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HARD CORAL ASSEMBLAGES ON SEAWALLS IN SINGAPORE

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ABSTRACT. — Singapore's shores have been extensively modified to meet the rising demands of economic and recreational activities, and seawalls are a resultant ubiquitous feature of the island state's coastline. In spite of the harsh environmental conditions, seawalls in Singapore are known to harbour rich intertidal communities. This study surveyed the hard coral assemblages at zones immediately above and below the chart datum of seawalls at the southern offshore islands. Seventeen genera of hard corals were recorded. Zones below chart datum had greater diversity (14–15 genera; 17 colonies/m^2) than those above (10–14 genera; 7 colonies/m^2) and of the physical characteristics analysed, only depth influenced the distribution of coral communities on seawalls. With increasing deterioration of natural reefs and degradation to loose rubble, the results indicate that seawalls can provide a suitable substrate for the recruitment and growth of hermatypic corals. If appropriately designed, seawalls can assist in the recolonisation of corals and reef communities and function as cost-effective forms of artificial reefs.

KEY WORDS. — Ecological engineering, scleractinian communities, seawalls, Singapore

INTRODUCTION

Nearly 40% of the global population resides within 100 km of the coast (Burke et al., 2011). Accompanying the increase in coastal population and urbanisation is extensive modification of coastal landscapes to support the rising demands from escalating numbers of commercial, residential and tourism-related activities (Bulleri & Chapman, 2010). Reclamation has expanded the land area for development and redefined coastlines, while urban infrastructure such as jetties, marinas and seawalls have become increasingly common to cater to the popularity of marine-based recreation as well as the demand for seafront housing (Kenchington, 1993; Pow, 2011). As with land-use activities that have been shown to disrupt the capacity of freshwater and forest ecosystems and cause significant downstream effects (Foley et al., 2005), the marine environment and its associated biodiversity are similarly impacted by coastal engineering. Alterations to coastal areas can severely affect the provision of ecosystem services. Examples include the reduction of nursery capacity (and subsequently reproductive capacity of associated organisms) from mangroves obliterated for aquaculture (Primavera, 2006) and the decline in beach nourishment from coastline erosion caused by the mining of sand (Chua, 2006). Additionally, the installation of artificial structures can cause the proliferation of biological invasions or the growth of biota that is disadvantageous to the economy (Bulleri, 2005; Glasby et al., 2007).

The ecological impacts of modifying the natural environment and replacing it with artificial structures can be substantial at local and regional scales (Airoldi et al., 2005). However, in areas which have already undergone coastal development, novel habitats may be created that can be conducive for the recruitment and establishment of certain species. For instance, assemblages of corals, molluscs, fish and algae have been observed to proliferate on seawalls, pilings and breakwaters, showing that such infrastructure may be able to help support some biodiversity (Rilov & Benayahu, 1998; Bulleri & Chapman, 2004; Wen et al., 2007). It has been suggested that these man-made environments cannot be considered as surrogates for natural ones, as fundamental ecological processes can be different between natural and artificial habitats (Bulleri & Chapman, 2010). In light of the degradation of ecologically important habitats such as mangroves and coral reefs however, it is imperative that artificial structures in marine ecosystems be assessed for their potential as reserves (García-Gómez et al., 2010).

The coasts of Singapore are heavily utilised for various economic and recreational purposes. Increasing land engineering in recent decades has altered the coastlines and replaced much of them with steeper sandy beaches, jetties, marinas and seawalls (Chou, 2006). Such developments have inevitably affected the biota associated with the original habitats, but there is appreciable biodiversity in these modified marine habitats. Soft corals, sea fans and tunicates have been observed to flourish on wharf pilings (Chou, 2006). The number of scleractinian species and coral cover on pilings of a jetty at Pulau Hantu (an island south of the mainland) were greater than that of the adjacent reef slope (Chou & Lim, 1986). A variety of organisms from the pelagic (fish of various trophic levels and niches) to the benthic (polychaetes) was recorded in one marina (Chou et al., 2004), while scleractinian surveys in two others revealed considerable diversity on their rock bunds (Chou et al., 2010; Tan et al., 2012).

Seawalls are ubiquitous artificial marine structures on engineered coastlines worldwide. Relatively homogeneous in design and material, they range from a consolidation of large granite rocks arranged on a steep inclination to cement walls built perpendicularly to the seabed. They function to reduce wave impact and protect against coastal erosion (Bulleri & Chapman, 2010). Seawalls can be categorised as intertidal, where the base of the wall is built above chart datum (CD), or subtidal (base extended below CD), and both are common on many of Singapore's reclaimed shores. Despite being subjected to extreme environmental conditions and having limited zones for the recruitment of organisms, the seawalls at the southern offshore islands are known to harbour relatively rich intertidal communities. These include various crustaceans, gastropods, bivalves, macroalgae and cyanobacteria (Chim & Tan, 2009; Lee et al., 2009; Lee & Sin, 2009). Other biota such as scleractinian corals have also been observed but are not well documented.

