Current Status of Coral Reef Restoration in Singapore

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Abstract

Since the mid-1960s, Singapore's coral reefs have been impacted by a variety of anthropogenic disturbances such as coastal development, land reclamation and seabed dredging. Up to 60% of reefs have since been lost, and the remaining ones are more compact and shallow due to chronic sedimentation and unstable bottom rubble that is easily moved about by currents. Since the late 1980s, various attempts at restoring and rehabilitating Singapore's reefs were initiated and an appraisal of these efforts is timely. We reviewed these reef restoration experiences and synthesized the lessons that are useful for future restoration strategies. The restoration approaches to date broadly include: mitigation measures, substrate modification, optimising methods for rearing scleractinian larvae, use of fragments and corals of opportunity (i.e. naturally fragmented corals and coral juveniles that have recruited on loose rubble) in *in situ* and *ex situ* coral nurseries, as well as transplantation of nursery-reared coral juveniles and fragments to degraded reefs and seawalls. The *El Niño* event in 2010 elevated sea surface temperatures and caused widespread bleaching of hard corals, which affected reef restoration efforts. However, the episode offered insights into the bleaching susceptibility of certain species as well as their suitability for rearing in nurseries and transplantation to other environments. The results from the various projects underscored the need to incorporate adaptive and flexible management strategies in reef restoration and the experience can be applied to future reef restoration to improve success.

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Introduction

Coral reefs are one of the world's richest and most biologically diverse ecosystems. They provide food, shelter and nursery grounds for a wide range of marine organisms – such as over 800 species of scleractinian corals and 4000 species of reef fish – and also supply various resources (e.g. seafood, pharmaceuticals, aquarium trade, tourism) and ecological services (e.g. coastal protection, carbon sequestration) (Moberg & Falke 1999; Burke et al 2011). These ecosystem goods and services have been estimated at a staggering US$375 billion annually (Costanza et al 1997). Coral reefs are thus critical to 40% of the global population who reside within 100 km of coasts, and even more so for some 275 million people living 30 km from the reefs (Burke et al 2011).

However, coral reefs are in a rapid state of decline as a consequence of anthropogenic activities – 19% have since been lost and up to 75% are imperilled by local and global threats (Wilkinson 2008; Burke et al 2011). Destructive fishing practices, coastal development and watershed pollution comprise the majority of local threats, while global factors such as climate change and ocean acidification are mounting stressors that endanger the future of reefs (Burke et al 2011). While reef restoration is deemed a poor substitute to habitat conservation, the former is increasingly employed as an active intervention method to assist in the rehabilitation of damaged reefs, because leaving the reefs to recover by themselves may be too slow and ineffective. Various techniques have since been attempted, ranging from stabilising the substrate, deploying artificial reef structures, establishing nurseries to rear sexual and asexual coral recruits, and transplanting coral material to target localities (e.g. Clark & Edwards 1995; Rinkevich 2005; Raymundo et al 2007; Edwards 2010).

Singapore's marine environment

Singapore is one of the world's busiest shipping hubs, with 80% of its territorial waters managed as port waters and the remainder utilised by sectors ranging from the military, petrochemical industries, aquaculture, to recreation (Chou 2008). To cater to the various demands arising from rapid development and population growth, extensive coastal development has been carried out since the 1960s. Much of the southern and north-eastern coasts of the mainland, as well as the southern offshore islands, have been reclaimed, and total land area has increased by more than 20% (Chou 2008). Coastal defence infrastructures such as seawalls are also ubiquitous, comprising more than 60% of the country's coastlines (Lai WYS, pers. comms.). Based on projections by the Singapore government, land area is expected to increase from the current 71000 hectares to 76600 hectares by the year 2030 (Ministry of National Development 2013).

