Title: Tracking growth and survival of rescuedboulder corals

Running head: Evaluation of rescued boulder coral success

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Abstract:

Patterns of survivorship and growth of rescued boulder corals from two vessel groundings in Biscayne National Park, Florida, USA, were evaluated over five years and compared to nearby undamaged reference corals. The rescued colonies had been dislodged, but reattached *in situ* ten-twelve years later (hereafter termed 'restored' corals). Change in live coral tissue area was assessed using novel contoured tissue measurements which proved useful in detecting small changes in tissue area for slow-growing coral species. At the initial survey, restored boulder corals had a higher level of partial mortality(33.8 ± 3.1%, mean ± SE) relative to reference corals (19.9 ± 2.5%), likely a result of prolonged detachment. During the course of the five-year monitoring period, whole-colony mortality was greater for restored corals (13.1%) compared to reference corals (3.3%). For surviving corals, restored coral growth and recent mortality rates were similar to reference corals even though restored corals, especially those of *Dichocoeniastokesii*, had greater disease prevalence (19.7%) than reference corals (6.6%). These results suggest that dislodged boulder coral rescue following an acute disturbance can be an effective tool in stemming tissue loss. If dislodged corals were reattached in a more timely manner, we predict the survival and tissue growth would be greater.

Key Words: reattachment, restoration, vessel grounding, disease, coral rehabilitation

Implications for Practice:

- Boulder coral rescue and reattachment is a viable tool that can be implemented in reef rehabilitation efforts following an acute disturbance. Although rapid reattachment is best, stabilization and growth of reattached boulder corals can be observed even when reattachment occurs after a prolonged period of dislodgement.
- Disease or corallivorous snail mitigation may be beneficial following coral reattachment as they differentially affected rescued corals.
- 'Contoured area' estimates provide greater resolution than standard dimension-based size estimates in detecting small growth increments for slow-growingboulder coral species. We recommend this method be used as standard practicewhen quantifying growth of boulder coral species.

Introduction

In recent decades, coral reefs worldwide have been subject to natural and anthropogenic disturbances resulting in severe coral losses (Carpenter et al. 2008; Wilkinson 2008;De'athet al. 2012; Jackson et al. 2014). Although conservation efforts should be primary in reversing these effects, they haveso far proven insufficient. As a result, restoration and rehabilitation efforts are becoming more widely recognized as an essential tool to stem coral reef decline. Restoration is defined as the act of bringing a degraded ecosystem back into, as nearly as possible, its original condition (Edwards 2010), while rehabilitation is the term applied to partial or, more rarely, full replacement ofparticular structural or functional characteristics of an ecosystem that have been diminished or lost (Edwards 2010). In this terminology, the vast majority of efforts on coral reefs, including those addressed in this study, constitute ‘rehabilitation.’

Coral reef rehabilitation efforts cover a wide range of scenarios and objectives. Rehabilitationactions may address natural and anthropogenic impacts and range from indirect action (e.g., removal of a point-source disturbance) to coral transplantation to otherwise replacing architectural structure. The most widely used methods for coral reef rehabilitationfall under some aspect of coral transplantation (Challenger 2006), either sourcing coral from healthy reefs or coral farms to repopulate a disturbed reef area or relocating coral from an area prior to planned damage (e.g., coastal construction projects). Such activities have been common and are relatively well-represented in the scientific literature (reviewed in Rinkevich 2005; Rinkevich 2014) and in practical guidance documents (Edwards 2010).

Dislodgment of coral due to acute disturbances is a common phenomenon in coral reef habitats due to natural events such as storms or anthropogenic events such as vessel groundings, anchoring, blast fishing or underwater construction (Precht 2006). The rescue of such physically damaged colonies, while sharing some elements of healthy coral transplantation (as described above), might be expected to yield substantively different results. Restoring disturbed reefs with coral transplants sourced from areas other than the disturbed site may be associated with potential ecological drawbacks including loss of coral colonies from donor areas, promotion of dominant coral species and potential negative genetic consequences (Edwards & Clark 1998;

Abelson 2006;Baums 2008). Reattaching corals dislodged from within the impact site following an acute disturbance may be a simple approach to reduce these potential drawbacks. However, the compromised condition of physically damaged corals may yield lower success after reattachment.

Few published studies have examined rescued corals from within a disturbed reef to evaluate the success of re-stabilizing dislodged coral, and those that do involve only fast-growing, branching corals (Bruckner et al. 2009; Williams & Miller 2010; Garrison & Ward 2012). Furthermore, even fewer studies have monitored rescued, transplanted coral growth relative to natural, undisturbed reference corals (Bruckner et al. 2009). Thus, very little literature exists evaluating survivorship and growth of rescued boulder corals dislodged from an acute disturbance event relative to undisturbed colonies (but see Monty et al. 2006 for a partial exception). Edwards and Clark (1998) argue that due to the low recruitment potential of slow-growing boulder coral species, yet generally high survival rate following transplantation, conservation and restoration studiesshould target evaluation of the effectiveness of transplanting rescued, slow-growing coral species.

