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Success and Growth of Corals Transplanted to Cement Armor Mat Tiles in Southeast Florida: Implications for Reef Restoration

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ABSTRACT

In 1997, 271 scleractinian corals growing on a sewer outfall pipe were used in a transplantation study offshore from North Dade County, Florida, USA. Corals were removed from the outfall pipe and transplanted onto concrete armor mat tiles used to cover the pipe. Success (number of corals still attached and alive), mortality (number of dead corals), and growth rates of the transplants were assessed between December 1997 and December 1999. Colony surface area and radius length were measured on scanned photographs to estimate horizontal growth rate. After two years post-transplantation, success rate and overall mortality were 87% and 7.8% respectively. In comparison, seven sites of nearby natural substrate corals had mean success rates of 83% and mortality rates ranging from 11-17%. The two most numerous transplant species, *Solenasrrea bournoni* and *Siderasrrea siderea*, had comparable success and mortality rates; however, *S. bournoni* had a significantly faster growth rate (increase in horizontal radius and surface area). The colony size at time of transplantation was not related to the rate of growth; however, mortality and partial mortality rates increased with smaller size colonies. The methodology used in this investigation is useful for assessing transplanted corals because it is non-invasive, allows continual monitoring, and is applicable to corals growing on natural and artificial substrates.

Keywords Transplantation, Scleractinian corals, Restoration

Introduction

Coral relocation and transplantation have been used to attach coral colonies to substrate in attempts to: a) restore damaged reefs caused by ship groundings (Gittings et al. 1988, Jaap 1999, Zobrist 1999), coral mining (Clark and Edwards 1995) and blast fishing (Auberson 1982), b) "re-seed" reefs that have experienced anthropogenic or natural destruction (Harriot and Fisk 1988a), and c) mitigate areas that are to be subject to potential impact, such as pier construction (Munoz-Chagin 1997). Relatively few investigations have used transplantation techniques to directly prevent predictable damage to corals.

Some workers have felt the cost/benefit ratio of coral transplantation may be too high; they have questioned using healthy donor colonies to reestablish damages areas, and contemplated the ability of colonies to acclimate and reproduce in a new habitat (see Miller et al. 1993, Edwards and Clark 1998). Practical transplantation difficulties include the cost of equipment, removal and reattachment of many colonies, and constructing a long-term monitoring program. In some cases, transplants are likely to have higher mortality rates than controls (Yap et al. 1992), especially within the first year (Edwards and Clark 1998). Conversely, coral transplantation studies offer a multitude of opportunities to acquire more information about the variables that determine coral growth, success, morphology, and interactions with the substrate. Importantly, transplantation, when done successfully, may help to maintain reef systems that are threatened in many regions.

Prior techniques

Removal of colonies for transplantation has included the use of hammer and chisel (Harriot and Fisk 1988a, Clark and Edwards 1995, Yap et al. 1998), crowbars (Auberson 1982), axes (Bak and Criens 1981), or hand (Guzman 1991). Placement has been secured by underwater adhesives (epoxy) (Zobrist 1999, see methodology in Thornton 1999), hydraulic cement (Hudson 1972), expansion anchors, and threaded rods (Graham and Fitzgerald 1999). Scattering of coral fragments and shards has been used (Bowden-Derby 1997), although mortality has been high compared to that of physically attached corals (Birkeland et al. 1979). Each technique has advantages and disadvantages, and transplant longevity is most likely dependent on species-specific and environmental variables. Success rates have ranged. from 50-100% (Harriot and Fisk 1988b, Becker and Mueller 1999, Gil-Navia et al. 1999).

The determination of long-term success requires monitoring and comparison to non-transplanted coral colonies. To test long term success, growth rate measurement may be utilized as a proxy for transplant health. Quantification of growth rate, however, may require partial or total sacrifice of colonies. For example, Alizarin staining followed by coring and/or slabbing and density band measurement are useful growth rate techniques that will also allow insight to the pre-transplant growth of relocated colonies (Barnes 1970, Dodge: and Vai3nys 1980). A non-invasive technique that does not interfere with colony longevity is required in some investigations.