The number of coastal defence structures is predicted to rise significantly in the coming decades in response to the threat of rising sea levels and potential for increasing frequency and severity of storms (Thompson et al., 2002). Research into the biological communities that can survive on seawalls is necessary to better understand the ecological implications of these structures and to improve aspects of their management, such as incorporating various ecological engineering techniques to enhance their value as marine habitats (Chapman & Underwood., 2011). This study documents the assemblages of scleractinian corals that have naturally recruited on the intertidal zone of seawalls at the southern islands of Singapore and provides an indication of the scleractinian diversity that can survive above the intertidal range.

MATERIAL AND METHODS

Study sites. — Scleractinian coral surveys were conducted between August and December 2009 on seawalls of seven offshore islands south of mainland Singapore: Satumu, Hantu, Kusu, Sisters, Semakau, St John's, and Lazarus (Fig. 1). These seawalls were selected due to their close proximity to existing natural reefs and a potential source of coral larvae. The seawalls at three islands (Semakau, St John's and Lazarus) extend beyond CD to depths ranging from 2.5 to 8.1m and are considered as 'subtidal seawalls'. Those at the other four islands (Satumu, Hantu, Kusu and Sisters) have bases around CD before levelling out to a sandy substrate and are referred to as 'intertidal seawalls'. Seawalls at the islands of St John's, Kusu, Hantu and Semakau were assembled with granite rocks only. Those at Semakau and Satumu were constructed from granite rocks with grouting, while those at Lazarus were made of concrete. With the exception of the seawalls at Lazarus which stand perpendicular to the seabed, the intertidal seawalls were 15–35 years old and angled at 45–60°, while the subtidal seawalls were 7–11 years old and angled at 33–37.5° (pers. comm., Surbana Corporation Pte Ltd).

Survey methods. — Hard corals on subtidal seawalls were surveyed by demarcating two zones above (0m to +0.4m) and below (-0.4m to 0m) CD, with reference to the 2009 Singapore Tide Tables (MPA, 2008) and a Uwatec Aladin Prime dive computer. Tidal height data were derived from stations nearest each study site, i.e. Raffles station for Satumu; Bukom station for Hantu and Semakau; Tanjong Pagar station for Sisters', St John's, Kusu and Lazarus. As coral colonies were spaced some distance apart from each other on these seawalls, line intercept transects (a method commonly used to survey coral cover) were deemed inappropriate to sufficiently represent the scleractinian diversity on the seawalls. Instead, belt transects were employed. Three 20-m belt transects at 5 m intervals were established per zone, with six transects for each subtidal seawall (three above and three below CD; belt width 66-74cm) and three transects for each intertidal seawall (belt width 46–57cm). On intertidal seawalls, surveys began from where the base of the seawall met the sandy

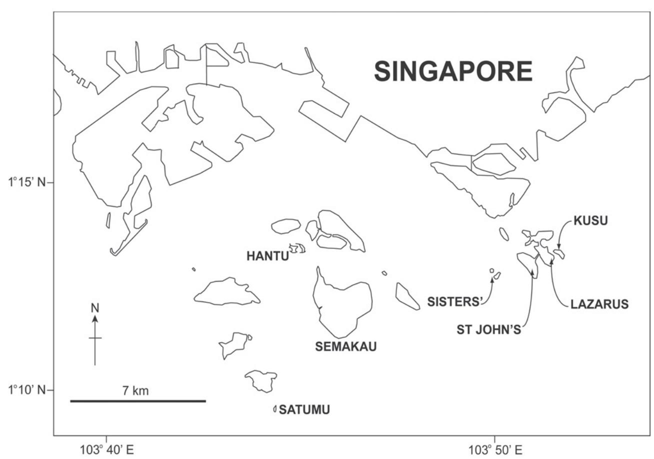

Fig. 1. Map of mainland Singapore and offshore islands. Scleractinian surveys were conducted on the seawalls of the islands indicated.

substrate till 0.4m above it. In total, seven zones above CD and three zones below CD were surveyed. A coral colony that was partially in a belt was counted if more than half of it was within the belt transect. All scleractinian corals were identified in the field to genus.

Data analysis. — Multi-dimensional scaling analysis was performed with the Vegan package for R (Community Ecology Package, version 1.15-1) (Oksanen et al., 2009) to investigate if the scleractinian communities at each site were influenced by the physical properties (depth, age, material and angle of inclination) of the seawall, using the function 'envfit'.

