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# Rehabilitation of Coral Reefs Exposed to Urbanization and Climate Change Impacts

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**Abstract**: *Over 60% of Singapore's coral reef habitat have been lost to decades of urban development pressure including land reclamation. Underwater visibility of less than 2m due to heavy sedimentation has restricted the healthy coral growth zone to the reef crest and upper 5m of the reef slope. Despite the impacts, coral species diversity has remained high together with predictable coral mass spawning events and vigorous growth of larval recruits. These features suggest that rehabilitation is viable and can improve reef resilience against urbanization as well as climate change impacts. Restoration techniques that are adopted must consider the high sediment environment, destabilized reef substrate, and biological community structure change. It is important to observe coral species dominance since this has shifted to favor those more tolerant of reduced light condition. Rehabilitation can be initiated with the dominant species to stabilize the rehabilitation site within the shortest time. Sloping hard substrates above the silt bottom disallow sediment accumulation and are more suitable for settling coral larvae or attached fragments. Coral nurseries comprising raised mesh-net platforms prevent sediment smothering and improves survival of coral fragments and juveniles. Corals have also naturally recruited and developed on seawalls constructed in areas which, did not support coral reef formation. Innovative design and engineering of structures can facilitate coral growth as sea level rises. Floating reefs and seawalls that incorporate terraced tidal pools can encourage continued growth and development of coral communities. Two approaches considered appropriate to rehabilitating coral communities exposed to impacts of urbanization and climate change are 1) increase live coral cover and diversity of degraded reefs, and 2) create reef communities in non-reef areas.*

**Keywords:** *coral reef, rehabilitation, urban, climate change impacts.*

## 1. Introduction

Singapore's extensive coastal development over the last five decades has resulted in a 60% loss of coral reefs[1,2]. Impacts of this rapid urbanization on the marine environment include increased sedimentation, which reduces underwater visibility and sunlight penetration resulting in healthy coral growth confined to the reef crest and the upper 5m of the reef slope[3]. Despite exposure to continued anthropogenic pressure, the remaining reefs remain vigorous in terms of growth[4], reproduction[5] and recruitment. There is no indication of scleractinian coral species decline[6] and modelling studies showed that the reefs are self-seeding[7] with adequate larval supply. New challenges are posed by climate change impacts. Elevated sea surface temperature caused two major coral bleaching events in 1998 and 2010 but the reefs have since recovered. A few reef rehabilitation projects have been implemented[8] and they demonstrate the feasibility of this intervention under the challenging conditions of urbanization and climate change.

## 2. The Case for Reef Rehabilitation

### 2.1. Improved management

Singapore's coral reefs have not been under any form of legal protection in the past and the lack of an integrated coastal management framework resulted in the low priority being given to their protection. The establishment of the Biodiversity Centre by National Parks Board in 1994 and the expansion of its mandate to cover the marine environment started to address these limitations. Improved management became evident from the mid-1990s when development projects had to account for impacts to living resources including coral reefs. Impact assessments and mitigation measures became embedded in these projects, including coral relocation to mitigate reef loss. At the same time, the formation of an inter-Ministerial Technical Committee on Coastal and Marine Environment in 2007 with representatives from all relevant agencies provided a framework that would support an integrated management approach. A significant step was taken in 2014 when Singapore's first marine park (Sisters' Islands Marine Park) was established, ensuring protection of the reefs there.

## 2.2. Biological attributes

Most of Singapore's coral reefs fringe the southern offshore islands. Reefs along the mainland have been totally eliminated, except for a small reef community at Labrador beach. There are also a few good reef communities associated with the northeast offshore islands. Although the abundance of many species is depressed, species elimination is not that evident. Of the 255 species of hard coral recorded from the reefs[6], only two are confirmed as locally extinct. Historical records depict a rich biodiversity[9] and despite the varied and persistent impacts, new records of species not previously known to occur are still being made today. Singapore's reef biodiversity trend shows that while species elimination is less than expected, the distribution and abundance of many species have been depressed[2].

Coral community structure has changed to favour foliose growth forms with suitably large surface area that can receive as much of the reduced solar energy as possible. Branching *Acropora* corals, which dominate reefs of the region, are now uncommon in Singapore reefs because of past harvesting pressure and present environmental impacts. The intertidal reef flat supports species that can tolerate periods of exposure, such as *Favia*, *Favites*, *Goniastrea*, *Platygyra*, and *Oulastrea*. The reef crest supports the best coral diversity where large colonies of *Porites*, *Diploastrea* and *Symphyllia* are seen. Those that have a foliose or laminar growth form, such as *Pectinia*, *Turbinaria* and *Pachyseris*, dominate the lower reef slope as their large surface area enables them to optimise the available low light energy.