Documenting small changes in tissue biomass of slow-growing coral species over relatively short time spans can be difficult. The typical methods used to monitor coralsuse two (length and width) to three (length, width and height) linear measurementsor photographs to calculate either a planar surface area or volumetric estimations (reviewed in Courtney et al. 2007). However, the utilization of linear measurements provides low, generally inadequateresolution to detect change in size of species with slow skeletal growth. Alternate methods should be investigated to document small increments of growth over feasible time spans of most monitoring efforts (e.g., 1-5 years), particularly for rescued, dislodged corals which tend to have a high degree of partial mortality making estimations of colony tissue area even more difficult.

Vessel groundings provide a common context for testing specific restoration techniques (Rinkevich 2005). Here, we evaluate ecological performance of rescued boulder corals dislodged during two vessel groundings in Biscayne National Park (BNP), Homestead, Florida, USA. In particular, we 1) monitored survival and growth of slow-growing, slow-recruitingboulder coral species in relation to nearbyconspecific reference corals and 2) evaluate a simple method of tracking growth in slow-growing coral species that may provide greater resolution of change in live tissue area than the common methodusing linear measurements.

Methods

Restoration activities were conducted between 13 August 2008 and 20 February 2009 at two vessel-grounding sites in bank-barrier reef habitats (6 – 10m depth) within Biscayne National Park (BNP), Homestead, Florida, USA, after a long delay following the initial grounding events which occurred in 1996 and 1998. Restoration contractorssecured detached coral headsto the damaged area of benthos using a cement based mortar (1:1 Portland cement and sand aggregate). These colonies had presumably been subject to additional physical disturbance during the 10-12 year interval following the grounding events that they remained dislodged. Thus, although the species composition of the reattached corals incorporated the dominant species in the area, it is important to note that the individual reattached corals within these species may have been selected as a result of surviving 10-12 years of dislodgement. A total of 61rescued, reattachedcoral colonies (hereafter referred to as 'restored') comprising the following species were subsequently tagged for monitoring in October 2009: *Colpophyllianatans*(CNAT)*, Diplorialabyrinthiformis*(DLAB)*, Diploriastrigosa*(DSTR)*, Dichocoeniastokesii*(DSTO), *Meandrinameandrites*(MMEA)and*Siderastreasiderea*(SSID). To compare the performance of this restored assemblage to that of the nearby reference coral populations, a comparable number of colonies of each species waslocated andtaggedwithin an adjacent (~100m away) section of the reef that was unaffected by the grounding.All colonies were mapped usingcircular coordinates from a central stake in order to relocate them. Sample sizes are presented in Table 1a.

Post-restoration surveys were conducted at restored and reference sites twice a year (spring and fall) fromOctober 2009 to April 2014, and were denoted with sequential survey numbers (i.e., S01 – S10). At each survey, corals were photographed and colony size was recorded as well as a visual estimation of percent live tissue cover, presence/absence of bleaching (any degree of discoloration observed on live tissue of the colony),recent mortality (i.e., bright white skeleton indicative of tissue loss within the previous couple of weeks) from disease and occupation by the corallivoroussnail, *Coralliophilaabbreviata*(referred to as 'snails' hereafter). Colony sizeduring the first two surveys (S01 and S02) wasestimated as a volume (cm^3) from measurements oflinear dimensions (i.e., volume = maximum height x length x width), and that volume was multipliedby the estimated percent livetissue cover to adjust for partial mortality (Fisher et al. 2007).However, it became clear that this approach would not provide estimates of adequate resolution to detect slow growth or re-sheeting that we hoped to quantify. Particularly, a portion of the monitored corals had partial mortality in a “horseshoe” pattern (dead on one side and top with live tissue as a collar shaped rim, likely due to spending a period of time upside-down following the initial disturbance) that was particularly problematic in this regard. Some studiessuggest estimating surface area of head corals using projected linear measurements to calculate surface area as a bottomless hemisphere (Alcala & Vogt 1997; Fisher et al. 2007). Although this estimation is more accurate than estimating volume, it still requires an estimation of percent live tissue on the entire skeleton and the use of linear measurements (see Fig. 1a,c)whichis often problematic and may introduce unnecessary error. Linear estimates require an observer to line their eye perpendicular with the measure pole and the edge of the coral colony; in marine environments, current and wave action can prevent proper eye alignment resulting in error. In addition, calculating the surface area for a bottomless hemisphere assumes that the coral is the same height on all sides (i.e., uses a single height measurement). This is often untrue, especially for colonies with a high degree of partial mortality.