As a result of the extensive coastal development, land reclamation and regular dredging of shipping channels over the past 50 years, Singapore's coral reefs, mainly located at the fringes of the southern offshore islands, are severely impacted by habitat loss and degradation. The present reef area at 13.25 km^2 is much reduced from an estimated 39.85 km^2 in 1953, with decreases in intertidal and subtidal coral reef areas by over 61% and 89% respectively since 1953 (Tun 2012a). Further decline in reef area is expected due to the proposed reclamation to meet land use demands by the year 2030 (Ministry of National Development 2013). In addition to direct habitat loss, high sediment loads are a major contributor to reef degradation. Sedimentation rates measured off the southern offshore islands have indicated levels as high as 44.64 mg/cm^2/day (Low & Chou 1994), smothering corals and increasing coral mortality. The high sedimentation rates also attenuated light in the water column and resulted in underwater visibilities of 2-3 m in the past decade compared to 10 m in the early 1960s (Fig. 1a; Chou 1996). The drastic reduction of light required for corals to photosynthesise resulted in the reefs compacting to shallower depths (Chou & Tun 2012). Many parts of the reef substrata have also degraded, becoming fragmented and unconsolidated especially on the reef slopes where loose rubble is frequently shifted about by currents (Fig. 1b; Chou & Tun 2012).

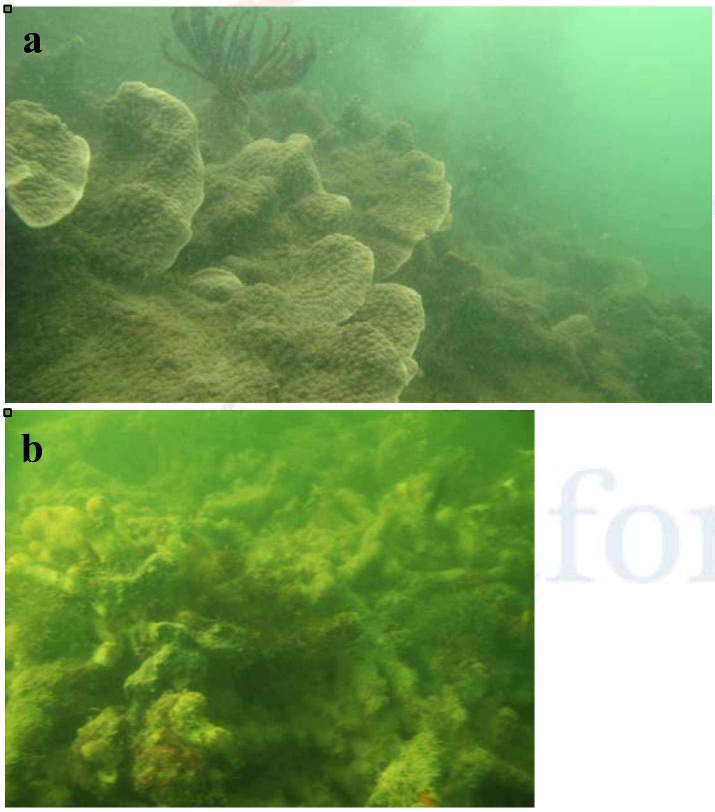

Fig. 1. Coral reef establishment in Singapore is limited by low light due to the high sedimentation (a), and loose, unstable substrate (b). Photo credits: Ng CSL.

Nevertheless, from recent species distribution assessments, Singapore reefs host 255 hard coral species which is approximately one-third of the world scleractinian diversity (Huang et al 2009), in part due to the annual coral mass spawning events that contribute to the seeding of local reefs (Guest et al 2005; Tay et al 2012). Yearly monitoring of the mass spawning events conducted by local researchers also indicated that coral larval sources are not limiting (Tun 2012b). However, coral larvae end up recruiting on loose rubble or unstable substrate, thereby affecting their post-settlement survival rates (Fox 2004).

There is thus a need to explore approaches to circumvent the problems of high sediment loads and unconsolidated substrate, in addition to promoting coral establishment in reef areas that are degraded or destroyed by coastal development.

