureau reported a record high of 1 million Asian tourists in 2004, a dramatic increase over past years despite economic setbacks (GVB 2004). Physical damage to reef structure from water sports is associated with premier tourist destinations (Hawkins and Roberts 1993; Rouphael and Inglis 2001; Burdick et al. 2008), increasing coral mortality and loss of reef structure (Edwards and Clark 1998; Bowden-Kerby 2003). Compounded by chronic nutrient inputs, sedimentation and pollution, and acute outbreaks of the Crown-of-Thorns starfish (Birkeland and Lucas 1990), recovery of Guam reefs has been slow to non-existent. A further complication is low coral recruitment (0.14 recruits/15-cm^2; Birkeland et al. 1981, 0.002 recruits/15-cm^2; Birkeland 1997, 0.013 recruits/15-cm^2; Minton and Lundgren 2006). The reasons for this are unclear and therefore difficult to mitigate. If Guam reefs are self-seeding due to minimal larval flow between islands, declines in coral cover will be self-perpetuating (Porter et al. 2005).

Restoration ecology explores approaches to mitigate damage to ecosystems, promote recovery, and reestablish specific attributes and function (Rinkevich 2005). Techniques currently employed range from coral gardening and transplantation to deploying artificial structures for recruitment substrate and habitat. In Guam, coral transplantation has been conducted since the late 1970s with various objectives, which have included: reestablishing coral communities in thermal effluent areas (Birkeland et al. 1979), preserving rare coral species (Plucer-Rosario and Randall 1987), translocating corals due to underwater construction and ship groundings (Naughton and Jokiel 2001), and mitigating coral loss from fiber optic landing development (Kolinski 2002). However, the challenging issue of persistent rubble fields from physically destructive events has been largely ignored. As Guam reefs will be subjected to increasing coastal and military development, continuous boat activity, and periodic typhoon surge, this problem requires urgent attention.

Despite the innate ability of corals to fragment, survival depends on attachment to stable substrate (Bothwell 1982). Corals can recover from natural calamities such as storms, but chronic fragmentation by human activity creates rubble fields which fail to consolidate because recruits do not survive. Practical approaches to rehabilitate rubble and facilitate coral reestablishment are few. Fox et al. (2005) and

Raymundo et al. (2007) found high transplant survival and recruitment on rubble stabilized by combinations of plastic mesh, rock piles and cement slabs.

This investigation tested the use of coral fragments to consolidate rubble while simultaneously relocating corals from a marginal habitat scheduled for dredging. These 'corals of opportunity' (Edwards and Gomez 2007) were a mixed community of *Porites rus* and *Porites cylindrica*. We compared the rubble stabilizing ability of plate-forming *P. rus* with the upright branching *P. cylindrica.* We predicted that *P. rus* would be a superior species to consolidate underlying rubble than *P. cylindrica* due to its morphology and rapid growth rate (Veron 2000).

Materials and Methods

Study site

The experiment was conducted on Sumay Mound, a nearshore seamount rising from 30 m to 15 m depth, 1 km south of the Apra Harbor inner channel dredge site. Approximately 20% of this reef was dominated by rubble from anchor damage in the 1950s. Recovery, to date, has been insignificant. Further, the rubble bed is seasonally dominated by the foliose macroalga *Padina sanctae-crucis* such that live hard coral cover constituted only 15% of the substrate (Fig. 1). The persistent rubble, protection from typhoon surge and proximity to the source site were attributes favorable for our recipient site.

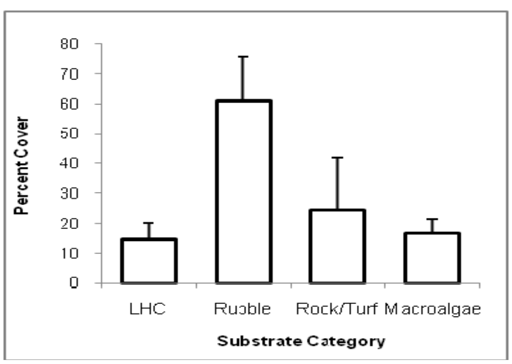

Figure 1: Benthic composition within the rehabilitation site on Sumay mound, showing a dominance of coral rubble.