For these reasons, after the first two surveys, we shifted to using a direct, contoured measurement (length and width) of individual live tissue isolates on each colony with a flexible tape (Fig. 1b,c), and using the formula for an ellipse(2-dimensional [2D], SA = À* [L / 2] * [W /

2])we estimated the live tissue area of the colony (cm^2).We use the term ‘contoured area’ for this parameter. Area of an ellipse was used because it most closely resembles the flattened tissue shape of boulder corals surveyed in this study. As dead patches may occur within continuous spans of live tissue, live tissue area measurements were still scaled by the visual estimate of percent live, which was now estimated only within the confined span of live tissue rather than over the entire skeletal unit. Because more coherent patches of live tissue were measured, these live tissue area estimates were more accurate. If multiple tissue isolates occurred on a single coral skeletal structure, the areas for each isolate were summed to provide a total amount of live tissue surface area for a single colony. Colony measurements were made using both methods for two following surveys (S03 and S04; Fig. 1a,b) to allow a comparison of the two types of colony metrics via linear regression. For surveys 5 through 10, colony size was measured using the contoured area method only. All colony measurements were conducted by the same individual (A.J. Bright) throughout the study.

For all analyses, colonies were pooled among the two vessel-grounding sites as sample sizes were not adequate to test sites individually. Initial colony size and initial proportion of living tissue on each colony were not normally distributed (nor were transformed proportion data) and, therefore, analyzed using nonparametric Mann-Whitney U tests. Growth was calculated as the percent change in contouredtissue area from S03 to S10. The restored treatment data were normally distributed, but the reference treatment data were not (nor were transformed data); therefore, the percent change in growth between the two treatments was analyzed using Mann-

Whitney U tests. For conditions causing tissue mortality, ‘cumulative prevalence’ was calculated, defined as the percentage of colonies that displayed signs of a condition at least once during the ten surveys (i.e., not an average). Pearson’s chi square tests were used to test differences in complete coral mortality, detached corals and cumulative prevalence of recent mortality, disease, snail occupation and bleaching between treatments. Lastly, to determine (post-hoc) if initial condition of restored colonies affected their subsequent risk of whole-colony mortality, we compared the initial size (live tissue volume) and initial partial mortality between reattached colonies that did versus did not suffer whole-colony mortality over the course of the study using Mann-Whitney Utests.

Results

An equal number of restored and reference colonies with similar species composition were tagged and monitored for growth and survival (Table 1a). The initial colony sizes were not different between treatment groups (average colony live tissue volume of 12,583.2 ± 3,628.1 cm^3 for reference corals and 8,060.3 ± 2,842.1 cm^3 for restored corals; mean ± SE; $p = 0.35$; Fig. 2a). However, the initial proportion of live tissue cover was lower on the restored colonies ($p = 0.002$; Fig. 2b).

For S03 and S04, colony size was estimated using both volume and contoured live tissue areaparameters to compare change in amount of live tissue between the two methods. The contoured tissue area parameter revealed a discernable changein tissue area for 82.3% of corals in both treatments during this six-month interval; whereas, volume estimates based on linear measurements showed a discernable changefor only 30.1% of corals reinforcing the expectation that contoured area estimates provide improved resolution to detect small changes in tissue growth over short time spans. A regression of the two parameters was plotted for a single survey and yielded high correlation between volume and contoured tissue area($R^2 = 0.97$;Fig. 3; Fig.S1, by spp.). However, back-calculating (i.e., calculating surface area from volume) even using such strong relationships still introduces some error (and greater proportional errors for small colonies); therefore,overall colony growth was evaluated only between S03 and S10 as change in the direct contoured tissue area measurements.

The general fate of tagged colonies is summarized in Table 1b. Consistent with higher levels of initial partial mortality, whole-colony mortality during the course of the study was higher in the restored population (eight colonies versus two reference colonies,p = 0.05; Table 1b). However, reattached colonies that suffered whole-colony mortality did not differ from surviving colonies in their initial partial mortality (37 ± 10% versus 26 ± 3%, mean ± SE; p=0.34), though they were significantly smaller in initial live tissue volume (1,216 ± 394 cm^3 versus 9,113± 3,258cm^3, mean ± SE;p=0.05). Two restored colonies were detached from the substrate while four reference colonies were detached during the course of the study (p = 0.4; Table 1b); upon detachmentthe colonies were excluded from further assessment. For the surviving corals at S10, change in contoured tissue area from S03 to S10 was not different between reference and restored treatments (p = 0.57; Fig. 4). Different individual colonies in both treatments showed both high positive and high negative values, as reflected both in individual colony growth estimatesand in visual observations (Fig.S2,S3).Furthermore, similar proportions of corals from each treatment showed a negative and positive change in contoured tissue area (Table 1c).When growth of surviving colonies was examined by species, treatment differences were not detected for any species ($p = 0.44 – 0.93$; Fig. 4).