The plethora of reef restoration projects that has been attempted in Singapore varied in scale and design, and can be broadly categorised as the following: mitigation, substrate modification, coral nurseries, and transplantation. Two decades after the initial reef restoration projects, it is now opportune to examine the effectiveness of these approaches. In this paper, we review the literature on Singapore's reef restoration experiences and synthesise the knowledge acquired. This will help shape future reef restoration strategies and will be relevant to localities with similar environmental conditions.

Mitigation

One of the earliest attempts at reef restoration was mitigation, which involved restitution procedures to compensate for reef habitats facing impending loss or damage (Edwards 2010). Coral colonies or fragments are removed from areas primed for coastal development ('donor sites') and transplanted to secure locations ('recipient sites') where they could establish themselves and continue to grow. This was a management response popularly employed in the coastal waters of the South China Sea by both government and non-government agencies (Chou et al 2009). In Singapore, this entailed the relocation of entire coral colonies away from sites destined for land reclamation. Two such exercises, Reef Rescue 1 and Reef Rescue 2, were conducted by volunteers of the Nature Society Singapore (a local NGO) in 1991 and 1993 (Chou & Tun 1997). As Buran Darat and Pulau Ayer Chawan were to be reclaimed, large coral colonies of various genera and growth forms as well as other reef invertebrates were collected from these areas and placed in large tubs of seawater, then transported to nearby Sentosa Island where they were transferred into containers and brought to the recipient site by divers and snorkelers. However, the recipient site was a shallow area (3-4 m depth at mean spring tides) that was constantly subjected to surge from high-speed vessels and high sedimentation from the nearby reclamation works, and as the coral colonies were merely wedged between boulders without the use of adhesives or ropes, they were easily dislodged by wave action. On subsequent surveys, many colonies were overturned and overgrown with algae. As a result, less than 11% of the transplants survived (Chou et al 2009).

Important lessons which helped shape future coral transplantation efforts were learnt, i.e. recipient sites in Singapore waters are best positioned 3-6 m deep to reduce fouling by macroalga which commonly occurs at shallower depths; transplants should be secured adequately to the recipient sites with adhesives to facilitate growth and survival; and massive and encrusting corals can survive relocation better (Chou & Tun 1997). With the commissioning of more relocation projects in the mid-2000s, scientific groups and environmental consultancies have since learnt from the mistakes of the earlier volunteer-led efforts and improved on their coral relocation strategies.

Substrate modification

An unstable reef substrate leads to current-induced abrasion and the burial of coral recruits, and is thus detrimental to the post-settlement survivorship of corals (Fox 2004). Consequently, substrate stabilization and modification was introduced as a means to facilitate coral establishment. One of the approaches was to provide stable recruitment surfaces in the form of artificial reefs to increase opportunities for coral recruitment. In 1989, precast hollow concrete modules and pyramids assembled from disused rubber tyres were deployed at depths of 15 m on a patch reef near Pulau

Hantu (Fig. 2a, 2b; Tan et al 2010), acting primarily as fish aggregating devices. Fish abundance and diversity increased around the artificial reefs within 1½ years with large fish preferring the concrete modules and small juveniles favouring the tyre-pyramids, as the latter contained crevices suitable for small fish to take refuge in (Chua & Chou 1994). Diversity and abundance of the fish communities reached equilibrium over seven years (Tan et al 2010). Interestingly, the encrusting assemblages growing on the concrete frames were more diverse than those on the tyre-pyramids. Soft corals recruited on the concrete modules, but on the tyres, hydroids and sponges were the dominant colonisers (Han et al 1994). For the purposes of reef restoration, concrete was found to be a more suitable material than rubber, possibly as processed rubber was more toxic and concrete was a more stable substrate (Han et al 1994). The depth of artificial reef installation is also an important consideration, especially since light penetration is reduced and scleractinian coral growth is restricted to the shallows in Singapore waters.