RESULTS

A total of 1216 colonies of scleractinian corals from 17 genera were recorded. Genera present in all study sites were *Cyphastrea*, *Favia*, *Favites*, *Galaxea*, *Goniastrea*, *Goniopora* and *Porites*. *Pectinia* (14.5%), *Platygyra* (11.5%), *Porites* (11.2%), *Goniastrea* (9.4%) and *Merulina* (8.6%) accounted for more than half of all the colonies surveyed. Zones that were above CD had fewer genera (10-14) and colonies (61-94) than those below CD (14-15 genera; 220-255 colonies) (Fig. 2).

MDS analyses indicated that hard coral communities of zones above CD and those below CD were significantly differentiated at 75% similarity (Fig. 3). These differences could be explained by the prevalence of *Lobophyllia*, *Pectinia*, *Merulina* and *Fungia* colonies on zones below CD. Of the physical parameters investigated, material, age and angle of inclination of the zone did not influence the distribution of coral communities significantly. The only parameter to significantly affect coral distribution was the depth of the seawall ($p < 0.05$).

DISCUSSION

Recent studies have shown that the diversity on artificial structures differs from those on reefs (Bulleri & Chapman, 2010). Consistent with these observations, the present study illustrated that scleractinian diversity on seawalls in Singapore is poorer than that of the natural reefs (17 genera on seawalls versus 56 on reefs) (Huang et al., 2009). Coral cover on the seawalls was not quantified in this study, but it was observed that colonies averaged one metre apart from other colonies. The most abundant genera on the seawalls (*Pectinia*, *Platygyra*, *Porites*, *Goniastrea, Merulina*) are also common on Singapore reefs (Huang et al., 2009) demonstrating that seawalls in Singapore are able to function as a suitable substrate for the recruitment and growth of some scleractinians.

Scleractinian communities on seawalls may instead be more comparable to those found on rocky shores. The former are subjected to environmental fluctuations similar to those on rocky shores, such as periodic inundation by the tides, pounding from waves, and irregular salinities (Thompson et al., 2002). These physical stresses are amplified at the upper intertidal zone, thus confining the distribution of scleractinian corals to the lower intertidal regions and beyond where environmental fluctuations are reduced. Nevertheless, only certain corals can withstand the stresses in such regions. Comprising mainly massive or encrusting growth forms, eight (*Goniastrea, Platygyra, Porites, Favites, Favia, Galaxea, Goniopora, Oulastrea*) out of the nine genera on seawall zones above CD can also be found 0.1-0.3m above CD at the natural rocky shore at Labrador Nature Reserve where 11 genera were recorded (Huang et al., 2006). This suggests that scleractinian assemblages of seawalls within

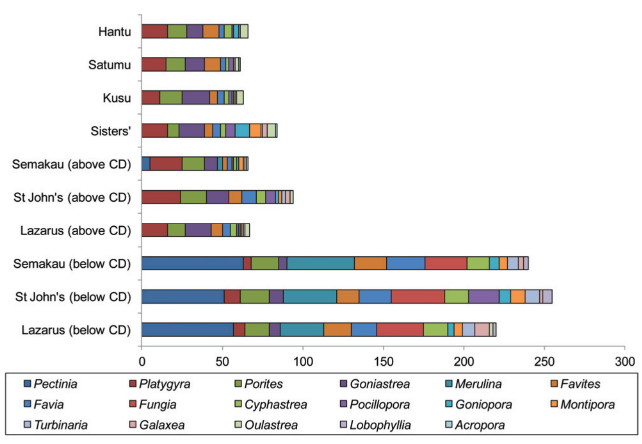

Fig. 2. Diversity of scleractinian corals on seawalls at the southern offshore islands of Singapore (CD = chart datum).