Coral translocation and establishment

Fifteen colonies each of *P. rus* and *P. cylindrica* were transported from the channel to Sumay Mound and allowed to acclimate for 12 weeks. Three 14 m^2 areas within the rubble field were manually cleared of macroalgae. Donor colonies were then fragmented into sizes of three to four branches and cemented upright to three rubble pieces using Z-Spar Marine Epoxy®. This fragment size provided refuge from size-specific mortality (Hughes and Jackson 1985; Harriot and Fisk 1988) and the rubble provided weight and stability. Twenty such fragments (10 per species) were positioned in rows within each plot, with the two species alternating within each row. Transplant performance was monitored at regular intervals for 18 mo. Weeding of *Padina sanctae-crucis* was undertaken as necessary and fragments that had become overturned or detached were repositioned and re-epoxied. Yap et al. (1992) found that corals transplanted during warm months survived and grew less than those transplanted in cooler months. Therefore, we monitored temperature using Stow-away Tidbits (Onset Corp.®).

Transplant performance was characterized per species as timing of basal attachment to substrate, basal growth (mm mo^{-1}), disease signs, tissue loss or compromised health (bleaching, algal overgrowth), recovery from partial mortality, and full mortality. Basal growth was expressed as mean maximum basal width in millimeters. Disease prevalence was calculated as the number of fragments showing disease / total fragment number * 100. As differences between plots were insignificant, data for each species were pooled for analysis using unpaired *t*-tests.

Results

Porites rus consistently demonstrated better overall performance than *P. cylindrica,* by having low partial mortality, high survival, less disease and high consolidation rates via rapid basal growth. Per species mean responses are summarized in Table 1.

Table 1: Summary of transplant performance, mean ± SD.

Performance parameter at 18 mo	Species	
	P. rus	*P. cylindrica*
% survival	93.3±0.05	23.3±25.1
% with partial mortality over 18 mo period	67.0±20.8	96.6±5.7
% with tissue regrowth at 18 mo	56.6±15.7	0
Mean basal width (mm)	62.8±6.1	37.4±6.7
Total basal growth (T_{final}-$T_{initial}$)	13.5±0.6	-1.2±0.20

Basal consolidation and growth

It took approximately three months for coral tissue to begin to overgrow the epoxy and rubble pieces. At this time, 74% of *P. rus* transplants showed initial cementation onto substrate, while only 27% of *P. cylindrica* transplants showed this response. By the end of our monitoring period, 10% of *P. cylindrica* fragments had attached to underlying rubble, as opposed to 62% of *P. rus* fragments. Basal growth rate averaged 0.75 mm mo^{-1} for *P. rus*, and 0.07 mm mo^{-1} for *P. cylindrica*, for the months when there was positive growth (t=8.51; $p<0.001$).

Partial mortality

Partial mortality involved tissue loss which usually began at the fragment base and progressed upward. Recovery involved tissue re-sheeting over dead skeleton. When this did not occur, skeleton was rapidly colonized by algae, resulting in additional tissue loss over time. While it was difficult to determine the causes of mortality, bleaching and coral diseases (ulcerative white spots and white syndrome; Raymundo et al. 2003; Willis et al. 2004) were observed periodically. Seasonal accumulation of *Padina* around the base of fragments resulted in bleaching of underlying tissue; this was the most common cause of tissue bleaching and loss. An average of 23% of *P. rus* transplants incurred partial mortality within the first three months and by the end of the study period, 67% had exhibited some tissue loss but 57% of these showed some tissue resheeting over the dead skeleton (Table 1). Partial mortality for *P. cylindrica* on the other hand, increased rapidly from 27% at 3 mo, to 97% by 18 mo (*t*-test of mean mortality between species; *p*=0.0164). Thus, whereas 57% of *P. rus* transplants that lost tissue showed recovery, *P. cylindrica* fragments with partial mortality died.