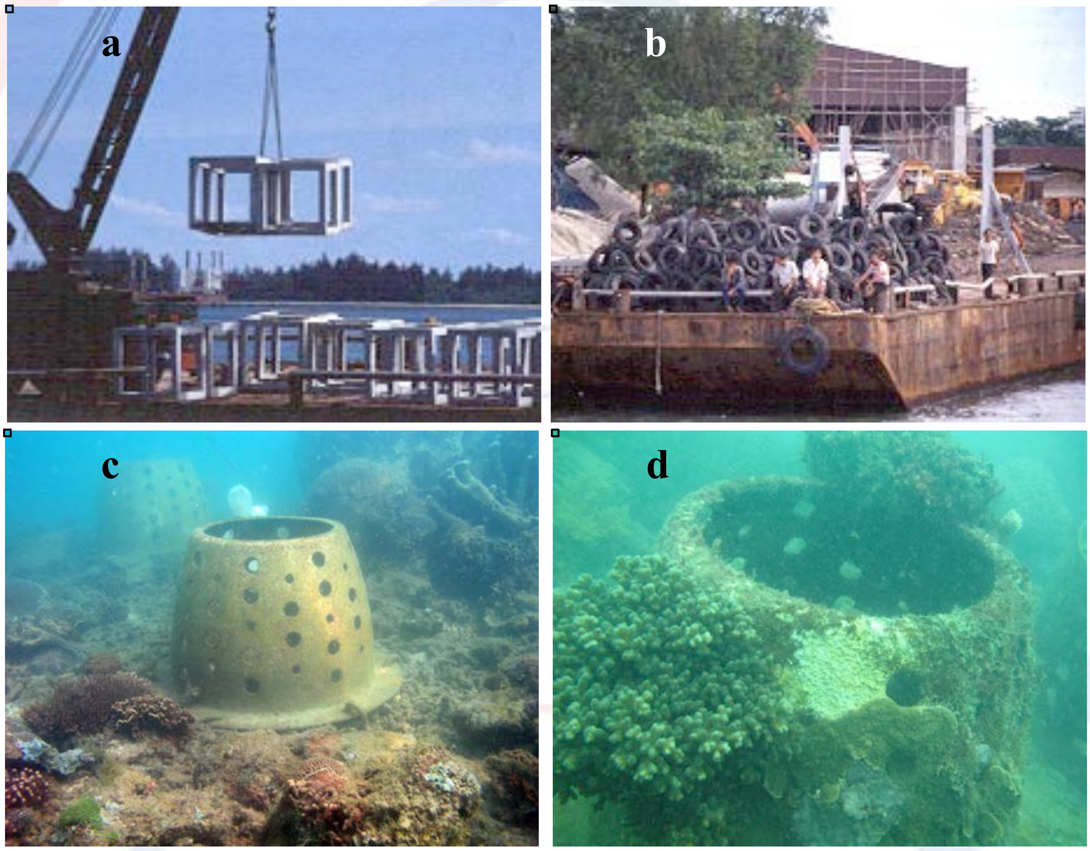

Fig. 2. Artificial reefs in Singapore. Deployment of concrete modules (a) and tyre-pyramids (b) with the use of barges; newly deployed Reef Enhancement Units in 2003 (c); Reef Enhancement Unit in 2013 (d). Photo credits: Reef Ecology Study Team (a, b, c), Ng CSL (d).

