Enhancing Marine Biodiversity in Singapore's Urbanizing Coastal Environment

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***Abstract*—Urbanization of coastal cities has resulted in extensive physical modification of the coast that is commonly accompanied by habitat destruction or degradation, marine biodiversity loss and ecosystem services decline. Conversion of the natural environment to a human-modified one is often permanent, and it is important that development considerations take into account biodiversity enhancement of the 'new' environment. Development of biological communities in the modified environment takes time and is unlikely to return to levels once supported by the original habitats, but efforts can be made to facilitate the establishment of biodiversity that is suited to the new environmental conditions. Active interventions such as water quality management and ecological restoration can help to transform the urbanized coastal environment into a suitable biodiversity support zone. Observations of marine biodiversity in marinas and restoration of corals on artificial structures in Singapore support this prospect. Assessment of the biodiversity in three marinas indicated that they can function as marine biodiversity refugia, especially with their relatively high artificial structural complexity and when designed with basic ecological considerations to enhance marine biodiversity. Separately, reef restoration projects give rise to the possibility of colonizing seawalls with corals and other reef-associated species, as well as improving degraded reefs and creating reef communities in areas originally devoid of corals due to the heavy sediment load of urbanized coastal waters. Maintaining marine biodiversity in challenging environmental conditions resulting from urbanization can help to ensure continued provision of some level of ecosystem services.**

***Index Terms*—Coastal, urbanization, biodiversity, Singapore.**

I. Introduction

The island nation of Singapore has undergone decades of rapid urbanization especially since the 1960s. Its human population of 1.65 million in 1960 swelled to 5.64 million in 2018 [1]. During the same period, land area increased from 581.5 km^2 to 724.2 km^2 [2] through coastal reclamation. The restricted sea space of about 740 km^2 is intensively used for shipping making Singapore one of the world's busiest ports. In 2018, the port managed over 140,000 vessel arrivals and handled over 630 million tonnes of cargo [3].

Coastal development has been extensive [4] and more than 60% of the country's coastline are now lined by seawalls [5]. Urbanization of the coastal area replaced many of the natural coastal habitats with seawalls or new sandy shores [6]. Original shores are restricted to short stretches of the coastline and are to varying degrees impacted by changes to the immediate adjacent coastal landscape. Singapore's coastal environment is defined by drastic physical change over the last five decades and this is likely to continue well into the future.

What impacts have these changed conditions had on marine biodiversity, and should biodiversity enhancement and management measures be considered? This paper discusses Singapore's coastal urbanization impacts on marine biodiversity and examines biodiversity in permanently changed habitats such as marinas, as well as reef restoration approaches to enhance degraded reefs and create reef communities in new urbanized habitats.

II. The Changing Coastal Environment

Urbanization has transformed much of Singapore's coastal environment [7] and an obvious change is the reduction of sea space arising from land reclamation. Loss of sea space means compression of the already busy maritime activities into a smaller area and intensifying competition for its use by different agencies. Land reclamation has obliterated and diminished the extent of nearshore habitats such as mangrove forests [8], seagrass beds [9] and coral reefs [10]. Habitats located further away from land reclamation and coastal development sites remain affected by the increased sediment load in the sea that causes smothering and reduced sunlight penetration, thus compromising their primary production potential.

Over 60% of natural coral reefs have been lost to land reclamation [10]. For the remaining reefs, a further reduction in the vertical zone that supports coral growth is seen with the lower depth limit raised from 10m in the past when waters were clearer to 6m now [4]. The reduced areal extent of coastal habitats resulted in a decline of abundance for many species but while species reduction has been recorded for some groups, e.g. mushroom corals [11] and pocilloporid corals [12], species richness diminution on the whole has been less apparent [13].

The full extent of Singapore's marine biodiversity richness has not been realized but a relatively recent 5-year Comprehensive Marine Biodiversity Survey from 2010 to 2015 revealed over forty species new to science and over 120 species listed as new records [14], [15]. On-going studies

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indicate high species richness, as new records, rediscoveries and new species continue to be documented [16].

Singapore has a rich marine biodiversity. It is located in close proximity to the coral triangle, a region that is recognized as the global marine biodiversity hotspot [17]. It is also on the periphery of the South China Sea, which is known for its high species richness [18], [19]. Despite the diminishing extent of its natural coastal habitats, species richness does not appear to have declined drastically [20]-[22]. 'New' habitats such as seawalls are actively colonized by intertidal species ranging from 26 to 51 taxa [23], many of which were known to inhabit Singapore's original shore habitats [24].

Other factors that contribute to biodiversity maintenance include the effective measures against marine pollution since the 1960s [13] and significant conservation and management efforts since the 1990s [4]. Prior to the establishment of the Sisters' Islands Marine Park in 2014, the first in Singapore, marine biodiversity protection was embedded in a few Parliamentary Acts [25]. Marine biodiversity protection came under these legislations as well as what was operating as 'de facto' protected areas, which were sites with prohibited public access.

