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THE RELEVANCE OF REEF RESTORATION IN THE CONTINUALLY CHANGING MARINE ENVIRONMENT OF SINGAPORE

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Abstract. Singapore’s marine environment has changed significantly over the past five decades through coastal modification and intense human activities. More than 60% of its coral reefs have been lost to land reclamation and the remaining reefs remain exposed to increased sedimentation. Reef restoration to address habitat loss and degradation is considered viable under the changing environmental conditions based on the persisting annual coral mass spawning events, active recruitment, high species diversity and recovery from mass bleaching impacts. These ecological attributes indicate that reef ecosystem integrity is still functioning and restoration measures are relevant. An analysis of past and ongoing restoration initiatives indicates their effectiveness in improving degraded reefs as well as establishing new reef communities on modified coasts.

Keywords: Coral reefs, restoration, degradation, changing environment.

INTRODUCTION

Relentless coastal development in the last fifty years has replaced many of Singapore’s nearshore habitats with coastal engineered structures and resulted in a 65% loss of its coral reef habitat [1, 2]. Today, more than 60% of Singapore’s coastline is lined by seawalls [3]. Impacts from continued coastal development include increased sediment load and reduced water clarity. The lack of sunlight penetration and high turbidity confines coral growth to the reef flat and upper 5 m of the reef slope [4].

Despite the loss and degradation of the country’s coral reef habitat, some prominent ecological resilience indicators are exhibited. They include the maintenance of a high scleractinian coral species diversity of more than 200 [5] with only two known to be locally extinct [4], the predictability of the mass spawning event during the April full moon of each year [6], the vigorous growth of newly-settled recruits [7], and the self-seeding process that maintains larval supply [8]. These provide indications that the reefs are able to tolerate impacts of the changing environmental conditions [9] including the mass bleaching episodes of 1998 and 2011 [10] and that active reef restoration is a viable intervention worthy of consideration. At the same time, natural settlement and development of coral communities on artificial structures such as seawalls suggest new opportunities for reef community growth [11, 12] and that restoration can be applied towards the creation of reefs in novel areas.

Artificial reef initiatives in Singapore began in the early 1970s with the sinking of few non-serviceable vessels by the former Port of Singapore Authority but the effectiveness was not monitored. The first artificial reef programme that was scientifically assessed started in 1988 using hollow concrete tubes and disused car tires lashed into pyramidal formations. These were located at depths of 12 m and not meant for coral development but for fish community development [13]. Subsequent reef restoration initiatives focused on coral development and were carried out at shallower depths that favoured coral community development. Techniques included substrate modification, transplantation of entire coral colonies or fragments, *in situ* and *ex situ* nurseries with various strategies to minimize sediment smothering [7]. It is obvious that the changing environmental condition will continue and there is no likelihood of sedimentation impacts ever reducing. Coastal development and maritime activities will also not slow down. Reef restoration is thus a necessary and relevant intervention.

SINGAPORE'S APPROACH TO REEF RESTORATION

This study reviews past and current reef restoration activities carried out in Singapore that had a scientific assessment component as part of the project. Some of these studies are referenced in Ng et al., (2016). The review includes a current project funded by the Maritime and Port Authority (MPA) of Singapore that investigates restoration of degraded reefs as well as the creation of reef communities in non-reefal areas. All these projects were conducted under the high sediment condition that characterizes Singapore's seas and constant heavy shipping and coastal development activity [14].

The reef restoration projects can be broadly categorized into two groups. The first is substrate modification making use of specialised benthic structures, while the second is coral transplantation. Only one project is known of benthic structures deployed at more than 10 m depth to enhance fish communities [13]. These are heavy hollow concrete modules and tires lashed together. All other substrate modification projects were carried out at shallow depths and made use of lighter and smaller structures that can be manipulated underwater by a single diver and placed at exact locations on a reef to avoid further unnecessary damage to degraded reefs. One such structure is a fibreglass hemispherical module of less than 1 m height and base diameter referred to as a Reef Enhancement Unit (REU). These were deployed on reefs across Singapore's southern offshore reefs in the early 2000s [15]. They were designed with sloping surfaces to reduce sediment accumulation and with holes of varying diameters to promote water flow and effectively served to trap sediment settling within them (fig. 1).