A decade after the first artificial reefs were established in Singapore, Loh et al (2006) observed that installing the concrete modules and tyre-pyramids required the use of barges, which were potentially destructive and inefficient if used in shallow areas where artificial reefs are recommended to be sited. Fibreglass modules known as Reef Enhancement Units (REUs) were fabricated and they were light enough to be stabilized at exact locations by SCUBA divers to prevent any unintended damage to other reef organisms (Fig. 2c, 2d). The steep sloping surfaces of the REU precluded sediment accumulation and the perforated sides facilitated water movement through the structure. The modules were anchored securely by stakes to bare patches on the reefs at St John's Island and Pulau Satumu. Within six months, they were readily colonised by crustose coralline algae, which are able to enhance the settlement and metamorphosis of marine larvae and inhibit the growth of other alga which can be detrimental to corals (Johnson & Mann 1986; Morse et al 1996). Corals which recruited on the REUs exhibited better survival and growth compared to those on adjacent rubble areas and the cavity within the REU also functioned as shelter for reef fish. The study demonstrated that fibreglass was a suitable material for supporting marine life. The relatively lower costs of installing the simple and lightweight REUs (at US$153 per module including six stakes) compared to deploying barges to do the same for large concrete frames allows for large-scale installation of these units where necessary.

In situ coral nurseries

Coral nurseries play important roles by acting as reserves, or 'genetic repositories' that preserve the diversity of reefs that are facing impending obliteration (Schopmeyer et al 2012). Comprising *in situ* and *ex situ* versions, nurseries serve to protect coral propagules in a sheltered environment until they reach a suitable size, so that their chances of surviving are increased before they are eventually used to supplement transplantation on degraded reefs (Epstein et al 2003; Rinkevich 2005). To date, scientists in Singapore have experimented with the use of both *in situ* and *ex situ* coral nurseries to augment the amount of coral material that can be used for transplantation.

In 2004, researchers from Singapore and Italy collaborated as part of a European Commission project to explore reef restoration techniques that would be applicable across the region (Chou 2011). The researchers built two *in situ* coral nurseries comprising tables made of PVC pipes and angle bars on the reef slopes of St John's and Lazarus Islands. Over 2900 small fragments (known as nubbins) from 13 hard coral species were adhered to plastic pins and reared on trays made from PVC pipes and plastic mesh (Bongiorni et al 2011). Initial mortality rates were high (66%) due to detachment, smothering by sediment and heavy fouling. However, the nubbins that survived had overall high growth rates and coral species which fared the best in the nursery were *Acropora millepora*, *Porites sillimaniana* and *P. lutea*. The results indicated that this *in situ* 'gardening' approach was viable in environments chronically impacted by high sediment loads.

Corals of opportunity ('COP') are naturally occurring fragments or corals which have recruited on loose rubble – these are common on Singapore's reefs and would otherwise have a low chance of survival in an environment of high sedimentation and low substrate consolidation. Combining scientific expertise from researchers at the National University of Singapore, funding from the private sector (Keppel Corporation) and support from government bodies (the National Parks Board and the National Environment Agency), an *in situ* nursery was established in 2007 at Pulau Semakau using COP as the source material (Chou 2009) (Fig. 3a). Over 600 fragments and juvenile COP from 36 genera were collected from various reefs and secured on elevated mesh frames which were designed to facilitate sediment falling through. Volunteer divers from the public were trained by the researchers and helped with maintenance and monitoring work at the nursery. Appreciable survivorship and growth of the COP were recorded over the course of the project, e.g. survivorship of juvenile COP of *Pectinia paeonia* and *Pachyseris speciosa* were 93% and 69.6% respectively. The results showed that COP could function as a suitable source of coral material for stocking nurseries, and demonstrated the feasibility of such an intervention method to improve the fate of the COP (Chou 2009; Ng & Chou 2013, in review).

