Ecological Engineering 40 (2012) 11–17

Contents lists available at SciVerse ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Testing the effectiveness of direct propagation techniques for coral restoration of *Acropora* spp.

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ARTICLE INFO

Article history:
Received 5 September 2011
Received in revised form
10 December 2011
Accepted 11 December 2011
Available online 4 January 2012

Keywords:
Coral restoration
Acropora
Asexual and sexual propagation
Direct transplantation

ABSTRACT

Possible coral restoration through active rehabilitation remains a challenge due to costs, scale of work involved, and poorly understood factors involved in post-transplant survivorship. This latter part remains a technological limitation in all restoration practices to date. In this study, we compared the growth and survivorship of *Acropora* spp. transplants at two reefs with variable seawater flow rates to determine the success and performance of asexual and sexual propagules using a novel coral restoration device. After 18 months, we found that the mean fragment survivorship did not significantly differ at the two reef sites ($P > 0.05$). In contrast, fragment growth was significantly greater at the reef site with faster rates of seawater flow ($P < 0.05$). For one-week post-settlement transplants, we found that both growth and survivorship were significantly higher after 1 year at the site with closer proximity to the inner lagoon and faster seawater flow rates. As the sexual propagation method described here resulted in a total of 134 recruits from harnessing the gametes from 4 donor colonies, the results show harnessing sexual propagation may be applied for coral restoration practices. In summary, both novel methods of propagation are shown to be effective but performance was shown to be dependent on habitat quality and type of propagation.

1. Introduction

Recent studies show a declining trend of coral reefs and associated trophic structures in many areas of the world (Pandolfi et al., 2003; Bellwood et al., 2004; Wilkinson, 2004). The cause of this decline has been primarily attributed to pollution (Williams et al., 2002; McCulloch et al., 2003), diseases (Harvell et al., 2002), and climate change (Hughes et al., 2003; Gardner et al., 2003). The effects of these local and global disturbances on the abundance and diversity of reef biota raises multiple issues as coral reefs provide many ecosystem services such as sustenance and economic welfare (Smith, 1978; Moberg and Folke, 1999) as well as having aesthetic and cultural values. Furthermore, assessment of current reef conservation and management practices to date has not shown any reversal of the declining trends (Rinkevich, 2005). To address some of these issues, active coral reef rehabilitation has been recently suggested to enhance coral propagation and to alleviate these stresses.

Possible enhancement of coral reef recovery through active rehabilitation remains a challenge due to costs, scale of work involved, and poorly understood factors involved in post-transplant success in survivorship (Spurgeon and Lindahl, 2000; Edwards and Gomez, 2007). Currently, most efforts at rehabilitation have focused on using asexual propagation of coral nubbins in nursery settings—*i.e.*, fragmentation and generation of existing natural corals for transplanting at a larger stage (Epstein et al., 2001; Rinkevich, 2005; Shaish et al., 2008; Levy et al., 2010; Lirman et al., 2010). Furthermore, coral restoration through sexual propagation has been suggested as an alternative to coral fragmentation (Hatta et al., 2004; Omori, 2005; Baria et al., 2010). Sexual propagation techniques that harness the high fecundity of corals offers the promise of greater genetic diversity and negligible damage to source colonies (Heyward et al., 2002), but established techniques using sexual propagation remain elusive because of high post-settlement mortality rates occurring in the first year (Babcock, 1985, 1988; Babcock and Mundy, 1996; Wilson and Harrison, 2005). However, recent demonstrations of successful culture of thousands of coral larvae (Heyward and Negri, 1999; Heyward et al., 2002; Omori, 2005; Petersen et al., 2006) and controlled induction of larval settlement (Morse et al., 1996, 1988; Morse and Morse, 1996; Heyward and Negri, 1999; Hatta et al., 2004) have made

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doi:10.1016/j.ecoleng.2011.12.026

coral propagation by harnessing sexual reproduction a promising technique.

