Effectiveness of Reef Restoration in Singapore's Rapidly Urbanizing Coastal Environment

Loke Ming Chou, Tai Chong Toh, and Chin Soon Lionel Ng

***Abstract*—Singapore's accelerated coastal urbanization since the 1960s resulted in 65% of its coral reef habitat lost to land reclamation. Increased sedimentation reduced underwater visibility from 10m then to less than 2m today. Under these conditions, reef restoration to increase coral cover of degraded reefs and initiate colonization of non-reef areas remains viable considering the precise mass spawning events, active settlement and vigorous growth of coral larvae. The restoration techniques employed should withstand the high suspended sediment and destabilized reef substrate. Coral fragments were translocated from a reef close to impending port development to reefs further away in a 4-year project aimed at assessing whether 1) restoration can assist recovery of degraded reefs and 2) non-reef areas can be transformed into new reefs. Within the first three years, over 1200 fragments from 22 genera were transferred to *in-situ* nurseries at the recipient sites, of which almost 900 were subsequently transplanted to a degraded reef site and a non-reef site with an overall survival rate of over 80%. The project's results will help to establish protocols to support management decisions on coral relocation and restoration in a rapidly urbanizing coastal environment.**

***Index Terms*—Coastal urbanization, reef restoration, Singapore.**

I. Introduction

Five decades of extensive coastal development has degraded much of Singapore's nearshore habitats [1]–[3]. More than 60% of coral reefs were lost to coastal reclamation that increased land area by more than 20% to 719.1km^2 since the country's independence in 1965 [4], [5]. The chronic sedimentation generated smothers reef life, while high turbidity levels attenuate light required by scleractinian corals and restrict coral development to shallow depths [6]. The reef substrate has also become less consolidated and more unstable, compromising the survival of newly settled corals [4]. Singapore's reefs are at risk of further land reclamation to support future needs [7], including plans to consolidate port operations and create a mega container terminal at Tuas on the western coast [8]–[10].

Reef restoration and rehabilitation strategies have been employed to slow the decline of Singapore's reefs and assist in the replacement of ecological structure and function of the degraded habitats [11], [12]. They are considered viable despite the continued anthropogenic impacts to the marine environment, as annual coral mass spawning events which occur with a high degree of predictability contribute significantly to the self-seeding of Singapore's reefs [13]–[15]. The overall approach to reef restoration since the 1990s is aimed at circumventing the problems of high sedimentation and destabilized substrate, and comprises physical (e.g. artificial reef deployment) and biological (e.g. nursery-rearing and transplantation of corals) techniques [12]. Based on the lessons learnt from restoration projects over the past two decades, a four-year long project was initiated as part of a long-term research framework to mitigate the potential loss of reef biodiversity from Sultan Shoal, an island with a fringing reef close to Tuas (Fig. 1).

II. Site Assessments

An Environmental Impact Assessment (EIA) was conducted in 2012 to evaluate the effects of the impending development at Tuas. Results indicated that the reef fringing Sultan Shoal (1°14.21'N, 103°38.52'E), an island 0.6 ha in size located 5.48 km from the Singapore mainland (Fig. 1), would be impacted by Tuas dredging and reclamation activities and more than 2800 coral colonies were at risk [16]. The EIA recommended the relocation of most of the corals to other sites to help preserve the scleractinian diversity from Sultan Shoal. It was recognized that the mass coral translocation exercise would inevitably generate coral fragments, which when retrieved will be a valuable source of research material for coral restoration investigations.

In 2013, assessments were made of reefs fringing six other southern offshore islands: St. John's (1°13.25'N, 103°50.58'E), Hantu (1°13.64'N, 103°44.80'E), Semakau (1°12.27'N, 103°45.26'E), Kusu (1°13.56'N, 103°51.58'E), Subar Darat (1°12.89'N, 103°49.87'E), and Satumu (1°09.60'N, 103°44.40'E), as well as two seawalls (Lazarus East, Lazarus West) (1°13'41.76"N, 103°51'19.82"E) for their suitability as recipient sites for the coral fragments. The reef sites are known to support diverse reef communities [17], while seawalls in Singapore are sufficiently stable for coral colonization [18]. The criteria used included site accessibility, water quality, availability of substrates for transplantation and tidal range. Benthic surveys and physical-chemical parameters (light levels, temperature profile, sedimentation rate, water movement and salinity) were determined at two depths (2-4 m, or 'Shallow'; 5-7 m, or 'Deep').