Full mortality

Overall, *P. rus* survived better to 18 mo than did *P. cylindrica* (Table 1, Fig. 2; *t*-test p=0.041). Sources of mortality were the same as those mentioned above, though while *P. rus* appeared to recover more frequently, *P. cylindrica* transplants more often showed a general decline in health over time with accompanying tissue loss and algal overgrowth. Further, because they failed to consolidate around the base of the fragment, overturning, detachment and subsequent abrasion and tissue loss were also causes of mortality.

Coral disease

Ulcerative white spots disease affected *P. cylindrica* much more than *P. rus* (*t*-test p=0.014), and most severely within the first three months after translocation. UWS prevalence reached a high of 23% at 3 mo in *P. cylindrica* transplants, though infected fragments showed subsequent recovery and none died of the disease. UWS was observed on *P. rus* at two census visits, October 2006 and March 2007, and all fragments recovered by the next census. What appeared to be putative white syndrome lesions appeared on several *P. cylindrica* fragments, though these lesions usually became fouled with algae by subsequent census visits and did not appear to progress. There was no evidence of a link between prevalence of either disease and seasonal warming seawater temperature.

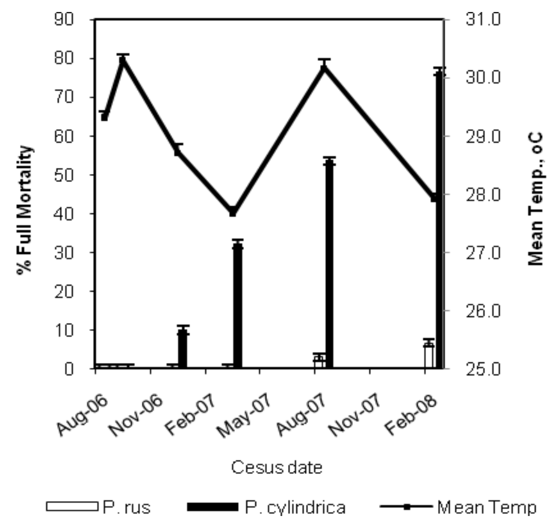

Figure 2: Cumulative mortality over time in two species of transplants, plotted against mean weekly water temperature. N=20 fragments per plot; mean ±SD

Temperature seasonality effects

Water temperature showed a seasonal trend; highest temperatures were recorded during August (31.2°C) and coolest temperatures occurred in January-February (27.5°C; Fig. 2). However, although bleaching was recorded at other sites around Guam during the warm season, no bleaching was observed in our transplanted population. Further, our data suggested no correlation between warm water and any of the performance parameters we measured.

Discussion

Our results showed that live coral transplants can stabilize rubble in low-energy environments. The morphology of our two closely-related species affected their ability to consolidate rubble, which was key to their survival and establishment. *P. rus* was superior in overall performance, demonstrating low partial and full mortality, more frequent recovery, less susceptibility to disease, and greater basal growth and consolidation compared to *P. cylindrica* (Fig. 3). Yap et al. (1998) noticed a similar response; *P. cylindrica* fragments showed significantly more partial or full mortality at one year post-transplant than other test species. However, not all of our success measures can be attributed to morphology alone, suggesting that *P. rus* may have greater acclimatization capability.

The growth rates we observed were lower than rates for other species reported in the literature. Raymundo (2001) reported an increase in fragment surface area of 5 cm^2 wk^{-1} in *Porites attenuata,* which is closely related to *P. cylindrica.* Similar rates were observed in *Acropora hyacinthus* transplants by Yap et al. (1992; 6.9-117 cm^2 mo^{-1}) and *Pocillopora damicornis* (~2.65 mm mo^{-1} linear growth; Birkeland 1979). However, we report here only basal extension

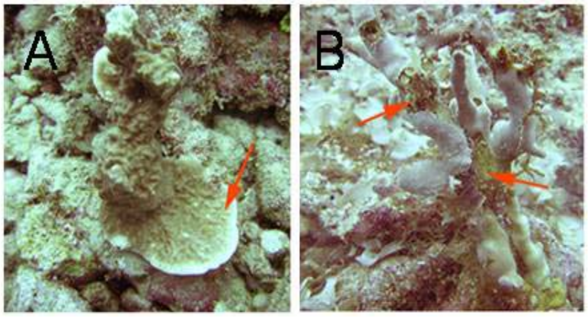

Figure 3: Transplants of (A) *P. rus* and (B) *P. cylindrica* at 18 mo. *P. rus* shows basal plate formation (arrow) and consolidation on rubble; *P. cylindrica* shows tissue loss and algal overgrowth (arrows).