Over the course of this study, the cumulative prevalence of recent mortality was not different between restored and reference treatments ($p = 0.66$; Table 1d). Recent mortality was attributed to many factors (e.g., Clionidboring sponges, overgrowth, competition with neighboring organisms), but the most common causes of tissue loss were from disease and snail predation(snails observed occupying primarily *Diploria* spp. and *C.natans*). The cumulative prevalence of disease was greater for restored corals than reference corals ($p = 0.05$; Table 1d) which was attributed primarily to the increased susceptibility of *D.stokesii*in the restored treatment ($p = 0.001$; Table 1d). Conversely, the cumulative prevalence of snail occupied colonies was not different between treatments ($p = 0.65$; Table 1d).Coral bleaching was observed only during the first survey and on approximately equal proportions of colonies in the two treatments (restored = 13.1%, reference = 14.8%; Fig. S4).

Discussion

Not surprisingly, rescued boulder corals showed some initial differences from reference treatment corals following an extended period (10-12 years) of dislodgement. By the end of the

5-year study, however,both treatments performed similarly. At the initial survey, approximately 8 months following reattachment, partial mortality wasgreater on restored corals (likely resulting from the vessel grounding and subsequent stress of dislodgement), and this was borne out in higher whole-colony mortality over the 5-year study. As elevated levels of whole-colony mortality are expected following transplantation (reviewed in Edwards & Clark 1998), results were not unexpected with 13.1% of restored colonies having died during the study compared to 3.3% of reference colonies. Yet, this level of whole-colony mortality for rescued corals is lower than most other transplantation studies which utilize fast-growing, branching corals (Plucer-Rosario & Randall 1987; Yap et al. 1992; Clark & Edwards 1995; Bruckner et al. 2009; Garrison & Ward 2012). However, for surviving corals, the long-term growth trajectories and cumulative prevalence of overall recent mortality revealed no discernable difference between treatmentswith the proportion of colonies showing positive growth being very similar. Furthermore, the mean percent change in colony live tissue area was similar between treatments for the coral assemblage as a wholeand for individual taxa. Thus, we conclude that boulder coral rescue and reattachment can be a viable tool in active reef rehabilitation following an acute disturbance event. It is likely that the initial differences in condition between treatments in the current study could be minimized if reattachment was undertaken in a more timely manner (i.e., months rather than years following dislodgement), further improving the outcome observed here.

Percent recent coral mortality has been proposed as a critical indicator of coral population health and performance (Lirman et al. 2014), and impacts resulting in recent mortality such as disease and predation have been associated with physical disturbance events. While in this study, the net change in live tissue area and cumulative prevalence of recent mortality was not different between treatments, disease did affect a greater proportion of restored corals. Not all species were affected by disease, andthe difference between treatments was driven primarily by *D.stokesii*of which half of the restored corals for this species were observed with disease (three leading to whole-colony mortality). The cumulative prevalence of snail occupation wasnot different between restored and reference treatments. However, when looking at individual surveys, the proportion of snail occupied colonies appeared higher in the restored treatment beginning in S04 (approximately 26 months after reattachment) and remained at elevated levels relative to reference corals through the end of the study (Fig. S4).Increased susceptibility to disease and predation following physical damage has been documented in a range of other studies (Knowlton et al. 1981; Brandt et al. 2013; Bright et al. 2015).Results in the present studyconfirm that associated stressors are likely to continue following coral rescue and reattachment, but surviving corals have the ability to overcome these stressors and grow at comparable rates to undisturbed conspecifics.

Restored colonies that died were of significantly smaller size in terms of live tissue volume relative to surviving restored colonies, though they did not differ in initial degree of partial mortality (i.e., reflecting the direct damage from physical injury). Given the apparent long-term susceptibility to associated disease or predation (i.e., indirect effects of physical disturbance), this smaller initial amount of live tissue logically would result in greater risk of whole-colony mortality. Although restored smaller colonies showed greater risk of death than larger ones, we cannot conclude that the benefit of reattachment is less for small colonies as we, like most evaluation studies, did not have opportunity to evaluate dislodged but unrestored controls. On the contrary, we would hypothesize that despite the whole-colony mortality observed in restoredcolonies (especially small ones), this vulnerability would be even greater in the absence of stabilization (Monty et al. 2006; Williams & Miller 2010).Further evaluation studies including damaged but unrestored treatments are needed to test this hypothesis and determine the relative benefits of reattachment for different types or conditions of colonies.