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Background

Miami-Dade Water and Sewer Department (MDWSD), Florida, USA has an outfall (concrete pipe, 229 cm inside diameter) extending 3,900 meters east from shore to depths of approximately 30 meters. When constructed, the pipe was completely or nearly buried into the seafloor. Significant portions of the crown of the pipe were exposed along the length of the outfall by Hurricane Andrew in 1992 (Rust Environmental and Hazen and Sawyer 1995). Several years later many reef-building stony corals were observed growing on the exposed sections of the pipe. Immediately prior to the exposed sections being repaired with an armor mat covering in 1997, some of the corals were removed from the original pipe and reattached to the matting. The transplants were monitored for success, mortality, and percent cover from 1997 until December 1999.

This investigation reports the success, mortality, and growth rates of the two- year coral transplant monitoring effort. Success is defined as those corals remaining attached and alive by the end of the 2-year observation period. Additionally, a technique is devised to measure growth rate that is non-invasive and repeatable.

Methods

Outfall Repair

Repair of the Miami North outfall (25'55.200" N, 80°05'937" W, Fig 1) began in September 1997. This repair consisted of covering exposed portions of the crown of the outfall with gravel followed by armor mat. Armor mat is "fabric" of 24 large concrete tiles (approximately 68 kg and 33x33 cm each) held together by Kevlar rope for a total weight of 952 kg. The 2.5 meter-width mat was draped about 4 meters from the center line over the outfall. Several mats were tied together to form a large flexible protective structure draped over the exposed pipe, minimizing wave erosion.

Coral Transplantation

The coral removal, outfall repair, and coral transplantation procedure was completed during a two-day period in September 1997. Coral specimens were collected by hammer and chisel from the exposed outfall pipe crown in depths of 13-18 meters. Once the armor matting was placed, corals were transplanted, typically to the upper most tiles (outfall crest); this minimized the potential covering of the corals by shifting sands. One coral specimen was typically attached per tile (Fig. 2), but in some cases as many as three small (<5 cm diameter) corals were attached to a single tile. Equal portions of Portland Type II cement and molding plaster (Hudson 1972, see US Department of Commerce 1991) were used to attach corals to the tiles. This combination was taken dry underwater in ziplock bags and mixed with seawater. Portions were then taken out of the bag and pressed against the top of the armor mat tile. The coral was then pressed gently into the cement. Care was taken to use minimal cement so that excess cement would not be forced over the lip of the coral base and hence impact living coral tissue. A total of 27] specimens were transplanted in September 1997. A map of transplant species and location was recorded.

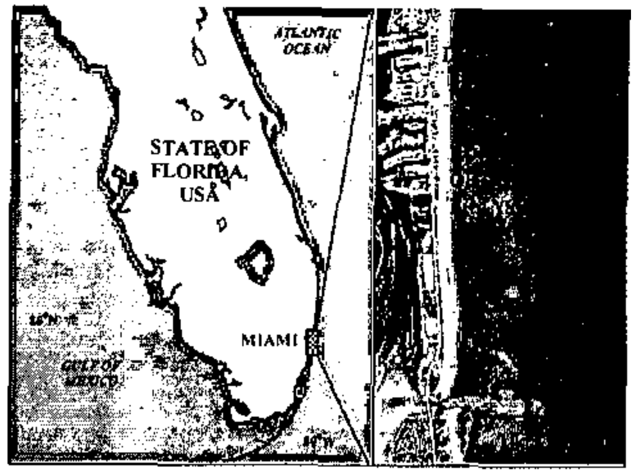

Fig 1 Location of outfall transplants offshore North Dade County, Florida, USA.

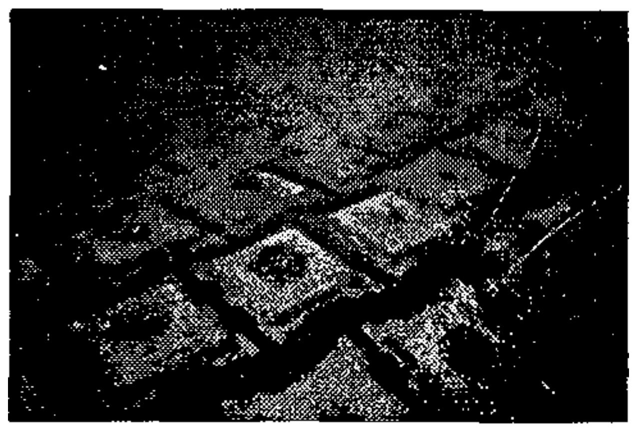

Fig. 2 Armor matting with attached coral colonies, September 1997.