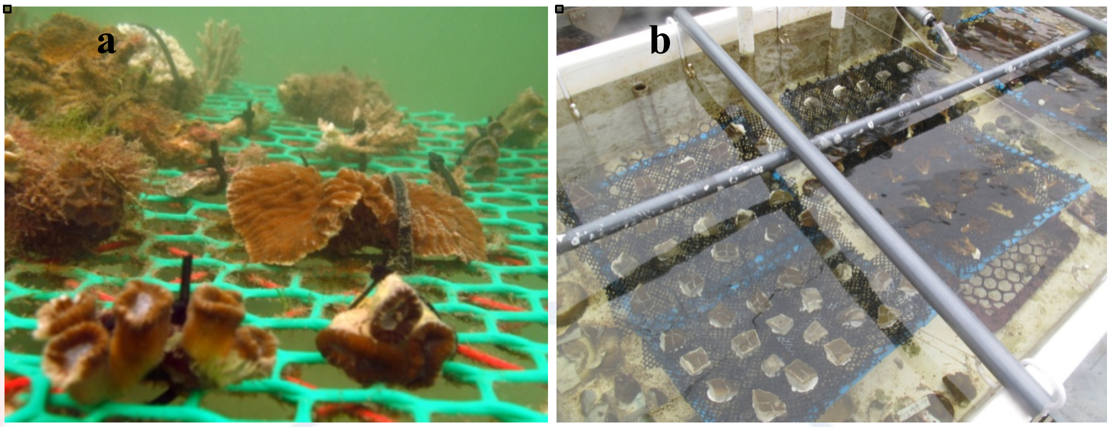

Fig. 3. 'Corals of opportunity' fragments secured on an *in situ* coral nursery frame with cable ties (a), and coral fragments reared in tanks at a mariculture facility which served as an *ex situ* nursery (b). Photo credits: Seow LA (a), Ng CSL (b).

Ex situ coral nurseries

Ex situ coral nurseries are sited on land and are considered short-term alternatives before the coral material is relocated to *in situ* nurseries or transplanted to reefs (Epstein et al 2003). While they are more expensive to run than *in situ* nurseries and are thus only operated on a small scale, they are nevertheless useful for preserving genotypes from reefs that face uncertain fates or where there are constraints in coral material (Epstein et al 2001). The Tropical Marine Science Institute's mariculture facility on St John's Island that supplied flow-through, sand-filtered seawater functioned as an effective *ex situ* nursery for the rearing of coral fragments, and facilitated the measurement of parameters indicative of coral health (Fig. 3b). After 12 weeks, *Porites lutea* and *Psammocora digitifera* fragments survived better than those of *Acropora digitifera* (100% and 98.9% versus 5.7%, respectively) (Ng et al 2012a). Additionally, fragments of 19 common hard coral species required between four to 12 weeks of *ex situ* rearing before they grew over the cement substrates and were thus less likely to detach if they were to be transplanted (Ng et al 2012a). Such information will be useful in estimating *ex situ* rearing times of fragments in future restoration efforts.

The St John's Island mariculture facility also provided a relatively controlled environment which minimised the effects of stressors such as chronic sedimentation in Singapore's waters. This was critical to facilitating the rearing of coral larvae and juveniles which required an extremely clean *ex situ* environment to enhance post-settlement survivorship. Early work on coral sexual propagation was initiated by marine biologists in the Philippines, from which Singaporean researchers learnt the relevant techniques and incorporated them to larval rearing efforts at the St John's Island mariculture facility to supplement restoration projects. The emphasis to date has been on basic coral larval biology. Researchers have elucidated developmental patterns of the common coral species (Toh et al 2012a; Toh & Chou 2013; Toh et al 2013a), enabling them to focus on improving the survivorship of newly recruited corals in an *ex situ* setting. Additionally, Tay et al (2011; 2012) modelled the dispersal patterns of coral larvae and demonstrated the close connectedness of reefs in the region.

Additionally, as with *in situ* nurseries, algal fouling often compromised the health of the reared corals. Researchers experimented with the use of herbivorous sea urchins and top-shell snails as biological controls and proposed less cost- and labour-intensive solutions to effectively manage the problem of fouling (Ng et al 2013b). Toh et al (2013b; in review) were also able to improve the *ex situ* rearing of juvenile corals by co-rearing them with the sea urchins and snails. In the presence of the biological controls, the juvenile corals had larger colony sizes, faster growth rates and deeper colouration.

