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An evaluation of artificial reef structures as tools for marine habitat rehabilitation in the Maldives

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ABSTRACT

1. In the Maldives, coral mining for the construction industry has resulted in widespread degradation of shallow reef-flat areas. Due to the loss of these coastal resources and the associated problems of coastal erosion, there is an urgent need to find practical methods for rehabilitating mined reefs.

2. The slow rates of natural recovery of mined reefs has prompted interest in the potential of artificial reef structures to rehabilitate these degraded habitats. An experimental artificial reef programme was initiated in 1990 to discover whether it is feasible to use a bio-engineering approach to kick-start natural reef recovery.

3. The main goals of the project were to restore the capacity of degraded reefs for sea defence and their ability to harbour fish species. Accordingly, 360 t of concrete structures of varying levels of topographic complexity, stabilising effect and cost were deployed on a heavily mined study site close to the capital island, Malé.

4. Within 1 year of deployment, the artificial reef structures had similar or greater species richness and densities of reef fish than did control pristine reef flats. However, the community structure of the fish populations on the artificial reef structures was significantly different to that on unmined reef flats.

5. Preliminary results of a monitoring programme indicated that substantial coral recruitment had occurred on the larger reef structures which were each supporting *ca*. 500 colonies, some of which were approaching 25 cm in diameter after 3.5 years. An evaluation of the effectiveness of the various artificial reef structures is discussed in relation to their design features and costs and in line with timescales for the recovery processes.

KEY WORDS: artificial reefs; habitat rehabilitation; Maldives

INTRODUCTION

Coral reefs are unique among aquatic ecosystems in that they form their own hard substrate which enables them to maintain their position at, or close to, sea level. These stable biogenic structures provide various functions and services, including essential coastal sea defence, fisheries, tourism and a variety of biological diversity functions. The socio-economic benefits of coral reefs are recognised; for example, a

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recent study (Costanza *et al.*, 1997) estimated the global socio-economic benefits of coral reefs as US$ 375 billion year^{-1}. Despite the recognition that coral reefs provide valuable resources, there has been a world-wide decline in reef status and health over the past 2–3 decades (Pernetta *et al.*, 1994). Wilkinson (1992) predicts that 70% of coral reefs will seriously decline over the next four decades as a result of both natural and anthropogenic disturbances.

The Maldives are located in the central part of the central Indian Ocean and form the largest part of the Laccadive–Chagos ridge (Figure 1). There are 26 geographic atolls and about 1200 islands, and of these, about 200 are permanently inhabited and a further 62 have been developed as tourist resorts. Over 80% of the islands are less than 1–1.5 m above mean sea level and coral reefs play a vital sea defence role, protecting the islands from storm damage and flooding. These islands are among the most vulnerable to the predicted rise in sea level as a result of global climate change (Pernetta and Sestini, 1989). Historically, the marine environment has supported all aspects of the traditional lifestyle (e.g. tuna fisheries) and forms the backbone of the economy. Since the early 1970s, tourism has developed rapidly and is now the principal source of national revenue, generating approximately 23.8% of the NDP (Maldives Statistical Year Book, 1994).

Environmental problems

For over two centuries, local people have used coral rock for building purposes. However, the demand for coral rock increased rapidly in the early 1970s due to population pressure and growth of the tourist industry. Brown and Dunne (1988) evaluated the capacity of North Malé Atoll to supply the demand for coral rock based upon extraction rates for 1980–1985. They predicted that all suitable sites would be worked out in a maximum of 30 years and that projected levels of extraction were not sustainable. Traditionally, massive corals, which are the primary reef frame-builders, e.g. *Porites* and *Favia* spp., were favoured. However, over the last 10 years the more fragile branching corals have also been selected for use in sea walls and groynes on tourist islands. In general, the sites selected for coral mining are the submerged reefs within the atolls known as faros, but where these reef structures are limited, the leeward side of the outer atoll rim is often mined.