Survivorship Determination

During December 1997 (three months post-transplantation) transplanted specimens were identified, assessed, and counted. Each colony was photographed with a Nikonos V camera, 28 mm lens, and close-up kit (fitted with a metric calibration ruler as a size reference). H the entire colony was too large to fit within the framer, the framer was removed, a calibration ruler placed next to the colony, and the photograph was taken from a distance appropriate for full inclusion of the coral. This procedure was repeated in December 1999 (two years post-transplantation).

To determine coral transplantation survivorship after two years, the colonies were assessed in December 1999 and categorized as: a) alive and showing apparent positive growth since 1997 (Fig 3); b) alive but showing partial mortality (tissue loss) since 1997; c) dead; or d) missing. The colonies that displayed partial mortality were represented in the survivorship values but their growth rates were not determined. Corals that were scored as dead were those that had no remaining live tissue and showed evidence of invertebrate/algal growth covering the entire skeleton. Corals categorized as missing were those in which the entire colony could not be located on the tile where it was originally attached, although, in some cases, a cement pedestal was still present.

a)

b)

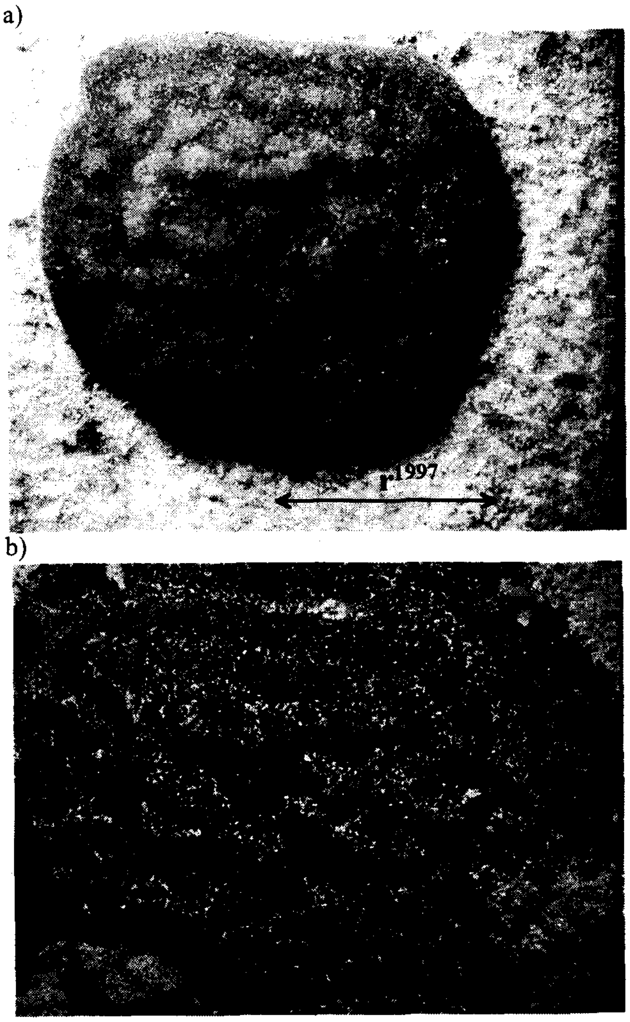

Fig. 3 A *Porites astreoides* colony exhibits horizontal growth from 1997 (a) to 1999 (b). The distance of the radius is shown, and the calibration ruler can be seen to the right of the image.

To calculate overall transplant survivorship, the number of live corals (including those displaying partial mortality) was divided by the total number of originally transplanted corals. Mortality was calculated from the number of dead corals divided by the total number of transplanted corals. All values were converted to percentages. The total number of colonies is equal to the sum of the number of successful (alive), dead and missing colonies.

Comparison to Control Corals on Natural Reefs

Images of corals from seven permanent monitoring sites were assessed and used as controls to compare survivorship with transplanted corals (see Table 3 for depths and information about control sites). These sites were photographed by Broward County Department of Planning and Environmental Protection in 1997 and 1999-2000 as part of their reef monitoring program.