Table I summarizes the impacts that coastal urbanization has on coastal biodiversity and the approaches that can be applied to alleviate them. These can enhance and optimize biodiversity in the modified habitats arising from urbanization so that ecological integrity can be maintained to provide valuable ecosystem services.

TABLE I: URBANIZATION AND COASTAL BIODIVERSITY ENHANCEMENT

IMPACTS	Natural habitat loss. Neighboring habitat degradation. Ecosystem service depreciation. Environmental quality deterioration. Biophysical and hydrodynamic change. Increased exposure to human activities.
MITIGATION	Enhance biodiversity capacity of new habitats. Active restoration of degraded habitats. Effective conservation measures. Environmental quality maintenance.

Two case studies on biodiversity enhancement in Singapore's urban setting are examined, one on marinas and the other on reef restoration. The first shows the opportunities offered by a human modified habitat to support natural colonization and subsequent development of biological communities suitable to the modified conditions, while the second shows the role of active intervention to rehabilitate degraded reefs and to create reef communities in human modified habitats, particularly in areas not known to support coral reefs in the past.

III. BIODIVERSITY IN MARINAS

Marinas are designed to provide sheltered conditions favorable to the berthing of yachts as well as convenient access by users. A variety of structures including seawalls, pilings, floating pontoons surrounding as well as within the marina do provide extensive and suitable submerged substrata (Fig. 1). Together they extend the entire water column from surface to seabed. Collectively, with some surfaces shadowed and others more exposed to sunlight, they offer a range of microhabitats and immense opportunities to different encrusting species, which in turn attract and support motile species. While a marina has displaced the original coastal habitat, it can function as a replacement habitat provided water quality is adequately managed.

Fig. 1. Rich biological community growing on the submerged side of a floating pontoon.

An assessment of epibiotic assemblages established on the submerged sides of pontoons in three coastal marinas revealed a combined diversity of 94 taxa [26]. Taxa at each marina ranged from 43 to 65 and variation in distribution within a marina is influenced by distance of pontoon to the marina entrance, with species richness and abundance declining away from the entrance where flushing is strongest. Biotic and abiotic factors also resulted in distinct assemblages among marinas. This study demonstrates that marinas can support rich epibiotic diversity. Biodiversity can be further augmented by improved pontoon design and layout to increase the capacity of marinas to function more efficiently as a marine biodiversity refugia and consequently contribute effectively to enhancing the ecology of the urbanized coast.

Marinas with their pontoons, pilings, seawalls and modified hydrodynamic conditions serve to aggregate fish. A total of 49 fish species from 31 families were recorded from the same three marinas [27]. One marina closer to mangrove and estuarine habitats harbored more estuarine species, while the other two, which were closer to reef habitats had more reef-associated species. Shade-preferring fish such as *Pempheris oualensis* (Blackspot sweeper,) was common under the pontoons. *Monacanthus chinensis* (Fan-bellied leatherjacket), which is commonly associated with artificial structures was the most abundant species in all three marinas. The structures and encrusting communities provided suitable shelter and food to many schooling and generalist species such as *Siganus javus* (Streaked spinefoot), *Scatophagus* *argus* (Spotted scat) and *Etroplus suratensis* (Pearlspot).

The marinas also supported diverse groups of macrobenthic taxa with a total of 73 taxa from eight phyla recorded, ranging from 48 to 50 taxa in each [28] marina. Taxonomic richness was similar in all three marinas but abundance and community composition differed. Polychaetes dominated all three marinas (80% of total faunal abundance), followed by arthropods, molluscs and echinoderms.

The high proportion of opportunistic and stress-tolerant species within the marina compared to the adjacent open waters suggests that little attention was given to prevent benthic quality deterioration during construction of the marina. This aspect should be looked into in the development of new marinas so that microbenthic populations can be enriched and contribute effectively to the trophic dynamics of the entire water column.

IV. Reef Restoration

The loss of more than half of coral reef habitats to land reclamation and the exposure of the remaining reefs to chronic sedimentation necessitate active restoration interventions. This will complement the observed natural colonization by corals on seawalls and other structures along modified shores [29], [30]. Reef restoration efforts employing techniques that overcome sedimentation challenges have been demonstrated to be viable [31], [32]. These range from the provision of sloping solid substrata [33] or horizontal mesh surfaces that prevent sediment accumulation [34].

In-situ coral nurseries (Fig. 2) have a significant role in reef restoration efforts in a sediment-challenged environment [35]. Studies on two scleractinian species, *Pachyseris speciosa* and *Pocillopora acuta* (previously *damicornis*) [36], indicated that fragments raised in nurseries for five months before being transplanted to the reef substrate, grew significantly faster by three to five times compared to those that were transplanted directly without a nursery phase [37]. The faster growth of transplants in nurseries augmented their size and continued to manifest after they were transplanted to the reef, enabling them to perform better than the directly transplanted fragments.

The coral nurseries themselves also served as microhabitats to enhance biodiversity despite the sedimentation, attracting a large variety of species such as fishes [38] and reef-associated invertebrates [39]. These nurseries also provided opportunities for recruitment, settlement and development of reef fauna. They enhance ecosystem functioning in degraded or non-reefal sites while at the same time nurture coral fragments for transplantation [32].