Environmental implications of coral mining

The extraction of coral removes the upper 0.5 m of the reef framework leaving a bare, flat surface comprised of broken rubble and unconsolidated sediment (Figure 2), resulting in a loss of live coral cover, topographic diversity and reef associated fish (Brown and Dunne, 1988; Dawson-Shepherd *et al.*, 1992). On a broader scale it is of much concern, since it impairs the capacity of the reefs to act as natural sea defences. This is further exacerbated because coral reef flats also supply the sediments which build up to form the islands (Edwards, 1989). The environmental problems associated with degraded reef flats take on particular significance when considered in relation to the current predictions of global climate change. If the recent predictions from the Intergovernmental Panel on Climate Change (IPCC, 1992) of a rise in sea level of 4 mm year^{-1} (i.e. 100 mm by the year 2020) are realised, then low-lying nations such as the Maldives will be at increasing risk of inundation, particularly if there is an increased frequency and intensity of tropical storms as some predict (Pernetta *et al.*, 1994). Reef accretion rates suggest that reef-flat areas will grow vertically towards the low tide level and should be able to keep pace with sea level rise provided that they are not subject to anthropogenic stresses (Buddemeier and Smith, 1988). However, in the Maldives the main uncertainty lies in the lack of information on the combined effects of climate change and anthropogenic impacts.