Currently, both asexual and sexual propagation techniques use nurseries or hatcheries as an intermediate step before transplantation (Omori, 2005; Levy et al., 2010; Baria et al., 2010). However, the use of nurseries raises several issues. Firstly, the maintenance required during the nursery phase increases costs and *in situ* nurseries may be susceptible to large tropical storms. Secondly, whether sexual or asexual propagation is used, propagating corals to the reef substrate remains a major issue because attachment may become more difficult and costly with increasing sizes of corals. Thirdly, corals acclimated to nursery conditions may not survive as well when outplanted to natural reef systems where conditions might be different. Finally, factors that determine the post-transplant success and performance are poorly understood. However, Baria et al. (2010) have recently showed that caging sexually propagated coral spat enhanced the survivorship in the first three months after outplant. They postulated that predator exclusion by cages could enhance survivorship of juvenile corals. Taken together, limiting the time in a nursery, determining an optimal method of attachment based on colony morphology, and evaluating the performance of outplanted corals on the reef system still requires considerable attention.

Seawater flow is perhaps one of the most important abiotic qualities for the performance of corals in the shallow water reef system. Seawater flow can influence the growth and metabolism of sessile marine organisms (Dennison and Barnes, 1988; Atkinson et al., 1994; Bruno and Edmunds, 1988) as well as remove waste products (Nakamura and Van Woesik, 2001) and affect photosynthesis (Nakamura et al., 2005). Therefore, we tested the growth and survivorship of directly transplanted fragments and sexually propagated coral spat of two *Acropora* species in two habitats with variation in seawater flow. In this way, we were able to gain insights into the effectiveness of either method as a function of the physical conditions of the reef.

2. Materials and methods

2.1. Field sites

Field experiments were conducted at two reef sites in the rock islands of Palau (Fig. 1). Ioul Lukes Reef (7°17.238N and 134°30.204E) and Lighthouse Reef (7°16.773N and 134°27.827E), on the eastern side of the main island chain of Palau, were chosen as the experimental sites for their proximity to the inner lagoon. Both sites are dominated by *Acropora* spp. colonies that are distributed at a similar depth (approximately 2–10 m).

Initial site surveys indicated that the seawater flow at the two sites differed. To determine if there was a significant difference in mean seawater flow, flowmeters (General Oceanics Inc., Model 2030 with a standard rotor S2030-R, Miami, FL) were deployed at each site at 4 m depth—the depth of the coral outplants—and placed on stainless steel rebar for a seven-day period. Flowmeters faced into the current direction at any given time due to free rotation. Flowmeters were placed at both reefs for eight days (24–31 March 2009). The total rotor revolutions on flowmeters in every 24 h were converted to seawater velocity (in cm/s) using calibration charts provided by General Oceanics.

2.2. Asexual propagation

Ninety fragments from *Acropora digitifera* colonies from depths of 3–5 m were collected from Ioul Lukes Reef on September 26, 2007. We collected coral fragments that were 3–5 cm in length to minimize the "take" from donor colonies and because previous studies have shown that branching corals less than 5 cm in length had a high probability of survivorship (Hughes and Connell, 1987; Herlan and Lirman, 2008). Fragments were placed in pre-weighed 4 cm lengths of Tygon tubing and zip-tied in place. These tubes were placed on egg crating racks submerged in containers and brought to the laboratory at the Palau International Reef Center (PICRC). The initial mass of each fragment was determined using a mass balance (Model AND GR-120, Louisville, KY). Seawater was shaken off each coral sample before measurement to minimize seawater weight on fragments and Tygon tubing. After weighing, fragments were outplanted back to bare substrates at Ioul Lukes Reef and Lighthouse Reef at 4 m depth—the depth at which bare substrates were commonly found at both reef locations. Tygon tubes with fragments were zip-tied in place using masonry pushmounts (Panduit, Tinley Park, IL) plugged into pre-drilled substrates at 20 cm intervals (Fig. 2B).