Fig. 1. Fibreglass Reef Enhancement Unit (REU) deployed to increase opportunities or coral settlement and this REU was deployed for more than a decade

The second approach is coral transplantation, which involves physical removal of whole colonies or fragments from a donor site to a recipient site. Entire colonies can be cemented directly to the substrate at the recipient site while fragments can be moved to a nursery and raised to a larger size before they are adhered to recipient sites. *In situ* nurseries are made of stiff mesh net platforms raised above the bottom to reduce sediment accumulation and improve the survival of coral fragments and juveniles [7, 16]. "Corals of opportunity", which are broken live fragmented pieces on the reef floor or recruits settled on loose rubble can be cultured on nurseries [17, 18].

Overcoming sedimentation impact. Observations from reef restoration investigations in Singapore's high sediment conditions showed that sloping surfaces are effective if they are solid [15, 19, 20], while a horizontal surface is effective when the substrate is mesh-like, allowing sediment to fall through instead of accumulating around the base of the corals [18, 21, 22]. This strategy is effective in enhancing growth and survivorship of "corals of opportunity" [23]. However, coral larval settlement on preferred sites may not confer advantages in subsequent development. Initially, coral mortality could be highest on highly sedimented upper surfaces but after a few further months, growth and survivorship could be highest on these surfaces [24]. This indicated the usefulness of making available, different slope inclinations of artificial substrate modules.

Natural recruitment. Juvenile corals were observed on the REUs as early as six months after deployment, and these fared better in terms of survival and growth than those that had been recruited on adjacent rubble on the surrounding reef bed [15]. A decade later, while turf algae still dominated the REUs, there was a significant increase in the diversity of lifeforms, and colonies from ten of the 30 scleractinian genera observed were sexually mature. More than 110 sessile and mobile reef taxa utilized the REUs for food and habitat [19, 20]. The results demonstrated that these structures could serve as environmental engineering tools to help develop biological communities and improve ecosystem functioning in sediment-impacted reefs.

Natural recruitment on seawalls [11, 12] is widespread with large coral colonies and coral recruits (fig. 2). This indicated that these artificial structures are suitable as new substrates or new areas for coral community development. Considering that 60% of Singapore's natural coasts have been replaced by engineered seawalls [3], there is a huge opportunity to transform the seawalls into coral-dominated habitats. The natural process is slow and can be hasten by active restoration.

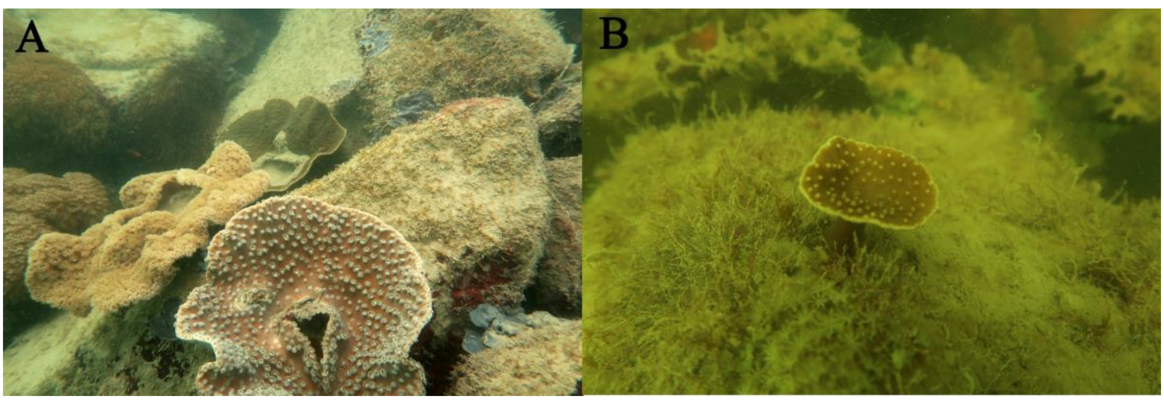

Fig. 2. Naturally recruited coral colonies (A) and juvenile corals (B) on seawalls

Coral transplantation. Among the many coral transplantation studies is the current one supported by the Maritime and Port Authority of Singapore. Following a large-scale transplantation of whole coral colonies from a reef site facing development impact [25], 1580 coral fragments at the site were collected and used as source material to investigate whether restoration with fragments can effectively assist in the recovery of degraded reefs, as well as whether new reefs can be generated in non-reef areas.