Growth Rate Image Analysis

After the 35 mm slides of the transplants (taken at 3 and 27-month monitoring) were processed, they were scanned (Hewlett- Packard Photosmart© S20) at a resolution of 900 dpi, viewed in Adobe Photoshop©, and saved as .jpg files. Using SigmaScan©Pro 4.01, the two-dimensional surface area (footprint) was measured. The calibration ruler (Fig. 3) was used to determine the number of pixels in a known distance within the image. In a small number of images the calibration ruler was unresolvable or not present, in which case the image was calibrated using the mean calibration value of a subset of the entire sample.

When defining the area to be measured (two-dimensional surface area), it was sometimes necessary to estimate areas of partial mortality. Unless the tissue was covered by a very small amount of unconsolidated sediment, only live tissue was included in the measurement area. Growth of each colony was measured in two parameters: increase in surface area and increase in linear radius between 1997 and 1999. Radius length increase (r_i) was determined from the following equation:

$$r_i = r_{1999} - r_{1997}$$

where

$r_{1997} = \sqrt{(A_{1997}/\pi)}$, and $r_{1999} = \sqrt{(A_{1999}/\pi)}$, A = the two dimensional surface area of each colony. All growth rate data were normalized to years or fraction of years.

Control coral (on natural substrate) images were photographed using a 15 mm lens and 0.75 meter quadrat (note the camera-to-subject distance was greater when photographing the control corals). The 35 mm slides were digitized in the same manner as the transplanted coral slides. Differences in photographic angle and amounts of fauna obscuring corals from year to year made obtaining a growth rate value unrealistic. Nevertheless, it was possible to assess the survivorship from 1997 to 1999 by confirming the absence or presence of a live coral within the quadrat from year to year.

Results

Monitoring

Table 1 provides information on the condition of the transplants after each monitoring and how they were used in analysis. After three months, 266 of the 271 transplants attached in September 1997 survived and remained in place. Two specimens were missing and three were found dead. After 27 months, 265 coral transplants were identified, photographed, and assessed. Six tiles with attached corals were not located and the corals were considered missing.

Of the living 235 transplants photographed in December 1999, 150 showed positive growth and were used in growth analysis; 37 transplants displayed partial mortality (negative growth) and were not used. Forty-two colonies were not suitable for measurement for reasons such as bad image quality, poor match of colony image from 1997 to 1999, and size of corals exceeding block or framer size. The 5 *Millepora alcicornis* colonies and 1 gorgonian were not used in the growth rate analysis because they were not scleractinian corals; however, their survival data were noted and included in the analysis.

Survivorship

After 27 months, 87% (235 out of 271) of the corals were still alive and attached. Overall mortality (those colonies attached but dead) after three months (September 1997 – December 1997) was 1.11%. Mortality after 27 months was 7.8%, and 5.5% of the transplants were missing (unattached). See Table 2 for each species represented in 1999.

Table 1 Condition of transplants and their use in analysis.

<table>
<tr><th></th><th>ALIVE</th><th colspan="2">MISSING</th><th colspan="2">DEAD</th></tr>
<tr><td>Total corals transplanted in September 1997</td><td>271</td><td colspan="2">NA</td><td colspan="2">NA</td></tr>
<tr><td>Corals located at 3 month monitoring (December 1997)</td><td>266</td><td colspan="2">2</td><td colspan="2">3</td></tr>
<tr><td>Corals located at the 27 month monitoring (December 1999)</td><td>235</td><td colspan="2">15</td><td colspan="2">21</td></tr>
<tr><td rowspan="3">Use of live corals in 1999 growth rate analysis</td><td>USED IN GROWTH RATE ANALYSIS</td><td colspan="4">NOT USED IN ANALYSIS</td></tr>
<tr><td rowspan="2">150 corals with positive growth from 1997-1999</td><td colspan="4">85</td></tr>
<tr><td>5 Millepora alcicornis</td><td>1 gorgonian</td><td>37 showing partial mortality (tissue loss)</td><td>42 not suitable for measurement</td></tr>
</table>

Mortality and Initial Size

The data suggest that corals transplanted at a smaller size are more susceptible to mortality. Fig. 4 displays the average initial size (surface area) of colonies broken down into health condition of alive, partial mortality, and dead. An ANOVA, followed by a Student-Newman-Keuls test, indicated a significant difference existed between the initial surface areas of the dead colonies and those that were alive and growing positively ($P = 0.015$).

Comparison to Control Corals on Natural Reefs

Control coral colonies on Broward County reefs had a mean survivorship rate of 83% from 1997 to 1999. Mortality assessment was confounded by obstructions in the photographs, i.e. it was not always possible to tell if a colony was missing or dead; however, mortality was estimated at 11 - 17% overall. Table 3 shows the survivorship results of the control corals.