The biodiversity of artificial substrates developed through natural colonization can be enhanced by active transplantation particularly in the intertidal zone. Natural colonization shows the viability of hard structures such as seawalls as habitats for biological communities [40] and transplantation can further enhance the structure's ecological value. Fragments of five species of scleractinian corals, three species of soft corals and three species of sponges reared in *ex-situ* nurseries prior to transplantation exhibited variable survivorship and growth. The scleractinian coral *Porites lobata*, soft coral *Lobophytum* sp., sponge *Lendenfeldia chondrodes* had high survivorship, rapid growth and extended mean survival times two years after transplantation. Species with massive or encrusting growth forms were best at establishing and developing on the seawall and observed to provide shelter and food for reef fish and gastropods.

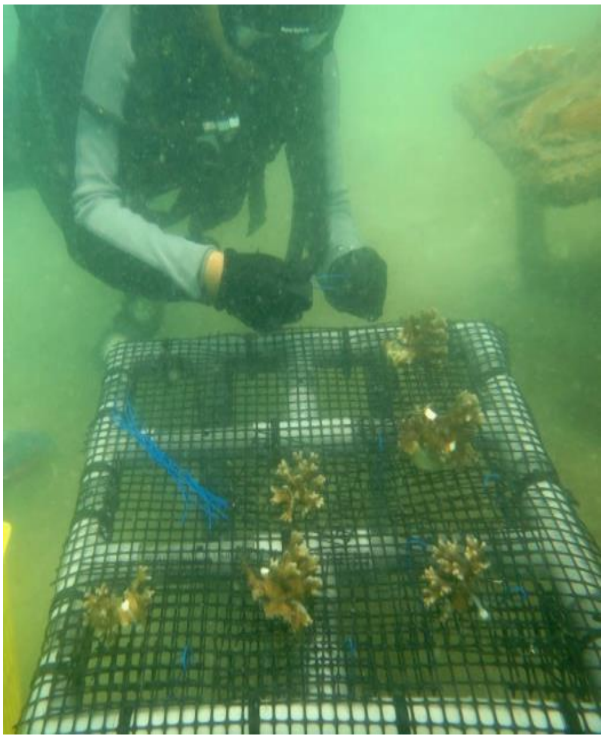

Fig. 2. *In-situ* coral nursery with coral fragments attached.

Active restoration can help to increase the intertidal biodiversity of seawalls but must take into account that not all species can survive conditions offered by seawalls particularly those with an early developing pioneering but competitive community. Similarly, not all species do well when transplanted to subtidal seawalls. Of six species investigated, *Hydnophora rigida*, *Podabacia crustacea*, *Echinopora lamellosa* and *Platygyra sinensis* had sustained growth and survival rates exceeding 90% after six months [41].

The study also showed how involvement of volunteers could lower the labor cost of the transplantation effort. In an ongoing transplantation project that commenced in 2013, 904 coral fragments were transplanted to cover 150 m^2 of degraded reef and to create 272m^2 of 'new' reefs [42]. The 'new' reefs are non-reefal areas on which, coral transplantation was attempted to determine if reef communities could be generated.

Long-term monitoring is essential for assessing the effectiveness of reef restoration efforts [43]. Many restoration initiatives are supported by short-term projects over durations that do not allow for long-term assessment. Sessile lifeform diversity on fiberglass reef enhancement units [43] increased significantly over a span of ten years with hard corals and coralline algae contributing most to the temporal dissimilarity. The reef units augmented ecosystem functioning with 119 sessile and mobile taxa utilizing them for food and shelter.

It is important to consider preserving a locality's genetic diversity when transplanting corals from that source under imminent exposure to development impact. Investigations of four coral species from such a reef showed that 33 to 40% of colonies per species can represent 80% of genetic diversity while more than 50% of colonies represent more than 90% of the species genetic diversity [44]. Hence not all colonies need to be relocated, which help to reduce financial and manpower costs. The research also indicated that for transplantation, colonies of hermaphroditic species can be collected from over a smaller area while gonochoric species over a larger spatial area, the latter having greater genetic variability over larger distances.

V. Conclusions

Coastal urbanization of Singapore as with many other coastal cities, resulted in permanent change to the coastal environment. Land reclamation obliterated original shore habitats and the modified coast is subjected to changed environmental conditions. However, the urbanized coast itself can be viewed as providing new habitats that can support marine assemblages best suited to the conditions they offer e.g. natural coral colonization of jetty pilings [45], [46]. At the same time, biodiversity can be enhanced through interventions that include active restoration, biodiversity conservation and management, and effective measures to contain pollution and water quality deterioration.

Marine biodiversity of urban coastal habitats should not be neglected as it can contribute significantly to the provision of ecosystem services. The marinas supported biodiversity with the establishment of structural complexity throughout the water column and biological communities could developed naturally in them. The reef restoration efforts indicated that enhancement of degraded reef habitats and creation of reef communities in non-reef habitats under high sediment conditions are possible and could be facilitated by active intervention to hasten the process.

Conflict of Interest

The author declares no conflict of interest.

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