With the goal of improved resolution of coral tissue growth over medium time scales (e.g., 5 years as for a restoration monitoring project), we chose a size parameter that incorporated both 2-dimensional (2D) and 3-dimensional (3D) aspects. That is, a 2D area parameter was estimated based on contoured measurements of the colony surface. Three dimensional coral size and resultant architectural complexity of reefs are directly responsible for many coral reef ecosystem functions (Loya 1972);hence, 3D coral volume estimates may be best suited for estimating reef structural complexity, habitat value and/or coral reef ecosystem function (Fisher et al. 2008). However, size metrics based on linear skeletal dimensions provide poor resolution of change for slow-growing boulder corals and hence do not provide a useful tool for tracking growth of individual colonies over medium time scales. Additionally, such metricsare particularly problematic for colonies that have a substantial portion of dead surface as is commonly the case with rescued corals. The methods employed in this study still incorporate the 3D morphology of the coral by using contoured length and width measurements and proved sufficient in detecting slow tissue growth with no added effort in the water. In fact, the contoured area approach allows for one less measurement (compared to 3D measurements using linear length, width and height) reducing potential for error and reduced visual parallax error(especially in conditions of surge) since contoured measurements are flush with the coral surface. Furthermore, we found that estimates of percent live for individual patches of live tissue were much easier (and likely more accurate) than estimating more complex patterns of live and dead tissue over an entire skeletal structure.

Acute physical disturbances, whether natural or anthropogenic, are common on coral reefs around the globe. Boulder coral rescue and reattachment *in situ*may be a useful tool in reef rehabilitation following many types of acute disturbance events such as vessel groundings, storm/swell damage, blast fishing, anchoring, impacts from SCUBA divers, etc. Methods used for estimating live coral tissue areain this study can be particularly useful for tracking short to medium-term growth of slow-growing coral species which are important targets for coral rehabilitation efforts.

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Table 1. Summary of (a) sample size, (b) colony fate, (c) mean change in live tissue cover and proportion of positive versus negative trajectories and (d) cumulative prevalence of detrimental conditions observed affecting tagged colonies for restored and reference treatments. Statistical comparisons between restored and reference colonies were conducted on all data in b, c and d withasterisks indicatingstatistically significant differences ($p < 0.05$).

a			b			c				d			
										Cumulative Prevalence			
Treatment	SPP	*N*	# Surviving	# Dead	# Detached	Average % Change	SE	Proportion Growing Corals	Proportion Shrinking Corals	Recent Mortality	Disease	Snail Occupation	Bleaching
Reference	CNAT	2	2	0	0					100%	50%	100%	0%
Reference	DLAB	8	8	0	0					25%	0%	50%	0%
Reference	DSTO	18	17	0*	1					33%	0%*	22%	0%
Reference	DSTR	9	7	2	0					44%	11%	67%	0%
Reference	MMEA	11	8	0	3					18%	0%	9%	9%
Reference	SSID	13	13	0	0					31%	15%	0%	62%
Reference	TOTAL	61	55	2*	4	8.8	5.2	0.7	0.3	33%	7%*	28%	15%
Restored	CNAT	8	5	2	1					50%	13%	88%	0%
Restored	DLAB	10	9	1	0					40%	0%	80%	0%
Restored	DSTO	13	10	3*	0					46%	46%*	0%	0%
Restored	DSTR	7	6	1	0					43%	29%	57%	0%
Restored	MMEA	11	11	0	0					18%	9%	0%	0%
Restored	SSID	12	10	1	1					25%	17%	0%	58%

Restored	TOTAL	61	51	8*	2	13.4	6.4	0.7	0.3	36%	20%*	31%	13%

Figure 1. Illustration of (a) straight line measurements used for calculating volume or surface area and (b) contoured measurements used for calculating the (2D) area of an ellipse. (c) Illustrates the likelihood for increased accuracy when using contoured measurements (white) of live tissue compared to using a volume estimated based on straight line measurements (black) adjusted by a visual estimate of live cover of the entire skeletal unit(e.g., ~40%) to estimate amount of live tissue.

Figure 2. (a) Colony volume adjusted with % live estimates for reference (*n* = 61) and restored (*n* = 61) corals at the first survey (October 2009), and (b) the visually estimated live tissue cover on each coral skeletal unit for reference and restored corals at the first survey (October 2009). Lines represent the best-fitting normal curve for each treatment.

Figure 3. Linear regression correlating colony volume based on linear measurements with colony surface area based on contoured measurements, each adjusted by a visual estimate (%) of live tissue cover. Data are from S03 (November 2010).

Figure 4. The mean (+ SE) percent change in live contoured tissue area for reference and restored corals from November 2010 through April 2014 (S03 to S10). Sample sizes (*n;* tagged colonies that survived the entire study period) are presented at the base of each bar. The difference in growth between restored and reference corals is not statistically significant (details in text) for any individual species nor for the whole assemblage.