60 out of the 90 fragments with similar initial weights were picked for the transplant experiment. These 60 fragments were randomly separated into two $n = 30$ fragment sets—one set for Lighthouse Reef and one set for Ioul Lukes Reef. Each set of 30 fragments was randomly separated into six replicates of five fragments each. Initial mean weights of the fragments were $6.3\,g \pm 0.3$ (mean ± standard error) and $7.7\,g \pm 0.9$ at Ioul Lukes Reef and Lighthouse Reef, respectively. There was no significant difference in the initial mean weight of the fragments between sites (Mann–Whitney–Wilcoxon, $U = 24$, $n_1 = 6$, $n_2 = 6$, $P = 0.3776$). Transplanted fragments were surveyed for survivorship on 16 March 2009 approximately 18 months after transplantation (536 days) and brought back to the laboratory for final weight measurements. Any algal growth on Tygon tubing was removed prior to weighing the fragments.

2.3. Sexual propagation

We began sexual propagation by harnessing the gametes from gravid colonies. Readiness to spawn can be determined by visual confirmation of pigmented gametes in fragmented coral samples (Baird et al., 2002). In this study, sections (~20 cm diameter) of four different gravid *Acropora hyacinthus* colonies were collected from Ioul Lukes Reef on April 9, 2009 (4 days before the full moon) and immediately brought back to an *ex situ* flow-through seawater tank (1500 L vol.) at the PICRC. Each night, all lights were turned off in the evening to reduce any light effects on spawning and the flow to each tank were turned off at the same time to harness spawned egg and sperm bundles from the surface of the seawater.

All four colony sections spawned on April 15, 2009 (5 nights after the full moon) at approximately 20:45 h local Palau time and the released egg and sperm bundles were collected for larval culturing. Gametes were collected and consolidated in 100 L polycarbonate containers. The seawater in the container was gently mixed to break up egg bundles and to facilitate cross-fertilization. After 30 min, gametes were washed three times with 10 μm filtered seawater to remove excess sperm and separated into four 100 L polycarbonate containers each containing 80 L of seawater. After removing the excess sperm, seawater in the containers was not exchanged for 24 h to allow differentiation and development of embryos without disturbance. Once larvae began swimming, seawater was exchanged three times daily with 10 μm filtered seawater. Planula larvae were cultured for 5 days post fertilization until they were determined to be about 50% competent for settlement. Indications for settlement competency was checked using 10 larvae in 12 well culture plates with 10 mL of seawater and a 3-mm chip of crustose coralline algae (see Heyward and Negri, 1999 for further details).

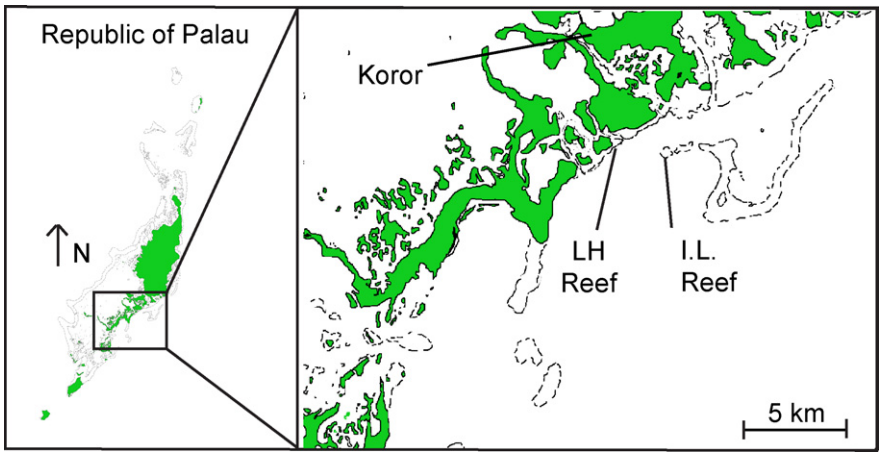

Fig. 1. Map of Palau and the study sites. (A) Lighthouse Reef (7°16.773N; 134°27.827E) is located at the mouth of a channel leading into the inner lagoon. (B) Ioul Lukes Reef (7°17.238N; 134°30.204E) is located about 4 km from the mouth of the channel.
Map adapted from Google maps.