Table 2 Survivorship and mortality for each transplant species in 1999

SPECIES	SURVIVORSHIP	MORTALITY	MISSING	# OF COLONIES
Siderastrea siderea	90%	7%	3%	129
Solenastrea bournoni	90%	7%	3%	93
Stephanocoenia michelinii	93%	0%	7%	15
Montastrea cavernosa	86%	14%	0%	7
Porites astreoides	100%	0%	0%	7
Dichocoenia stokesii	67%	33%	0%	6
Diploria strigosa	100%	0%	0%	4
Diploria labyrinthiformis	100%	0%	0%	2
Meandrina meandrites	0%	0%	100%	1
Montastrea annularis	100%	0%	0%	1
Millepora alcicornis	60%	40%	0%	5
Eunicea sp.	100%	0%	0%	1
TOTAL	**87%**	**8%**	**5%**	**271**

Growth Rate and Species Comparison

Table 4 presents the mean extension rates (radius and surface area increase) per year for all transplant species measured over 1997-1999. The two most abundant species, *Siderastrea siderea* and *Solenastrea bournoni*, were statistically tested for differences in growth rate (both increase in radius and total surface area). *S. siderea* and *S. bournoni* displayed mean radial increases of 2.37 (±1.54) and 3.81 (± 3.06) mm yr^{-1}, and mean surface area growth of 4.30 (± 4.17) and 10.56 (± 8.99) cm^2 yr^{-1}, respectively. A Mann-Whitney Rank Sum Test revealed a difference in both radius increase per year (P = 0.01) and surface area increase (P = <0.0001). The sample sizes for the other species were too small to be statistically compared, but their mean radial increase ranged from 2.36 - 7.75 mm yr^{-1}.

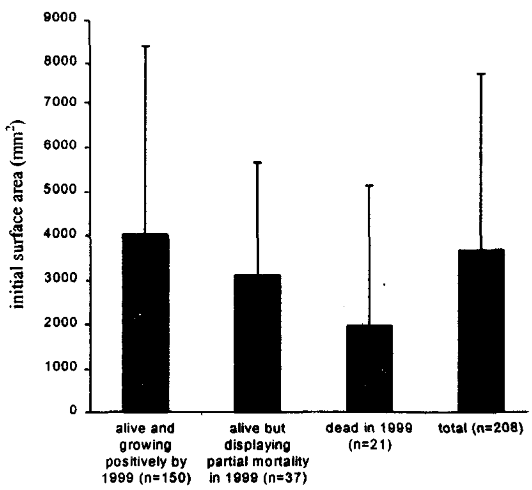

Fig. 4 Mean initial surface area (± 1 s.d) vs. success of all colonies, 1997-1999.

Table 3 Species, depth and survivorship of control natural substrate) coral colonies.

Site	Depth (m)	Survivorship (%)	Number of Colonies Assessed (1997-1999)
1	14	100	10
2	19	96	25
3	13	54	11
4	8	100	10
5	17	72	18
6	17	80	15
7	5	78	9
Total		**Mean: 83%**	**98 colonies**

Growth Rate and Size Categories

When all corals exhibiting positive growth were divided into four initial size classes based on surface area (footprint), a Kruskal-Wallace one-way ANOVA revealed that the smallest size class (1 – 1000 mm^2) showed a smaller radius increase per year than the 1001-5000 mm^2 corals (p = .007). It should be noted that, while all species demonstrating positive growth were included in this analysis, *Siderastrea siderea* composed 90% and 46% of the 0-1000 mm^2 and 1000-5000 mm^2 size classes, respectively. Because of the unequal species distribution in the size classes, the results should be interpreted cautiously. Fig. 5 illustrates the mean radius increase of each of the four size classes.

Table 4 Mean radial annual extension rates (± 1 s.d.) of transplants between 1997 and 1999.