Transplantation

Along with improvements in the scale and techniques of rearing corals in nurseries, researchers have focused on transplanting both asexually- and sexually-propagated coral material to rehabilitate Singapore's marine environment in recent years. With seawalls currently lining more than 60% of the country's shores (Lai WYS, pers. comms.), one project explored the feasibility of introducing marine life onto these coastal defence structures (Gunasingham 2009; Ng 2011). Hard coral, soft coral and sponge fragments were reared at the *ex situ* nursery at St John's Island and transplanted onto seawalls at Pulau Tekong and St John's Island using marine epoxy (Fig. 4a). As the seawalls were constantly exposed to strong wave forces and impacts from floating debris, transplants that were able to encrust quickly and hence self-attach securely over the granite rock substrates fared better in terms of growth and survivorship (Ng et al, in prep).

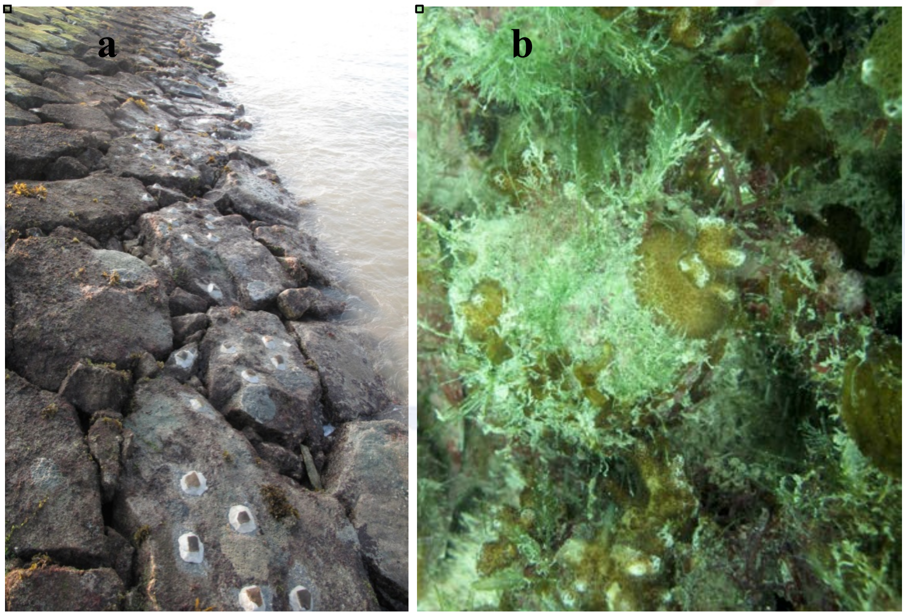

Fig. 4. Coral fragments newly transplanted onto a seawall using marine epoxy (a), and sexually propagated juvenile coral transplanted onto a reef (b) in Singapore. Photo credits: Ng CSL

Corals were also attached to intermediate substrates to facilitate transplantation to impacted reefs. A "plug-in", consisting of a wall plug embedded in a cement mortar hemisphere, was designed to allow coral larvae to settle and grow. After a period of *ex situ* rearing, the juvenile corals were then transplanted by inserting the plug-ins into holes drilled into the reef substrate (Fig. 4b). Marine epoxy was used to further secure the plugin and prevent it from detaching. The use of the plugin minimised direct contact with the juvenile corals, which are especially vulnerable to mechanical stress, and was thus a practical way of rearing and handling sexually propagated corals. Detachment rates of the juvenile corals in sites of high wave energy have since significantly reduced to 2% with the employment of the plugins. Survivorship of the corals three months after transplantation has also been maintained at approximately 80% (Toh et al, in prep).