Pushmounts (Fig. 2A) were placed out on Lighthouse Reef four weeks prior to April for ocean conditioning and subsequent inducement of larval settlement. Ocean conditioning of artificial substrates has been used in previous studies for inducing settlement of *Acropora* spp. larvae (Harrison and Wallace, 1990). $n = 760$ pushmounts were strung through 50 lb. fishing line and nailed into a bare reef area. Two days before introduction of coral larvae for settlement, pushmounts were brought into the *ex situ* aquarium system. All pushmounts were lightly brushed with wire brushes to remove any excess turf algal growth and placed horizontally in custom made plastic racks. Once 50% competency for settlement was determined, about 100,000 *A. hyacinthus* larvae were introduced into a 1500 L tank with 1000 L of seawater. Seawater flow was turned off for 24 h and turned back on in the tanks (1 L/s) to remove any lysing larvae from the system and to add fresh seawater. All 760 ocean conditioned pushmounts were determined to have settled coral spat when inspected after one week. The mean number of coral spat was 15 ± 2.2 (mean $\pm$ SE) per pushmount.

After four days in the *ex situ* aquarium system, skeletal deposition by the newly settled coral spat was visible under a dissecting microscope. These newly settled coral spat were outplanted on April 24, 2009 (9 days post fertilization) and checked for growth and survivorship on April 23, 2010. 13 replicates of 20 pushmounts ($n = 260$) with *A. hyacinthus* coral spat settlement were placed into predrilled 1.2 cm holes at Lighthouse Reef and 25 replicates of 20 pushmounts ($n = 500$) with coral spat were placed into predrilled holes at Ioul Lukes Reef. Predrilled holes were placed at 20 cm intervals. The disparity in the number of replicates for each site was related to the availability of bare reef substrate—*i.e.*, Ioul Lukes Reef had more bare areas for transplantation.

In previous post-settlement survivorship studies, mortality of newly settled corals was reported to be highest during the first year (Babcock, 1985, 1988; Babcock and Mundy, 1996; Wilson and Harrison, 2005). In this study, we assumed that coral spat has a higher probability of surviving after the first year and thus we treated survivorship after 1 year as a fair assessment of recruitment success for sexually propagated outplants. Therefore, outplanted coral spat was surveyed for growth and survivorship at the two sites after one year. As a proxy for growth, the diameters of the surviving recruits were measured using Scienceware Vernier calipers (Fort Lauderdale, FL) and the mean diameter of all the replicates were compared for the two reefs.

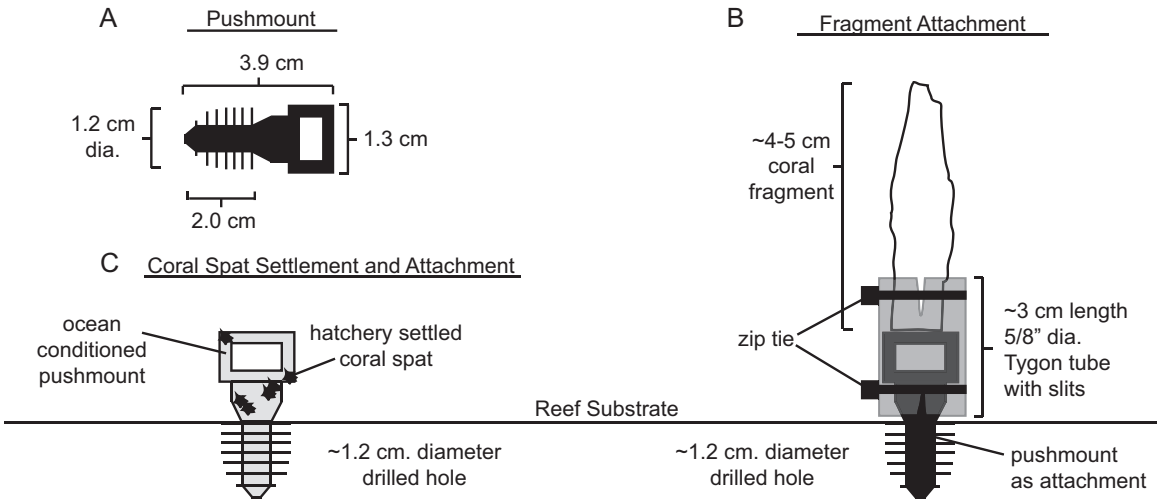

Fig. 2. Schematic of coral attachment devices. (A) Schematic of Panduit masonry pushmount. (B) Schematic of coral fragment in a Tygon tube that is attached to the substrate *via* zip ties and pushmount. (C) Schematic of an ocean conditioned pushmount (gray coloration) with newly settled larvae in the reef substrate.