Figure 1:

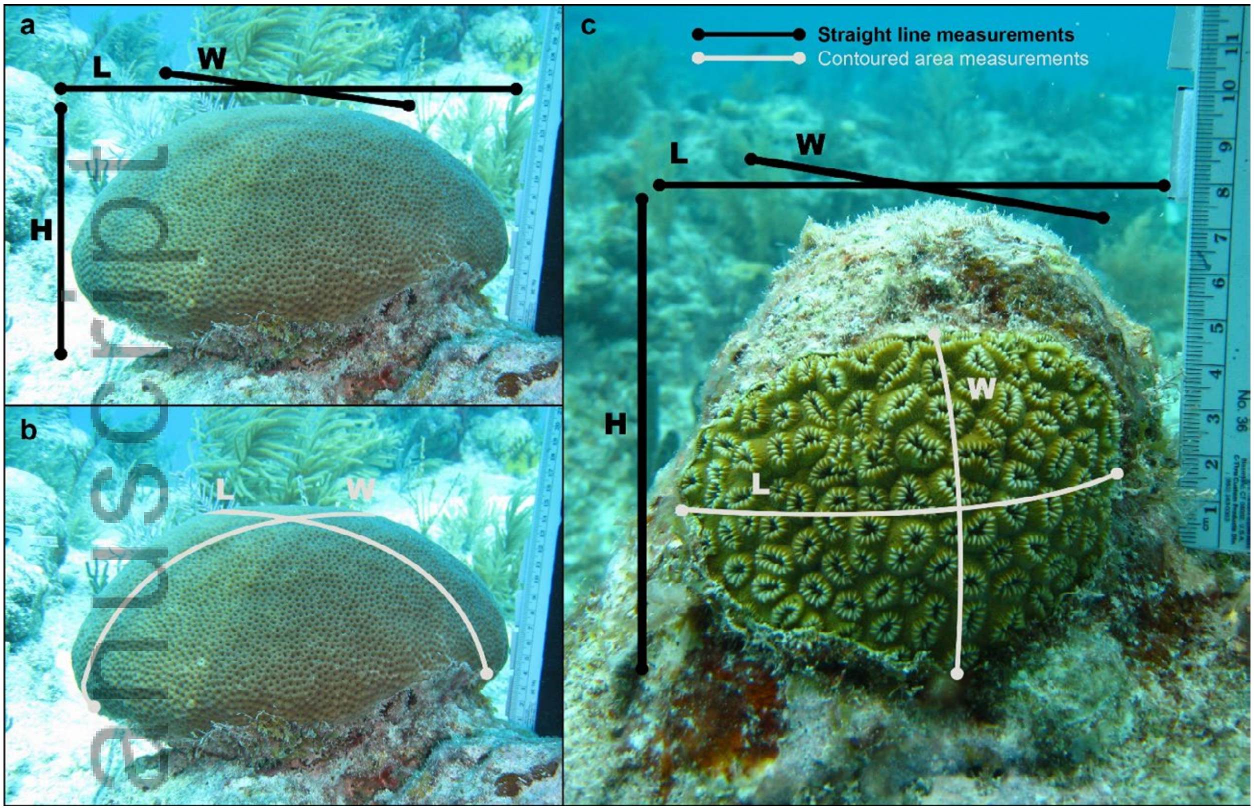

a
L
W
H
b
L
W
c
Straight line measurements
Contoured area measurements
L
W
H
W
L

Figure 2:

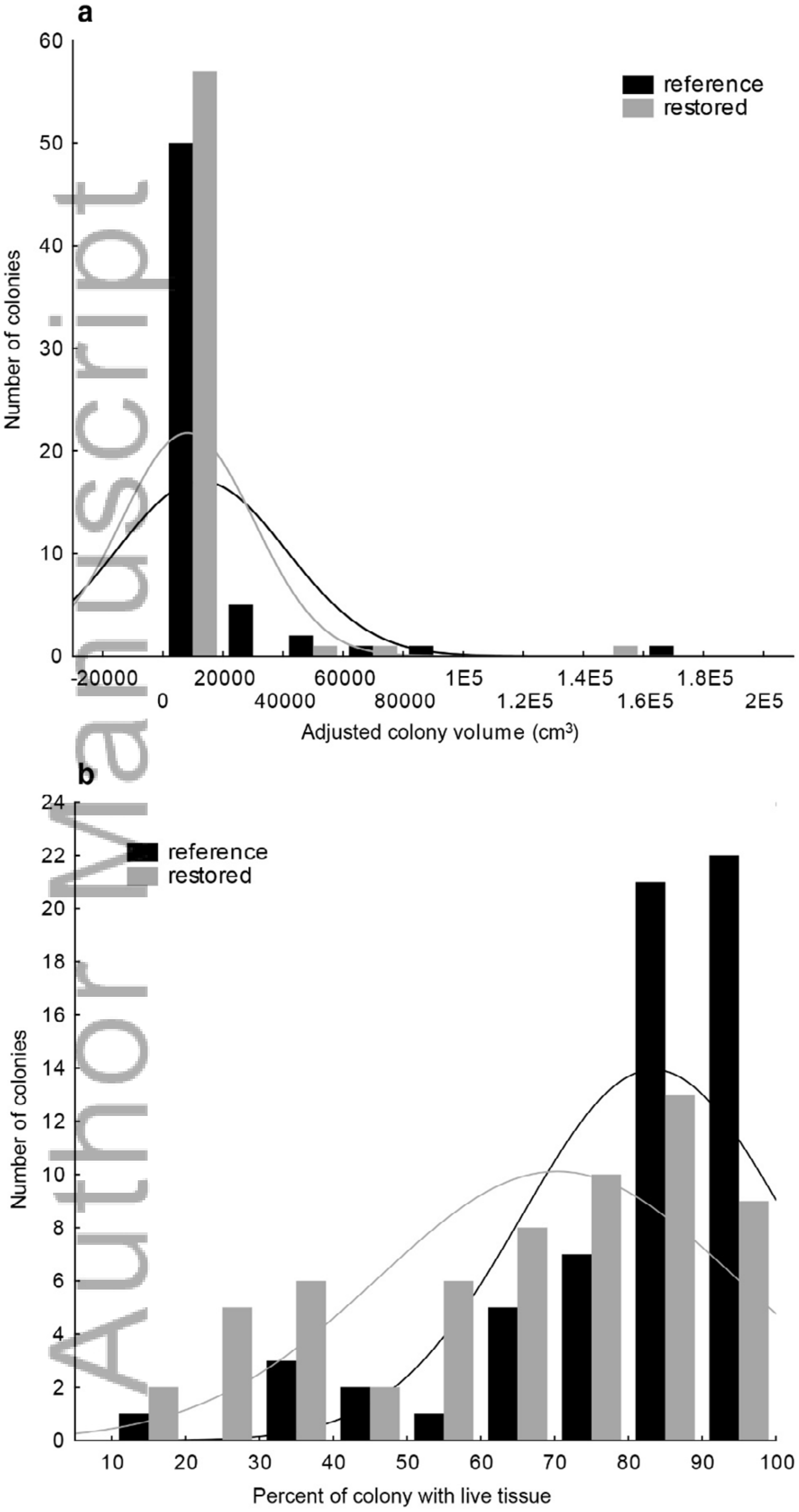
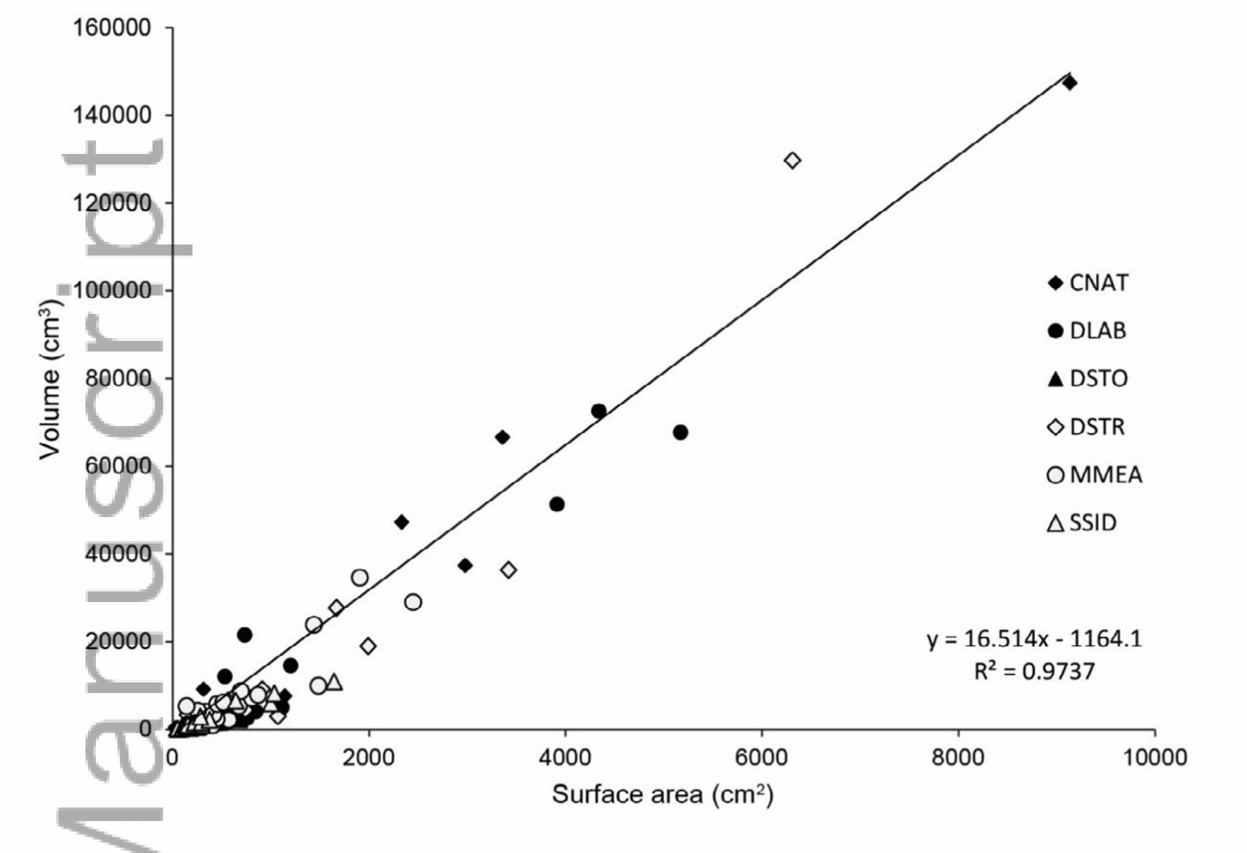
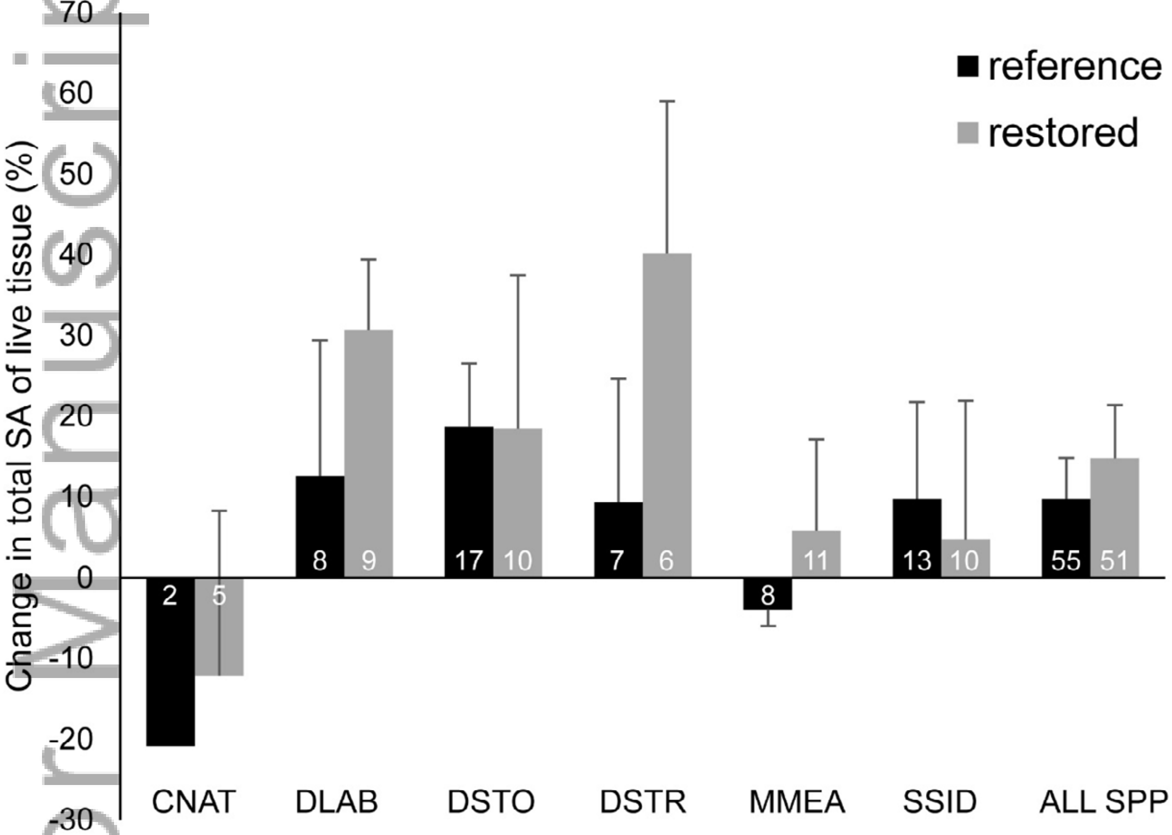

a
Number of colonies
60
50
40
30
20
10
0
reference
restored
-20000
0
20000
40000
60000
80000
1E5
1.2E5
1.4E5
1.6E5
1.8E5
2E5
Adjusted colony volume (cm³)
b
Number of colonies
24
22
20
18
16
14
12
10
8
6
4
2
0
reference
restored
10
20
30
40
50
60
70
80
90
100
Percent of colony with live tissue

Figure 3:



160000
140000
120000
100000
80000
60000
40000
20000
0
Volume (cm³)
0
2000
4000
6000
8000
10000
Surface area (cm²)
◆ CNAT
● DLAB
▲ DSTO
◇ DSTR
○ MMEA
△ SSID
y = 16.514x - 1164.1
R² = 0.9737

Figure 4:



■ reference
■ restored
Change in total SA of live tissue (%)
70
60
50
40
30
20
10
0
-10
-20
-30
CNAT
DLAB
DSTO
DSTR
MMEA
SSID
ALL SPP
2
5
8
9
17
10
7
6
8
11
13
10
55
51