Despite urbanization impacts, important biological processes remain intact. Mass spawning events where many coral species synchronously release eggs and sperm or fertilized egg bundles, occur consistently during the April full moon[5]. This is followed by a smaller event in September or October and timed to coincide with the inter-monsoon lull to improve larval survival. The pomacentrid fish species also spawn during the inter-monsoon periods[10].

Sea surface temperature elevation associated with the El Niño Southern Oscillation (ENSO) events in 1998 and 2010 affected Singapore's coral reefs on unprecedented scales. The 1998 warming caused more than 90% of all corals to bleach and a 20% mortality. The 2010 event caused another mass coral bleaching with a 10% mortality. However, differences in species mortality patterns were observed[11] where species that were badly affected in the 1998 event appear to be less affected in 2010. In both cases, vigorous natural recruitment helped to hasten recovery.

Newly-created and modified habitats continue to support life. Species extinction is not high, as many are redistributed by the changing seascape. Ecosystem processes have not been completely overwhelmed. Seasonal mass spawning of corals, recruitment and growth patterns of other marine species all indicate that ecological integrity is still maintained[4].

## 2.3. Relevant reef rehabilitation approaches

Marine environment utilization remains intense and there is a need to examine approaches that not only minimizes coral reef degradation but also enhances coral establishment in degraded reefs and non-reef areas. Reef rehabilitation can help to reduce the rate of loss as well as reverse the trend. Research should address 1) how effectively restoration can assist recovery of degraded reefs, and 2) whether 'new' reefs can be created from transplanted corals.

Coral nurseries, whether *in situ* or *ex situ* play important roles by acting as reserves to protect the diversity of reefs facing impending impact from coastal development, particularly sedimentation. The establishment of coral nurseries is a useful initial step in rehabilitation as they serve to protect coral fragments in a more secure environment until they reach a suitable size for transplantation where their chances of surviving are increased[12,13]. *In situ* nurseries with stiff mesh net platforms raised above the reef bed are most relevant in high sedimentation conditions where sediment accumulation around coral fragments is prevented.

Studies involving the rearing of 'corals of opportunity' (i.e. naturally fragmented corals or coral juveniles that have recruited on loose rubble)[14] and nubbins (small fragments)[15] have shown that appreciable survivorship and growth rates can be achieved in Singapore's sediment-impacted waters with the use of carefully sited *in situ* coral nurseries. These studies have also highlighted the feasibility of establishing coral nurseries in reefs that will be directly affected by coastal development in order to preserve scleractinian genotypes from these localities.

Under conditions of urbanization impact, rehabilitation success can be enhanced by observing coral species that have become dominant as they have adapted well to changed environmental parameters. Rehabilitation can be initiated with the dominant species to stabilize the rehabilitation site within the shortest time and research on community structure dynamics is important. While the initial emphasis is on the adaptable species, the holistic approach necessitates the use of other species so that rehabilitated reefs retain sufficient species diversity.

## 2.4. Rehabilitation for the future

Seawalls are a common engineering feature in urban coastal settings. Their primary functions are to prevent erosion of reclaimed land and resist strong storm surges. They need to be raised to retain their defensive role against sea level. Seawalls provide a hard substrate that is suitable for coral recruitment and growth and such natural recruitment has been observed[16]. The study showed that depth influenced the distribution of coral communities on the seawalls and only the chart datum zone supported coral growth. Active restoration enhanced the biodiversity of this zone of the seawall[17]. Seawalls line more than 60 percent of Singapore's coastline[18] and offer a huge potential as alternative areas for coral community development. The potential can be enhanced by increasing the surface complexity of seawalls[19].

Eco-engineering of seawalls can optimize their role further so that they not only provide defence against sea level rise, but also provide alternative sites for habitat development. Incorporating terraced cells that simulate tidal pools can increase the zone for coral community growth up to the high tide level as they are filled during high tide and retain water as the tide ebbs. These cells should be sufficiently large and deep to prevent overheating and evaporation of the contained water. Variation in size, height, volume and shape will increase the difference in environmental conditions within and between them so that they become more conducive in sheltering and supporting a greater diversity of reef species.

Another approach is to have floating reefs where coral and other reef-associated species are placed on support structures attached to a floating platform, which overcomes the impact of sea level rise. The platforms can be towed to areas of stronger water flow or the support structures lowered to deeper depths when sea surface temperature elevates, so that the corals are less exposed to bleaching.

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