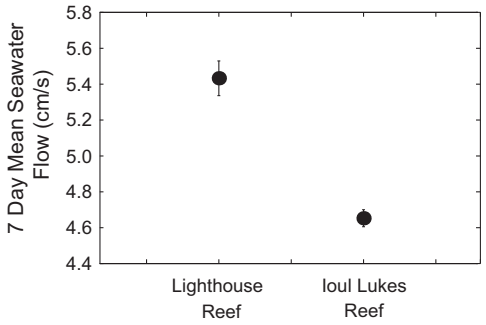

Fig. 3. Mean seawater flow rates at study sites. Data of 7 day mean seawater flow rates at Lighthouse and Ioul Lukes Reef. Error bars are standard error.

2.4. Data analysis

The mean number of fragments and sexual recruits were determined for each reef site and tested for significant differences between the two reef sites. Due to limited number of replicates and non-normal distribution of the data, we used a nonparametric analysis—*i.e.*, Mann–Whitney–Wilcoxon two-sample test—to determine if there were any significant differences in the mean growth and survivorship of the fragments and sexual recruits (Mann and Whitney, 1947). To compare the mean flow rates between the two reef sites, permutation tests were carried out to determine if there were any significant differences in the mean flow rates of the seven-day period. Permutation tests are suitable with limited data and do not require specific population shapes such as normality and give accurate *P*-values (Manly, 1997).

3. Results

3.1. Seawater flow rates at Lighthouse versus Ioul Lukes Reef

Measurements of long-term seawater flow rates at the two sites were beyond the scope of this study. However, the seven day measurement of seawater flow rates at each site showed that the mean flow rate at Lighthouse Reef (5.4 cm/s ± 0.3, mean ± standard error) was significantly higher than the seawater flow rate at Ioul Lukes Reef (4.7 cm/s ± 0.1) (permutation test, $n = 10{,}000$ permutations, $P < 0.001$). The mean seawater flow rates are illustrated in Fig. 3. These results showed higher seawater flow rates at the site close to the channel into the inner lagoon.

3.2. Growth of asexual and sexual outplants

Fig. 4A, B, D and E visually illustrates the differences in the initial size of a fragment and the coral spat and the final size of the fragment and coral recruit. The difference in mean weight of transplanted *A. digitifera* fragments and the mean diameter of outplanted sexually propagated *A. hyacinthus* coral spat are shown in Figs. 4C and F. After a period of ~18 months, the mean weight of the *A. digitifera* fragments was significantly higher at Lighthouse Reef (120.6 g ± 21.8, mean ± standard error) than at Ioul Lukes Reef (59.6 g ± 9.7) (Mann–Whitney–Wilcoxon, $U = 32$, $n_1 = 6$, $n_2 = 6$, $P < 0.05$). We also found that coral spat growth—*i.e.*, the final mean diameter—at Lighthouse Reef (13.4 mm ± 0.9) was significantly greater than the final mean diameter at Ioul Lukes Reef (8.8 mm ± 0.5) after a period of one year (Mann–Whitney–Wilcoxon, $U = 280$, $n_1 = 13$, $n_2 = 24$, $P < 0.001$). These differences showed that both fragments and coral spat had significantly higher growth rates when outplanted closer to the inner lagoon or the site with the greater flux of seawater.