as the relevant growth parameter for our study, as consolidation rate was the metric of concern. As basal plates are generally circular to ovoid in area, this translates into substantial surface area. For instance, mean maximum basal width for *P. rus* transplants at 18 mo was 7.3 cm. Using the formula for surface area of a circle, this would provide roughly 44 cm^2 of basal skeleton cemented onto the underlying rubble. An increase in maximum width by 1 cm would translate into an increase in surface area of 12 cm^2. Although these figures are rough estimates, they provide some idea of the rate at which *P. rus* would cover rubble substrate over time.

Mortality was higher in *P. cylindrica* and most prevalent during seasonal abundances in *Padina* spp. The alga overgrew the base of most fragments. Direct contact of corals with macroalgae is energetically costly (McCook et al. 2001), and diverts resources for growth toward tissue repair (Lirman 2001). Although both species were equally susceptible to algal overgrowth, *P. rus* more often recovered after initial contact with algae.

In Guam, *P. rus* dominates many coral communities, often occupying ~ 80% of the substrate (L. Raymundo, pers. obs.). This species demonstrates several traits which contribute to its dominance: an ability to rapidly co-opt space, outcompete other species (such as *P. cylindrica;* Caballes 2006), low susceptibility to disease (Raymundo et al. 2005). Holbrook et al. (2002) also noted that *P. rus* provides superior fish habitat to massive *Porites* species. All of these traits point to its suitability in rehabilitation efforts. However, it is important to bear in mind that the establishment of single-species stands should not be a goal of rehabilitation. Hardy, plate-forming species may be suitable for initial stabilization efforts, but other species should be introduced later to increase species and structural diversity.

Stabilized coral rubble provides a suitable substratum for recruitment and for asexually-produced fragments (Bothwell 1982; Fox et al. 2005). Raymundo et al. (2007) noted higher recruit survival on stabilized, rather than loose, rubble and recruits then further consolidated rubble as they grew. Stabilizing rubble also eliminates further damage to the reef, as when unconsolidated rubble shifts during storms (Clark and Edwards 1995; Fox et al. 2003). Finally, as rubble is replaced by live hard coral, macroalgal abundance may decline. This effect is particularly visible during periods of seasonal algal abundance (Gleason 1999).

Ulcerative White Spots (UWS) was first described as affecting the genus *Porites*, but has recently been observed on several other genera (Raymundo et al. 2005; Kaczmarsky 2006). The pattern of occurrence we observed suggested a link with fragment stress rather than seasonal temperature trends; transplanted fragments may have been stressed, and their immuno-defense capacity compromised, by the transplantation process. A similar pattern was observed in fragments of *P. attenuata* transplanted to a site with poor water quality in the Philippines, when the disease was first observed and described (Raymundo 2003). Disease is a potentially devastating source of mortality for transplants, and transplantation a potential source of disease introduction. To date, these issues remain untested but suggest a line of research that could improve transplant survival and be utilized to improve best practices for rehabilitation efforts.

Persistent rubble fields remain a challenge for restoration and are often ignored in favor of efforts which may result in higher survival. However, destructive fishing and boat groundings continue to create patches of "dead space" in reef communities. In the Philippines, patches created by destructive fishing practices banned 20 or 30 years prior persist with negligible coral growth (Raymundo pers. obs. and fisher interviews). Thirty years ago, Alcala and Gomez (1979) predicted dynamite-blasted reefs would take 50 yr to recover 50% of their original coral cover; Riegl and Luke (1998) increased the predicted regeneration time to several hundred years. Clearly, persistent rubble is an issue increasingly difficult to ignore. However, this source of damage frequently occurs at a scale at which many rehabilitation efforts currently operate (10^{-2} to 10^{-1} ha; Edwards and Gomez 2007). Therefore, efforts to develop methods to encourage regeneration will likely result in success.

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