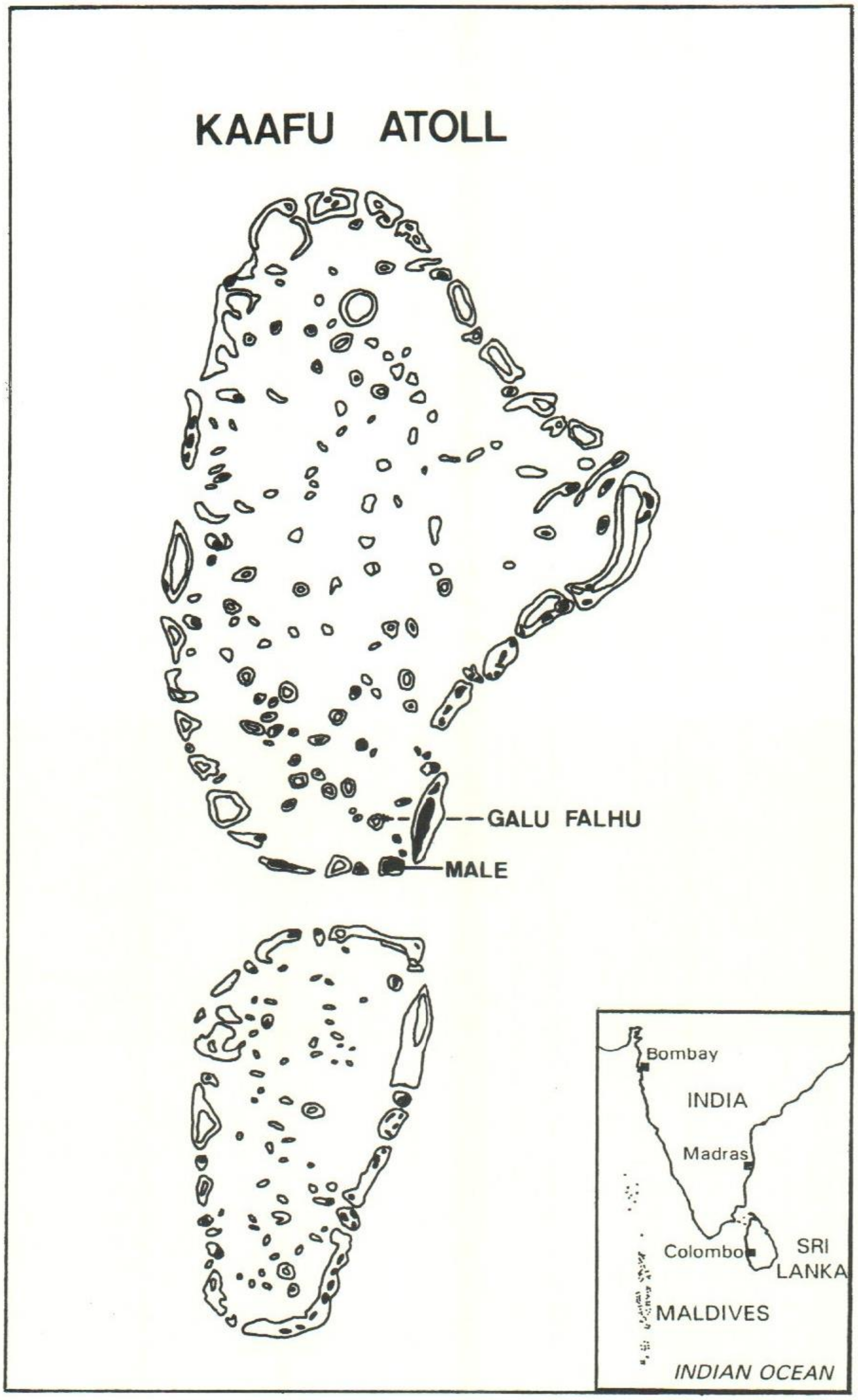

Figure 1. Location of the Maldives and of the study area in Kaafu Atoll.

Why is it necessary to rehabilitate degraded reefs?

Reefs which have been severely mined for corals have shown no evidence of recovery over periods of up to 20 years. Brown and Dunne (1988) tentatively attributed the absence of recovery to the lack of stable surfaces for the settlement of coral planulae and permanent environmental changes (i.e. increased sedimentation and substrate mobility). Where degraded reefs show no signs of recovery over human timescales, it can be argued that there is a need for technical solutions to promote recovery in areas where it would not otherwise occur.

In Malé, where reefs have been sacrificed for land reclamation, sea defence is now provided by a series of detached breakwaters (composed of concrete tetrapods) at a cost of US$ 14 million to protect 1.52 km of shore. This gives a value of £5625 (US$ 9000) per linear metre, indicating the replacement costs for low lying islands that are dependent upon the adjacent coral reefs for protection from waves (Edwards, 1989).

Coral mining also has implications for the tourist industry, since the loss of healthy reefs will destroy the very resources which attract the visitors in the first place. The traditional pole-and-line tuna fishery may be indirectly affected, since it is dependent on bait fish collected from shallow reef areas, in particular the faros, which are the preferred areas for coral mining.

Reef rehabilitation techniques

Despite the successful application of restoration activities to improve resource management in agriculture, forestry, lakes and wetlands (Cairns, 1988), such interventions have rarely been applied to coral reef systems. In reviewing reef rehabilitation techniques, Woodley and Clark (1989) found the primary method to be passive, i.e. mitigation of the impact to allow natural recovery processes. Active rehabilitation (i.e.