The completed first phase of the project established coral nurseries at recipient sites to raise coral fragments collected from the donor site. Fixed horizontal table nurseries were examined to be the most suitable in Singapore's sedimented environment and had the highest coral fragment survival compared to other nursery designs [22]. The structures elevated coral fragments above the sedimented bottom and provided stable substrates for the attachment of fragments. However, routine maintenance of the nurseries to reduce sediment accumulation and proliferation of fouling organisms is required. One year into the project, fragments from 22 hard coral genera that were reared in the nurseries had 92% survivorship [25]. Rearing corals in *in situ* nurseries not only expedited recovery from fragmentation wounds, but also promoted faster post-transplantation growth rates [16]. The coral nurseries also supported abundant and diverse marine organisms [26]. Reef organisms such as juvenile eight-banded butterflyfish, juvenile harlequin sweetlips, chocolate hind and stellate puffer were observed utilizing the coral fragments and nursery structures for food and shelter (see Taira et al., (2016) [27]; fig. 3). These observations highlighted the role of *in situ* nurseries as platforms for reef fauna recruitment and settlement. Coral nurseries can also enhance ecosystem functioning in degraded or non reefal areas while propagating corals for reef restoration.

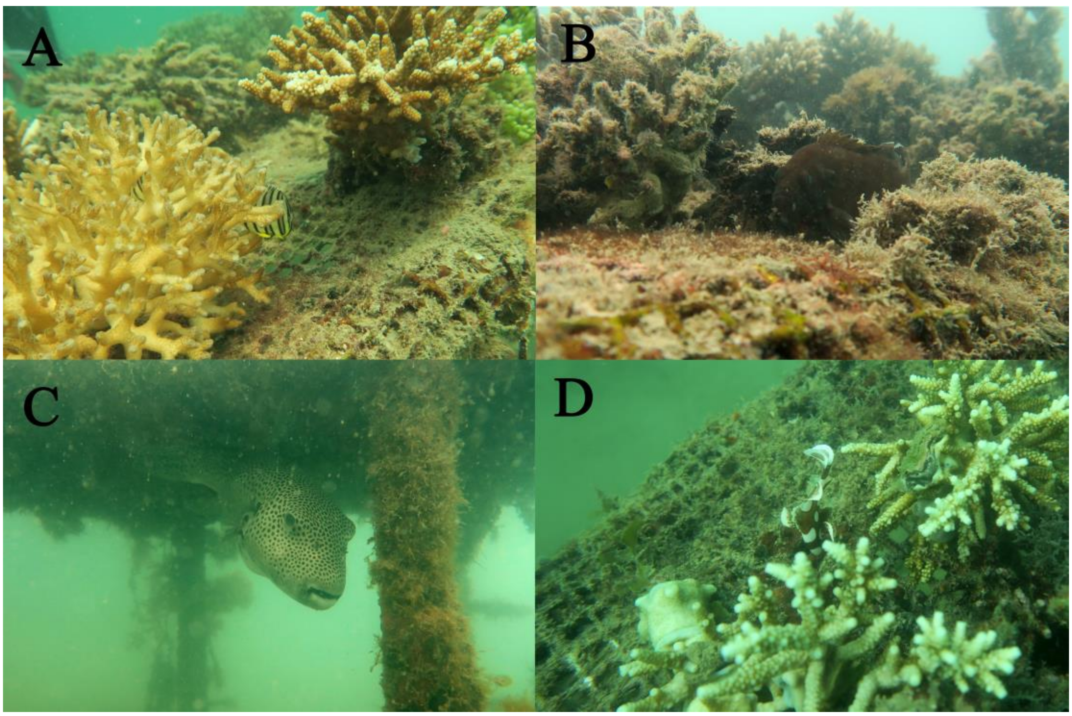

Fig. 3. Reef associated fauna *Chaetodon octofasciatus* (A), *Cephalopholis boenak* (B), *Arothron stellatus* (C) and juvenile *Plectorhinchus chaetodonoides* (D) observed utilising the coral nursery for food and shelter