3.3. Survivorship of asexual and sexual outplants

The difference in mean survivorship of *A. digitifera* fragments and the mean survivorship of *A. hyacinthus* coral spat are shown in Fig. 5A and B. After ~18 months on the reef, 73.3% ± 8.4 (mean ± standard error) of the fragments at Lighthouse Reef survived while 80.0% ± 8.9 of the fragments survived at Ioul Lukes Reef. Test for differences in the mean survivorship showed that *A. digitifera* fragment survivorship was not significantly different at the two sites (Mann–Whitney–Wilcoxon, $U = 22$, $n_1 = 6$, $n_2 = 6$, $P = 0.5456$). In contrast, we found significant differences in survivorship for the 1-year post settlement outplants of *A. hyacinthus*. More specifically, the final mean survivorship of the coral spats at Lighthouse Reef (24.6% ± 2.2) was significantly higher than at Ioul Lukes Reef (14.4% ± 1.8) (Mann–Whitney–Wilcoxon, $U = 279.5$, $n_1 = 13$, $n_2 = 23$, $P < 0.01$). However, we increased the number of corals from 4 donor colonies to a total of 134 coral recruits by harnessing sexual propagation.

4. Discussion

The coral restoration methods investigated here resulted in varying degrees of performance dependening on the type of propagation. As indicated by the results here and in recent literature, propagation by fragmentation is relatively successful in terms of survival (Epstein et al., 2001; Rinkevich, 2005; Shaish et al., 2008; Levy et al., 2010; Lirman et al., 2010). Our investigation also showed that high survivability of fragments is possible *via* direct transplantation. However, this may have been a result of the initial fragment size that we used in our experiment. Our study used fragments that were 3–5 cm in length and at smaller sizes, fragments may likely require a nursery phase (Shafir et al., 2006). The goal of any fragment transplantation project should be to cost effectively get the corals to grow on to the reef substrate for permanent attachment. Subsequently, corals that grow to larger sizes would require a more complicated attachment method that can have a significant effect on the coral restoration effort (Lindahl, 1998; Bowden-Kerby, 2001; Levy et al., 2010). However, the methods described here for relatively small fragment propagation are conducive to faster and more cost-effective permanent attachment to reef substrates because it does not require a nursery phase. Although the attachments of coral fragments were not designed to be permanent because corals needed to be brought back for weight measurements in this study, a modification of this method could be used in future studies or restoration practices for permanent attachment for some branching coral species.

In context of sexual propagation, our method of directly outplanting less than one-week old coral spat was not as successful as the fragment transplantation in terms of survivorship. However, we were able to propagate a total of 134 coral recruits from 4 sections of *A. hyacinthus* donor colonies. In light of this moderate success, there are two possible ways that the technique described here could be modified to enhance coral spat survivorship. Firstly, an increase in the density of larval settlement before outplanting could lead to subsequent fusion of the polyps that ultimately could enhance growth and survivorship. For example, Raymundo and Maypa (2004) showed that the post-settlement mortality of coral spat could be dependent on the size and polyp fusion in the coral species *Pocillopora damicornis*. Additionally, caging outplanted coral spat to reduce predation has been shown to increase juvenile coral survivorship (Baria et al., 2010). Although, using cages may not be practical on a large spatial scale, it may be appropriate for smaller scales or effective in multiple small-scale efforts. In summary, while the methods for harnessing sexual