Based on the observed similarities to conditions at Sultan Shoal (Table I), Lazarus East, Lazarus West, and Kusu (Shallow) were selected as recipient sites for the coral fragments. Compared to Sultan Shoal, sedimentation rates at Hantu and Semakau were two to five times higher, and water

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motion at Satumu and Sisters were twice as fast.

The availability of stable substrates in the form of boulders and granite rocks at the recipient sites made them ideal for the transplantation of corals to be carried out.

The similar environmental conditions were also beneficial towards reducing stress on the transplanted corals and improving survival rates [19].

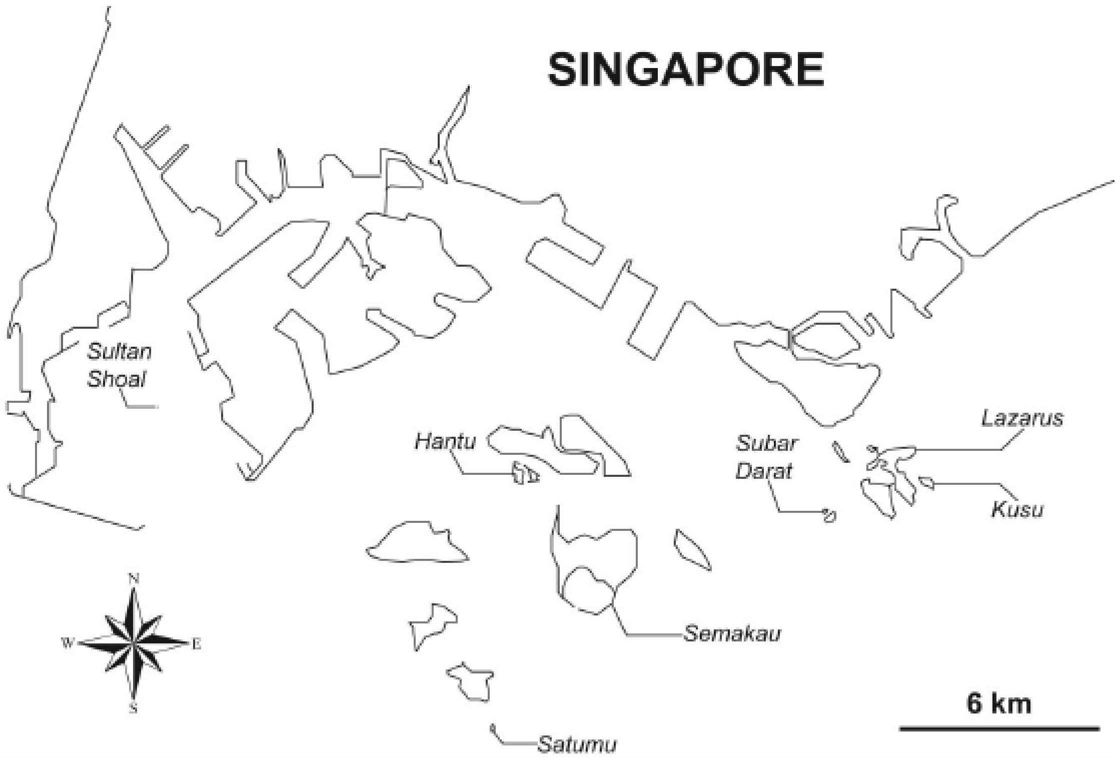

Fig. 1. Map of Singapore showing the seven study sites.