The second phase of the project involved progressive transfer of coral colonies from the nurseries onto degraded reefs and granite substrates in non-reef areas. After transplantation, coral cover at a recipient site increased from 3% to 20% [28]. The efforts supplemented those from previous restoration projects which reared and transplanted 27 known coral species (see Ng et al., (2016) [7]. Post-transplantation responses have since been gleaned from 47 coral species in Singapore with new growth and survival information (table 1). In the current study, the corals had wide ranging survivorship (0–100%) nine months after transplantation and four species (*Mycedium elephantotus, Turbinaria mesenterina, Pachyseris speciosa* and *Psammocora contigua)* did not survive past 14 months post transplantation. All coral species that survived are deemed suitable for transplanting on subtidal seawalls. Long-term monitoring will be necessary to assess the establishment of transplants at their recipient site and identify resilient species for rehabilitating Singapore's marine environment.

Table 1. Survivorship of 'corals of opportunity' transplanted to a seawall at Lazarus island, Singapore

Species	Number of transplants	Survivorship (%)
Goniastrea retiformis[a]	1	100
Favites halicora[a]	3	100
Goniopora sp. [a]	5	100
Symphyllia recta[a]	4	100
Acanthastrea rotundoflora[a]	3	67
Pavona decussata[a]	3	67
Turbinaria peltata[a]	2	50
Favites pentagona[a]	6	50
Mycedium elephantotus[a]	2	0
Turbinaria mesenterina[a]	2	0
Pachyseris speciosa[a]	1	0
Psammocora contigua[a]	1	0
Acanthastrea echinata[b]	1	100
Cyphastrea microphthalma[b]	1	100
Echinopora gemmacea[b]	2	100
Lithophyllon undulatum[b]	2	100
Turbinaria stellulata[b]	2	100
Hydnophora exesa[b]	2	50
Lobophyllia hemprichii[b]	2	50
Pavona frondifera[b]	1	100

Notes: a: Coral species with transplantation period of 22 months; b: Coral species with transplanted period of 13 months.

CONCLUSION

Reef restoration in Singapore has to address two chronic environmental challenges, which are high sedimentation and unstable reef substrate. Artificial substrates are useful in these respects. The experience so far indicated that reef restoration is viable under changing environmental condition and relevant to slowing down the full extent of the impact. The conventional approach of reef restoration is to rehabilitate degraded reefs in order to improve resilience. It is also possible and worthwhile to incorporate an innovative approach to create new reef communities in areas that did not previously support reefs. However, rehabilitation should be guided by scientific principles in order to ensure optimal outcomes [7]. Long term monitoring and assessment of restoration efforts must be included to evaluate the overall effectiveness of the project and adaptive measures can be implemented to mitigate the impacts of episodic disturbances such as mass coral bleaching.

Management and cost are two other considerations that need to be looked into. Improved marine environment management can enhance the benefits of restoration. Singapore's marine management became more holistic from the mid-1990s to include biodiversity protection [29]. This was when development projects had to account for impacts to living resources including coral reefs. Institutional strengthening was evident from the establishment of the Biodiversity Centre at the National Parks Board in 1993 and the expansion of its mandate to include the marine environment. The recommendations of Singapore Blue Plan 2009, a comprehensive proposal for the Government to designate high marine biodiversity areas, led to the establishment of the Sisters' Islands as Singapore's first Marine Park [20]. The marine park, managed by the National Parks Board, will serve as a platform to conserve and raise awareness of Singapore's marine biodiversity [30]. In addition, St John's Island National Marine Laboratory was launched in 2016 by the National Research Foundation as a facility to advance Singapore's marine science research [31]. Restoration is always expensive and largely contributed by high labour and transportation cost [32, 33]. Innovative ways of reducing it, such as involvement of volunteers, can be adopted. Stakeholders such as government agencies, research institutions and private sectors can collaborate and enhance restoration outcomes [29]. Toh et al., (2016) [28] showed that community engagement can reduce total project expenditure by 5.8%, and that the overall cost effectiveness of such projects could be further improved with greater volunteer involvement. Such efforts are important in generating greater awareness of natural heritage and instilling marine stewardship among stakeholders [34].

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