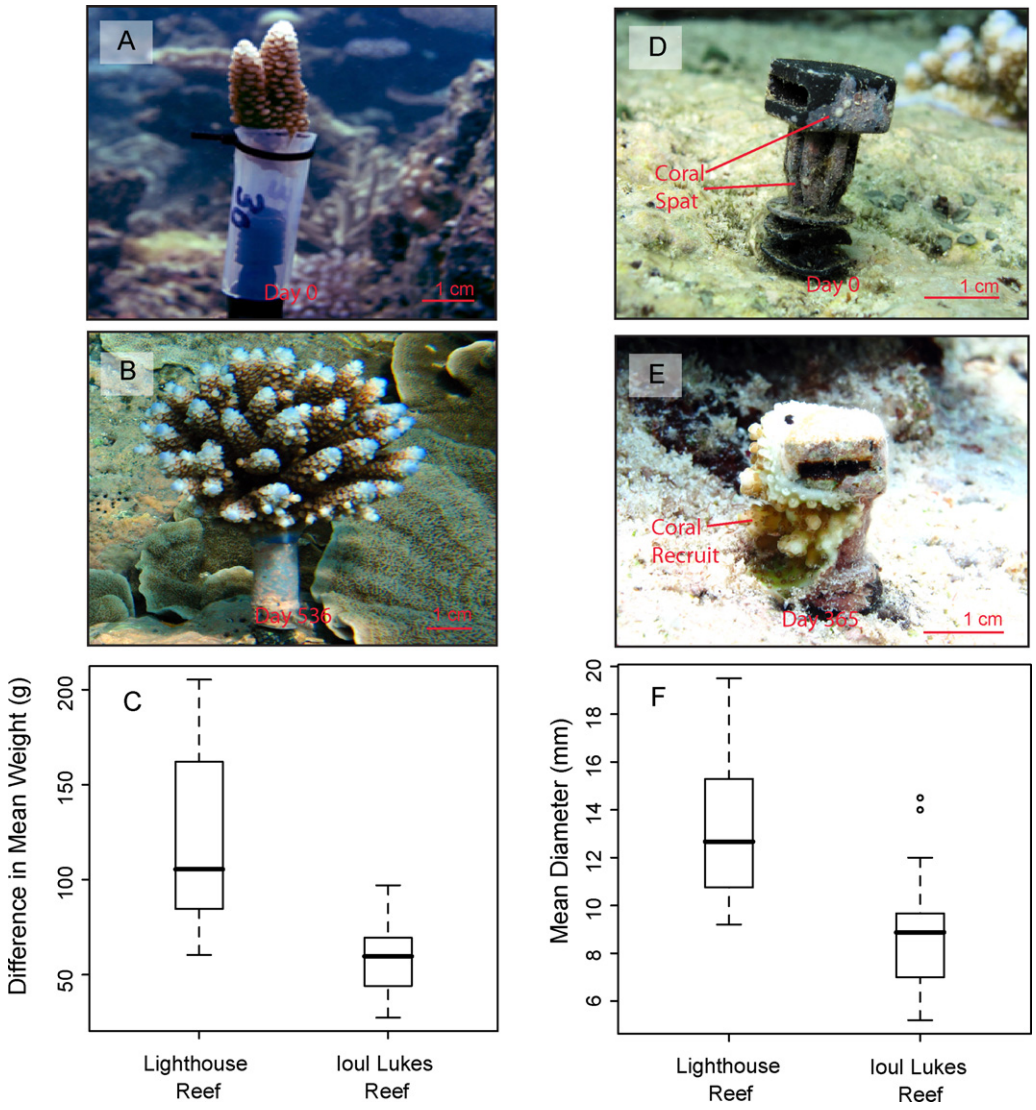

Fig. 4. Fragment and coral spat growth. (A and B) Photograph of a sample *Acropora digitifera* fragment in the first day of transplant (Day 0) to the final day of the study (Day 536). (C) Box-whisker plots of the mean growth of *A. digitifera* fragments. (D and E) Photograph of a sample *Acropora hyacinthus* coral spat in the first day of outplant (Day 0) to the final day of the study (Day 365). (F) Box-whisker plots of the final mean diameter of *A. hyacinthus* coral spat. The boldline in each box indicates the median, the upper and lower lines of the boxes represent the upper and lower quartiles, and the whiskers mark the 1.5-times the interquartile range. Outliers are represented as circles. Scale bars are shown as size reference.