TABLE I: MEAN VALUES FOR PHYSICAL-CHEMICAL PARAMETERS RECORDED FROM STUDY SITES IN 2013

Site	Location	Reef Zone	Light levels (microMoles/s/m^2)	Temperature (℃)	Salinity (ppt)	Sedimentation (grams/day)	Water Motion (weight loss in grams)
Semakau	South	Shallow	620.63	30.3	30.1	2.55	13.96
	South	Deep	176.78	30.32	30.1	0.94	8.71
Kusu	East	Shallow	197.82	30.34	30.2	0.28	13.99
	East	Deep	33.53	30.39	30.2	0.82	11.14
Lazarus	East	Shallow	391.61	30.21	30.3	0.18	9.81
	West	Shallow	197.41	30.3	30.2	0.13	6.38
Sultan Shoal	South	Shallow	348.55	30.53	30	0.13	9.64
	South	Deep	243.25	30.45	30.2	0.15	7.31
Sultan Shoal	North	Shallow	208.16	30.12	30	0.18	7.99
	North	Deep	101.74	30.43	30	0.17	5.92
Subar Darat	West	Shallow	277.87	30.15	30.2	0.77	16.25
	West	Deep	234.78	30.13	30.3	0.50	16.80
Satumu	East	Shallow	309.51	30.84	30	0.29	13.76
	East	Deep	196.81	30.74	30	0.31	16.71
Satumu	West	Shallow	953.00	30.72	30	0.08	15.20
	West	Deep	275.70	30.641	30	0.23	10.96
Hantu	West	Shallow	684.32	29.96	30	0.42	12.09

III. ESTABLISHMENT OF CORAL NURSERIES AND CORAL PROPAGATION

Coral nurseries are beneficial to reef restoration efforts as they provide a sheltered environment that facilitates the growth of coral material prior to transplantation to degraded sites [20].

Two nurseries were established on the sandy seabed adjacent to the Lazarus East and Lazarus West seawalls, while a third was sited at Kusu (nursery areas of 36.5 m^2, 12 m^2, and 2.5 m^2 respectively). Coral nursery tables were constructed from polyvinylchloride frames elevated 0.5 to 1m above the substrate. Plastic mesh nets were mounted taut across the tops of the nursery tables to facilitate the attachment of coral fragments, as well as reduce sediment accumulation around the base of the attached fragments. (Fig. 2)

Loose coral fragments lying on the Sultan Shoal reef floor during the mass coral translocation were collected and secured to the nursery tables in 2014. These fragments, collectively known as "corals of opportunity" (COP), would have otherwise perished from being swept about by currents [21]. In total, 1251 fragments from 22 coral genera were raised in the nurseries (Table II). Overall survivorship after one year was 92%. Corals of the genera *Turbinaria*, *Pectinia* and *Pocillopora* had the lowest survival rates of 75%, 71.6% and 65.7% respectively (Table II).

Fig. 1. 'Corals of opportunity' reared at the *in situ* nursery.

Thirty-six fragments from each of six species (*Podabacia crustacea, Echinopora lamellosa, Merulina ampliata, Hydnophora rigida, Pocillopora damicornis, Platygyra sinensis*) that spanned the range of coral growth forms (foliose, branching, massive) in Sultan Shoal were selected for further monitoring in the nursery. Compared to earlier restoration efforts in Singapore where 61% of coral fragments survived after a six-month nursery-rearing period [22], survival rates in the current study were high (99% in eight months), with mortality recorded from only one *H. rigida* and two *M. ampliata* fragments. The high survival is attributed to the high frequency of maintenance effort, which included scrubbing of the supporting mesh net material to remove fouling organisms.

In addition, mean colony sizes of all species increased. *Pocillopora damicornis* and *H. rigida* exhibited the fastest growth (by 1.9 and 1.8 times respectively), while *P. crustacea* and *P. sinensis* grew slower (by 1.2 and 1.1 times respectively) [23]. Growth in the nursery is essential to improve survival chances upon transplantation, as smaller sized corals are more affected by environmental stressors than larger ones. The results demonstrated the feasibility of propagating COPs in nurseries to supplement reef restoration efforts instead of harvesting directly from source colonies on the reef.