Species	mean radius increase $year^{-1}$ (mm)	mean surface area increase $year^{-1}$ (cm^2)	n
S. siderea	2.37 (± 1.54)	4.30 (± 4.17)	69
S. bournoni	3.81 (± 3.06)	10.56 (± 8.99)	56
S. michelinii	2.55 (± 1.56)	4.69 (± 2.73)	9
M. cavernosa	4.53 (± 2.47)	10.27 (± 6.53)	5
P. astreoides	7.75 (± 5.62)	26.72 (± 33.69)	4
D. stokesii	2.86 (± 1.30)	5.33 (± 1.16)	3
D. strigosa	7.59 (± 3.49)	40.70 (± 37.45)	2
D.labyrinthiformis	2.36	6.96	1
M. annularis	3.30	11.08	1

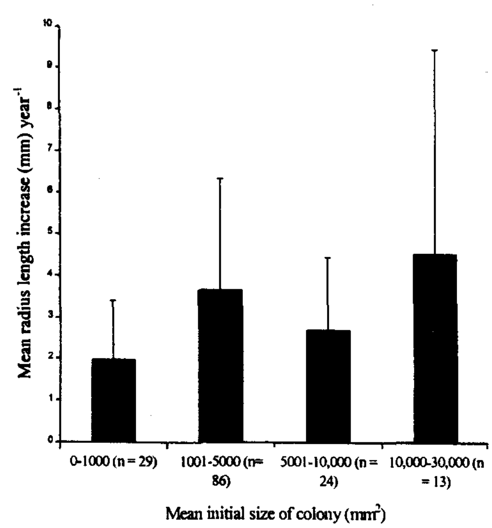

Fig. 5 Mean radius increase vs. initial size (± 1 s.d.) of all transplanted colonies.

Discussion

Coral Transplant Survivorship

Corals transplanted to the repaired outfall showed greater survivorship (87%) over two years in comparison to the survivorship of the nearby natural substrate corals (83%). This, coupled with a low instance of partial mortality, indicates that the 1997 transplantation on the outfall armor mat was successful in rescuing the corals from the repair activities. The removal and attachment of, the colonies did not apparently adversely affect their survival. One of the principal concerns about successful coral transplantation is the effect of relocation on coral colonies (see Edwards and Clark 1998).-Many workers have moved colonies to different environments and experienced difficulties due to changes in habitat or environmental variables (Plucer-Rosario and Randall 1987, Laydoo 1996). The high success rate for the corals in this investigation may be attributable to the lack of these relocation effects.(with, the exception. of a small, depth change for some).

The data presented here suggest the possibility of higher mortality rate for smaller coral transplants, which is a finding of potential importance to future transplantation projects. Larger size may contribute to lower grazing by herbivores and greater-sediment removal capability (Bak and Engel 1979). On natural substrate in Discovery Bay, Jamaica, larger corals were reported to have higher survivorship (Rylaarsdam 1983), however, it has been reported that partial mortality is less of a factor in small corals relative to larger ones (Bak and Monsters 1998). Conflicting results have been documented between workers regarding size and mortality (Plucer-Rosario and Randall 1987, Harriot and Fisk 19886, Bowden-Kerby 1997, Yap et al. 1998).

With regard to species-specific transplant survivorship and mortality, the two' most numerous transplants, Siderastrea siderea and Solenaslrea bournoni, had comparable and high survivorship rates. It appears that the perturbation associated with transplantation did not affect the two species differentially. On the other hand, Dichocoenia stokesii exhibited 33% mortality, the highest recorded in this study. Other species-specific trends have been observed regarding transplantation success (Yap et al. 1998); however, further studies are warranted. Many of the previous studies have concentrated on branching corals (such as Acropora species) due to their affinity for fast growth and fragmentation fecundity (Shinn 1972). Unfortunately some branching species also display the highest mortality rates among transplanted species (Yap et al. 1992, Clark and Edwards 1995). Edwards and Clark (1998) have reviewed the tradeoff for immediate increased coral cover using branching corals versus the long-term but ecologically expensive success of massive colonies. Studies using massive species are lacking and warranted, as colony size, morphology, and species are important to consider when making restoration decisions involving transplantation. A longer period of monitoring will undoubtedly offer more insight to the fate of transplanted massive corals in this investigation.

Growth Rate

Coral growth rates (linear extension) are typically measured using Alizarin Red-S or X-radiography (Barnes 1970, Buddemeier and Kinzie 1976, Dodge et at. 1984). This investigation employed a surface area measurement to derive colony radius values. An 'increase in radius provides an estimate for skeletal accretion since the radius increase is considered to be synonymous with linear accretion such as that which is measured with Alizarin Red-S. We observed that a small number of the samples in this study produced a rapid, encrusting veneer of tissue across the substrate; these observations contributed to the high variance affecting the data analyses.