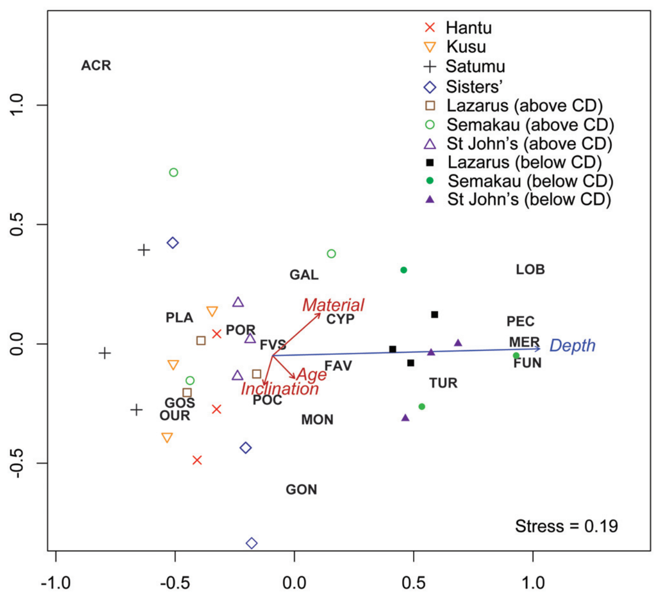

Fig. 3. Non-metric multidimensional scaling plot showing distribution of hard coral assemblages on seawalls of Singapore's offshore islands. Shaded symbols represent zones below chart datum (CD), and unshaded ones refer to those above. Physical parameters affecting hard coral distribution are represented by vectors, of which only depth (represented by the blue vector line) significantly influenced distribution. (ACR: *Acropora*; CYP: *Cyphastrea*; FAV: *Favia*; FUN: *Fungia*; FVS: *Favites*; GAL: *Galaxea*; GON: *Goniopora*; GOS: *Goniastrea*; LOB: *Lobophyllia*; MER: *Merulina*; MON: *Montipora*; OUR: *Oulastrea*; PEC: *Pectinia*; PLA: *Platygyra*; POC: *Pocillopora*; POR: *Porites*; TUR; *Turbinaria*).

this tidal range can be similar to communities of low-shore taxa on rocky shores and other seawalls (Bulleri et al., 2005; Moschella et al., 2005).

Some scleractinian genera (*Fungia*, *Lobophyllia*, *Merulina* and *Pectinia*) were only found on subtidal seawalls but not intertidal ones. Apart from the seawall at Lazarus, all the intertidal seawalls are older and steeper than the subtidal seawalls. Although aged substrate may enhance biodiversity (Burt et al., 2011) and steeper slopes provide less area for habitat colonisation (Chapman & Underwood, 2011), only depth had significant effects in shaping coral cover and diversity on seawalls in Singapore. While the transects surveyed on subtidal seawalls were wider, there were more colonies per unit area (17 colonies/m^2) on subtidal seawalls than intertidal ones (7 colonies/m^2). Subtidal seawalls extend below chart datum and may facilitate the growth and survivorship of more coral species as there is more environmental stability. In contrast, apart from more extreme variations of temperature, light and salinity, intertidal seawalls are constructed on sandy or silty bottoms and the resultant scouring from sediment particles tossed up by wave action may increase mortality and reduce diversity. Genera that were prevalent on zones below CD are less tolerant of such conditions. At the higher intertidal zones, free-living *Fungia* colonies can be flipped over frequently by wave action, fleshy *Lobophyllia* colonies can be injured by sand scour, while fragile *Merulina* and *Pectinia* can easily be fractured by flotsam smashing against the seawall.

Least common on the seawalls were colonies of *Acropora* (0.2%), *Goniopora* (2.8%), *Lobophyllia* (0.9%), *Montipora* (2.7%) and *Turbinaria* (2.3%). The scarcity of these genera suggests low recruitment and/or high juvenile mortality and reinforces the understanding that seawall environments are generally challenging towards the settlement, survivorship and growth of many scleractinian corals. However, the results indicated that coral growth on these artificial structures is still possible and if appropriately designed, seawalls may be able to function as an artificial reef. Early colonisation of this rock substrate by the more common corals such as the faviids may pave the way for the formation of a reef framework that provides microhabitats favourable to post-recruitment growth and survivorship, especially for the less hardy species. This is especially pertinent in a climate of declining global reef health.

In Singapore, reefs are impacted by chronic sediment stress resulting from anthropogenic activities, as well as the degradation of parts of the reefs into loose rubble. These unconsolidated substrates are unstable and can be shifted about by currents, leading to high post-settlement mortality despite scleractinian larval sources being non-limited (Guest et al., 2005). A stable substrate would help to negate this problem. Although substrate stabilisation or the deployment of artificial structures (Loh et al., 2006) are possible options for reef restoration in Singapore, existing seawalls can also be considered as a cost-effective form of artificial reef. Apart from protecting the coast, as illustrated in this study, they are able to provide appropriate surfaces for coral recruitment at shallow depths of up to 0.4m above CD. Seawalls may not be equivalent surrogates to natural ecosystems (Chapman & Bulleri, 2003), but with increasing reef degradation, possibilities of refuge on these artificial structures may exist for some scleractinian genera (Wen et al., 2007).

Although the building of coastal defence structures can be detrimental to the original biodiversity in an area, proper planning and design combining aspects of biology and engineering may help to ameliorate the impacted environment. Apart from having the potential to act as ‘stepping stones’ (Airoldi et al., 2005) and connect communities of intertidal taxa, seawalls can aid in increasing available habitat for hard corals. The results indicate that scleractinian diversity increases with the depth of inundation of the seawall. This suggests that seawalls extending below CD could assist scleractinian recolonisation and reef establishment. If the coastal geography favours the creation of intertidal seawalls, they might be modified such that the base of the seawall is extended seaward with granite boulders to increase the range of the lower intertidal zone so that environmental fluctuations are reduced. This would facilitate scleractinian survivorship and growth on the stable and hard substrate and decrease mortality from sand-scouring of colonies nearer to land.

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