IV. Coral Transplantation

Following methods described by Ng *et al.* [24], a total of 213 live coral fragments (*P. crustacea, E. lamellosa, M. ampliata, H. rigida, P. damicornis, P. sinensis*) were transplanted on the granite seawall off Lazarus East and monitored for seven months. The overall survival rate of the transplanted corals was 88%. All transplants of *E. lamellosa* and *H. rigida* survived, while those of *P. damicornis* had the lowest survival rate (47%). Mean sizes of the transplants reduced slightly in the first month – likely due to transplantation stress – but increased in subsequent months.

TABLE II: Genera Collected from Sultan Shoal and Survival Rates of Coral Fragments after One Year of Rearing in Nurseries at Lazarus and Kusu

Coral genus	Number of fragments collected	Survival rate (%)
Acanthastrea	3	100.0
Cyphastrea	7	100.0
Diploastrea	8	100.0
Echinopora	191	95.8
Favia	17	100.0
Favites	12	100.0
Goniopora	5	100.0
Hydnophora	56	100.0
Leptastrea	7	100.0
Lithophyllon	13	100.0
Lobophyllia	4	100.0
Merulina	124	89.5
Montipora	11	100.0
Oxypora	15	100.0
Pachyseris	2	100.0
Pavona	11	100.0
Pectinia	81	71.6
Platygyra	334	96.7
Pocillopora	108	65.7
Podabacia	236	97.9
Porites	2	100
Turbinaria	4	75
Overall	1251	92

Transplants of *P. crustacea* and *P. damicornis* were most impacted by corallivorous gastropods (*Drupella* spp). Similar to the nursery phase, transplants of *P. damicornis* and *H. rigida* grew the fastest (by 1.4 and 1.3 times respectively), while those of the remaining species increased by 1.1 to 1.2 times in size [23]. Coral cover at the transplant site rose to 20% from 3%, and generic richness increased from two to eight. The high transplant survival rates showed that it was possible to ecologically engineer subtidal seawalls and enhance the biodiversity of these artificial structures.

From 2015 to 2016, a total of 904 coral fragments from 17 genera (*Acanthastrea, Echinopora, Favia, Favites, Goniopora, Hydnophora, Merulina, Mycedium, Pachyseris, Pavona, Pectinia, Platygyra, Pocillopora, Podabacia, Psammacora, Symphyllia, Turbinaria*) were transplanted to the seawalls at Lazarus East and Lazarus West, as well as the reef fringing Kusu (Table III). This generated a total restored area of 422 m^2 (150 m^2 degraded reef and 272 m^2 new reef). Monitoring programs are in place to assess the long term effectiveness of these habitat enhancement initiatives. Species that responded favorably will be selected for future efforts to assist the recovery of degraded sites or hasten coral colonization on artificial structures.

This study has demonstrated the viability of harnessing restoration strategies to improve the biodiversity of degraded reefs, and to create new habitats that contribute to the ecological functioning of urbanized coastal environments. The findings will be relevant in helping to reduce the loss of reef life from future coastal development.

TABLE III: SUMMARY OF CORAL RESTORATION EFFORTS

Location	Habitat type	Coral species	Number of fragments transplanted	Area restored
Kusu	Degraded reef	*Pachyseris speciosa*	120	150 m^2
		Platygyra sinensis	90	
		Pocillopora damicornis	90	
Lazarus East	Seawall	*Pocillopora damicornis*	156	224 m^2
		Podabacia crustacea	104	
		Merulina ampliata	70	
		Platygyra sinensis	68	
		Echinopora lamellosa	36	
		Hydnophora rigida	35	
		Favites pentagona	6	
		Goniopora sp.	5	
		Symphyllia recta	4	
		Favites halicora	3	
		Pavona decussata	3	
		Acanthastrea rotundoflora	3	
		Turbinaria mesenterina	2	
		Turbinaria peltata	2	
		Mycedium elephantotus	2	
		Goniastrea retiformis	1	
		Pachyseris speciosa	1	
		Psammocora contigua	1	
Lazarus West	Seawall	*Echinopora lamellosa*	37	38 m^2
		Platygyra sinensis	32	
		Podabacia crustacea	32	

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