Growth Rate and Species Comparison

Both Solenastrea bournoni and-Siderastrea siderea had comparable mortality rates; however, S bournoni grew significantly faster per year than S. siderea (both radius increase and total surface area). 'In other studies, S. bournoni and S. siderea demonstrated linear extension rates (measured with Alizarin Red-S :and/or X-radiography) of 8.4 - 8.9 nun yr and 3.9 s 7.6 nun yr·', respectively (Foster 1980, Hudson et al. 1989, Dodge 1997, Guzman and Tudhope 1998). The mean annual radii of the S. bournoni (3.81 ± 3.06 mm yr"') and S siderea (2.37 2 1.54 mm yr·') samples in this study are lower than the aforementioned; however, the outfall transplants are a) deeper than the prior reports, b) existing at a higher latitude, and c) not measured in the same manner. Nonetheless, the growth rates of the two species are in agreement with prior work relative to one another. his important to note that, although S. bournoni was among the most frequently occurring coral on the exposed outfall, it-is not similarly represented on the resident natural reefs when compared to abundant species such as Siderastrea siderea, Montastrea cavernosa and Dichocoenia stokesii (Dodge et al. 1995). The high frequency exhibited in this study may be due to a local recruitment event or the affinity of the species for occupying new substrate.

Growth Rate and Size Categories

In the reported data set, the only significant difference for radius increase existed between the smallest size category (0-1000 mm^a) and the next larger category (1001-5000 mm^1). This might, indicate that the colonies must attain a certain size before growth rate becomes relatively consistent. Fitzhardinge (1988) reported differences related to size and growth of juvenile recruits on artificial reefs in Kaneohe Bay, Oahu, Hawaii, however the colonies used in that study were much smaller than this investigation (< I year old). Maragos (1974) documented transplants larger than 20 cm diameter growing faster than smaller (dianieter < 10 Om); in general, it appears that larger transplants should present a smaller. risk than small corals for transplantation, but species-specific differences may also play a role. An optimal size class for transplantation has not been determined.

It is important to note. that the growth rate, when measuring footprint, may be underestimated if the growth axis is greater in the vertical direction (such as observed in Solenastrea bournoni), or overestimated where a veneer of skeleton is radiated from the base of the coral (see Auberson 1982). The latter can be seen in Porter astreoides, Acropora palmate), and other shallow water species (pers. obs.) that may vigorously attempt to occupy reef space. The technique would not be appropriate for branching corals.

It would seem that growth rate (skeletal linear accretion) would be an important proxy by which to compare similar species in similar environments. Generally skeletal growth rate may be measured using Alizarin Red-S staining (Barnes-1970, rev. in Lamberts 1978, rev. in Buddemeier and Kinzie 1976, Dodge et al. 1984), density banding (rev. in Buddemeier and Kinzie 1976, Dodge and Vaisnys 1980, Highsmith 1979), and/or buoyant weighing (rev. in Jokiel et al. 1978, Dodge et al. 1984), however, these proxies require either whole or partial sacrifice of the coral skeleton. Semi-invasive methods of measuring growth, such as using a nail or fixed object in the coral colony (Shinn'1972, Goreau and McFarlane 1990, Laydoo 1996) or coring may provide data without complete sacrifice, thus allowing the colony to continue to accrete. A method requiring minimal impact on the coral colony would: a) be repeatable, b) improve colony success over many years, and c) support the ultimate goal — restoration of the original habitat. The method used in this investigation is non-invasive and can determine relative' growth rate for an. indeterminate amount of time.

Conclusions

Two hundred and seventy-one reef-building corals were transplanted in September -1997 from an exposed outfall pipe to protective concrete armor mat used to cover the outfall. Two hundred and sixty-six specimens survived and remained in place after 3 months, and 235 were alive and remained in place after 27 months. Overall survivorship was 87% compared to 83% over a similar period for corals growing on natural substrate. The transplants have demonstrated growth comparable to naturally occur'ing corals. The armor matting covering the outfall pipe has demonstrated that it provides a suitable substrate for successful transplantation of stony corals.. Ongoing research is possible on the transplants due to non-invasive growth rate determination and will provide valuable information on the aesthetic and. ecological importance of coral transplantation.

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