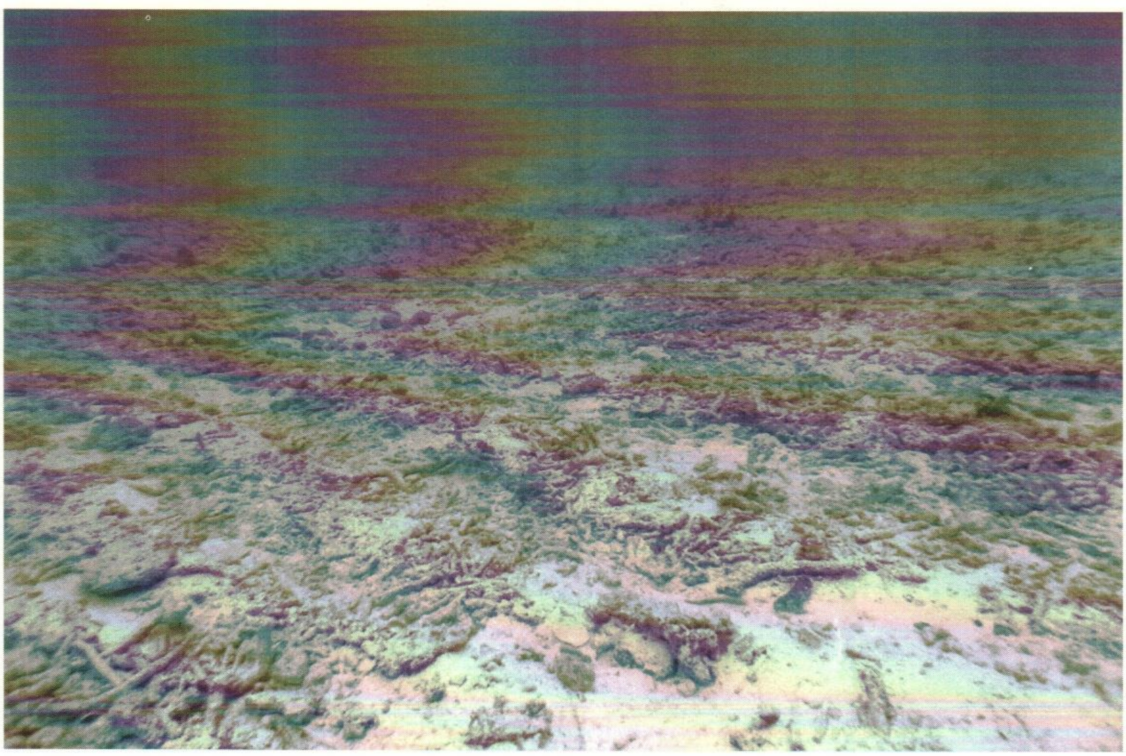

Figure 2. The degraded reef flat at Galhu Falhu, showing the unconsolidated sediment and loose coral rubble.

manipulation of the reef organisms to facilitate recovery) was limited to small-scale studies involving transplanting adult colonies, repairing injured colonies and removing predators. Since that time, very little substantive progress has been reported. An evaluation of reef restoration capabilities and methodologies to restore reefs damaged by large ship groundings in Florida (Miller *et al.*, 1993) recommended the following: cementing the fractured reef framework, removing loose rubble and fine sand, repairing excavations, coral transplantation, increasing habitat complexity and manipulating key species groups which influence community structure.

Artificial reef structures for habitat restoration

Artificial reefs have been used as a tool to enhance fisheries production for many years (Seaman and Sprague, 1991); however, there has been very little substantive research on their application in reef rehabilitation programmes. In the Philippines, Gomez *et al.* (1982) demonstrated successful colonisation by 30 species of coral on automobile tyre reefs at depths of 16–23 m and estimated that it would take 15 years to develop a community with 50% coral cover. A few studies have recorded coral reef development on artificial substrata, such as concrete pillars used in construction projects in Singapore (Chou and Lim, 1986), harbour moles at Eilat, Red Sea (Schuhmacher, 1974, 1977) and concrete blocks in Hawaii (Fitzhardinge and Bailey-Brock, 1989).

The slow rates of natural reef recovery prompted our interest in the potential of artificial reef structures to rehabilitate damaged reefs and coastal habitats. One of the reasons for the high productivity of coral reefs is the amount of surface area and textural variety provided by the reef framework. Therefore, for artificial reef structures to be successful they must mimic and perform the same functions as natural reefs (e.g. provide stability, topographical relief, shelter and refuge). This project set out to discover whether it is feasible to use artificial reef structures to rehabilitate shallow reef flat areas which had been severely degraded by coral mining.