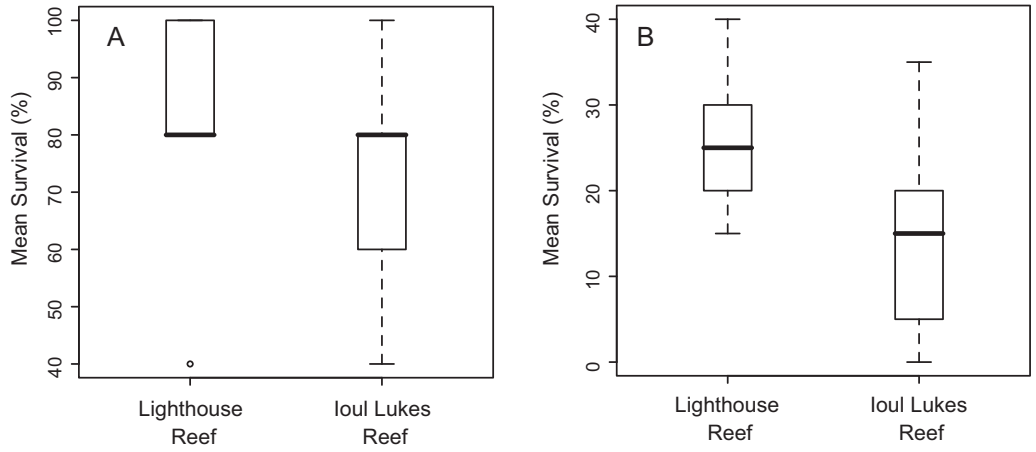

Fig. 5. Fragment and coral spat survivorship. (A) Box-whisker plots of the mean percent survivorship *Acropora digitifera* fragments. (B) Box-whisker plots of the mean percent survivorship of *Acropora hyacinthus* coral spat. The boldline in each box indicates the median, the upper and lower lines of the boxes represent the upper and lower quartiles, and the whiskers mark the 1.5-times the interquartile range. Outliers are represented as circles. Note, the *y*-axis on (A and B) are not on the same range.

propagation continue to be optimized, identifying the factors that affect survivorship and recruitment remain a challenge.

We recognize that the correlation of growth to seawater flow rate is limited in power and precision due to the limited number of measurements and the scope of our study. Factors such as luminosity, temperature, salinity and flux of sediment may also synergistically or independently affect coral growth (Coles and Jokiel, 1978; Yap and Gomez, 1985; Stromgren, 1987). However, the results reported here are similar to previous findings on the effects of seawater flow on coral growth (Dennison and Barnes, 1988; Schutter et al., 2010). Therefore, seawater flow was determined to be a factor influencing the growth of corals in this investigation. Growth could be affected because the seawater flow at Lighthouse Reef could bring a greater flux of nitrogen rich nutrients from the inner lagoon and remove metabolic wastes through tidal exchanges. Additionally, survivorship of juvenile coral spat could be affected in higher seawater flow areas because herbivorous fishes might avoid reef tracts where greater energy is needed for swimming during feeding. This avoidance could ultimately lead to less susceptibility to predation. However, in order to completely assess how coral performance is affected in a habitat, an assessment of both abiotic and biotic factors must be conducted both in a controlled laboratory and in the field.

Active restoration for the rehabilitation of coral reefs is a developing field. The causes of reef degradation must be identified before active restoration measures are taken (Edwards and Gomez, 2007). However, the success and development of fragment nurseries makes asexual propagation an enticing option for enhancing coral propagation at larger scales and in a time efficient manner. Moreover, advances in culturing coral larvae and controlled larval settlement make harnessing sexual propagation an intriguing possibility for large-scale projects aimed at enhancing both recruitment and genetic diversity. The Caribbean corals, *Acropora palmata* and *Acropora cervicornis* have been listed as Critically Endangered on the IUCN Red List of Threatened Species (2008) and thus represent ideal candidates for these types of techniques. In addition, applying these restoration concepts—for both corals and other reef biota—as an active reef management tool may ultimately help reverse the declining trends for reef conservation.

Acknowledgements

The authors wish to particularly thank the staff at Palau International Coral Reef Center for providing excellent logistic support, facilities, and hospitality. We also thank Neal Hooker, Shane Anderson and the many volunteers who helped with various aspects during the project. We are also grateful to Alasdair Edwards and the three reviewers for many constructive comments on this manuscript. The work presented here was supported by the Global Environment Facility/World Bank, Coral Reef Targeted Research & Capacity Building for Management (CRTR) program.

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