Effects of mass bleaching event on reef restoration efforts in Singapore

In 1998, sea surface temperatures (SSTs) rose up to 2°C above the average monthly readings for up to three months, causing unprecedented widespread bleaching on Singapore's coral reefs (Toh et al 2012b). Over 90% of corals bleached – 20% of which did not recover as conditions normalised (Chou et al 2012). A large-scale bleaching event occurred again in 2010 in response to a rise in SSTs (Guest et al 2012). Up to 10% of scleractinian corals died, but 80% of the bleached hard corals recovered in four months, followed by close to full recovery in six months (Chou & Tun 2012). There was an apparent reversal in bleaching susceptibility patterns, as coral genera which were severely impacted in 1998, were not as affected in 2010, and vice versa (Guest et al 2012).

The consequences of the 2010 mass bleaching were more acutely felt with the initiation of more reef restoration projects at the turn of the century. At the mariculture facility at St John's Island where the *ex situ* rearing of coral fragments was underway, temperatures in the tanks were as high as 31°C in May 2010, similar to that recorded on the reefs (Ng CSL, unpublished data). Adaptive measures to reduce the thermal stresses imposed on the corals included increasing the water flow in the tanks to prevent overheating and providing shade nets to reduce excessive solar irradiation. Monitoring frequencies were increased and a range of responses was observed across the coral genera: those that rapidly succumbed and died from the thermal stress (e.g. *Pocillopora* sp.), those that bleached but showed full recovery in six months (e.g. *Psammocora* sp. and members of the family Faviidae), and those that exhibited little or no bleaching (e.g. *Acropora* sp. and *Goniopora* sp.). The settlement patterns of coral larvae in the *ex situ* nursery varied as well, with greater settlement percentages recorded for larvae derived in April 2010 (~80%) compared to April 2011 (~30%) for one of Singapore's commonest species, *Pectinia lactuca* (Toh TC, unpublished data).

At the *in situ* coral nursery in Pulau Semakau, coral bleaching trends were similar to those reported for the natural reefs (see Guest et al 2012). Fifty percent of COP bleached, but 60% of these recovered; in addition, unlike fragments of other species, those of *Acropora* sp. – a group of corals considered highly vulnerable to stressors – did not bleach (Tong HYC, pers. comms.). Coral fragments transplanted on the seawall at Pulau Tekong started bleaching in May 2010, accompanied by a decrease in live coral tissue. All *Pocillopora damcornis* and *Hydnophora exesa* fragments bleached and died by July 2010, but nearly half of *Porites lobata* fragments survived the bleaching event and proceeded to grow over the granite rock substrate in the months that followed (Ng CSL, unpublished data).

With reference to the nursery-reared corals and transplants, it is clear that the effects of global stressors such as the 2010 mass bleaching episode can be wide-ranging. In light of increasing climatic variability, the importance of close monitoring and adaptive management measures to safeguard the coral material intended for reef restoration is further underscored. This will allow actions to be taken to remediate any potential damages that may occur.

Conclusions

The various approaches and techniques that have been tested have provided useful lessons to reef restoration practitioners and these experiences will help define upcoming restoration efforts. The results thus far have indicated that restoration is feasible in a marine environment as challenging as Singapore's, and that the methods used will be applicable to locations that experience similar conditions of high sediment load and unconsolidated rubble. There remains an urgent need to explore ways of reducing degradation and enhancing coral establishment on Singapore's reefs. For example, coral larval dispersion modeling and reef connectivity studies such as those by Tay et al (2011; 2012) will help in prioritizing sites for restoration.

It is, however, encouraging that the public and the government agencies appear to be more conscious of the natural environment. This is apparent from observations that environmental impact assessments (EIAs) are more common before the commencement of major developmental work, even though EIAs are not mandatory by law (Chou 2008). Mitigation procedures (e.g. coral relocation exercises) are also increasingly conducted before development projects begin. It is increasingly important to continue to explore various avenues of educating the local community and the authorities to facilitate coral reef conservation efforts. As demonstrated by the *in situ* coral nursery project at Pulau Semakau, articles published in the local media (e.g. Kesava 2007) are a useful way of raising awareness.

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