Aims of the rehabilitation project

For most degraded coral reef systems, recovery is a slow process and it is therefore important that both short- and long-term goals are set. From a conceptual viewpoint, the long-term goal of the present study could be defined as the restoration of the full range of services and functions provided by the original reef (i.e. to restore the capacity of the degraded reefs for sea defence and restore their biodiversity). However, such a goal is unrealistic in a 3.5 year time frame and therefore, the following short-term objectives were set:

1. to determine which rehabilitation techniques are cost-effective in promoting coral settlement and growth in places where it would not otherwise occur;
2. to test the hypothesis that lack of recovery in the mined areas is due to the lack of stable surfaces for settlement of coral planulae from the plankton;
3. to restore fish populations and coral biodiversity; and
4. to investigate the biological and physical conditions conducive to reef recovery.

MATERIALS AND METHODS

The site selected for rehabilitation experiments was a 4-ha area of reef flat on a 950 × 725 m severely degraded faro called Galu Falhu, 2.4 km north-west of the Maldives' capital Malé. The faro was mined for both coral and sand for use in construction about 20 years ago and has shown almost no recovery to date, with aerial cover by corals generally less than 3%, compared with 35% on nearby unmined reef flats.

The study area was 0.5–1.8 m below Lowest Astronomical Tide (LAT) (tidal range approximately 1 m) and consisted largely of unconsolidated sand and loose coral rubble.

The artificial structures

During the design phase, the main functions of the artificial reef structures were identified as follows: 1) to stabilise the mobile rubble surface; 2) to attract herbivorous fish onto the reef flat to graze the filamentous algae which can inhibit coral settlement; 3) to promote coral growth in areas where it would not otherwise occur; and 4) to provide shelter and topographical diversity to re-establish reef fish populations. Following the design phase, a feasibility study was conducted to evaluate the stability of the various structures before deployment to ensure that they would survive the wave regime predicted for the reef flat (Parle, 1990). Accordingly, four sets of artificial structures totalling 360 t in weight were deployed on the reef flat in late 1990 and early 1991 (Clark and Edwards, 1994). Each set was comprised of three approximately 50 m^2 (5×10 m) replicate sites, each positioned at the centre of a 50×50 m grid square. The four sets of structures were of varying topographic diversity, stabilising effect and cost:

(a) One-cubic-metre Shephard Hill Energy Dissipator (SHED) hollow concrete blocks, modified with infills (concrete and PVC) to reduce internal space, providing a high level of stability, design features and cost.
(b) Armorflex-220 flexible concrete mattresses, providing a high level of stability, and an intermediate level of design features and cost.
(c) Armorflex onto which corals were transplanted—as above but designed to test whether coral transplantation accelerates recovery processes.
(d) Chain-link fencing anchored by paving slabs, providing low stability, design features and cost.

As controls, three 50 m^2 sites on the mined reef flat were also monitored. Finally, as a yardstick against which rehabilitation measures could be assessed, three 50 m^2 sites on the reef flat of the nearest healthy unmined reef (Feydhoo Finolhu) were monitored.

Fish censuses

Fish populations on the various reef structures, and on mined and pristine control areas were monitored by conducting 30 min visual censuses (Edwards and Clark, 1993). A fish count was carried out at approximately weekly intervals for the first month after deployment at each reef structure. Counts were then made at approximately monthly intervals until about 6 months after emplacement, and thereafter at approximately 3–5 monthly intervals, weather permitting. Fish species abundances (adjusted to numbers per 50 m^2 where necessary) were subjected to analysis of covariance and non-metric multi-dimensional scaling (MDS) ordination to determine the significance of the effects of different structures and the effectiveness of rehabilitation of the fish communities.

Biomass

Data on fish length and weight were collected from one of the large SHED structures (B1) using a rotenone station, which involved sealing off the area under study with nets and applying rotenone (a fish-specific poison which acts on respiration) to collect the fish.

Rehabilitation of coral communities

Recruitment of corals from the plankton onto the artificial structures was monitored at 8–12 monthly intervals throughout the study. Visible recruits to the artificial structures were identified as far as possible (initially to genus and later to species level) and their position and the orientation of the surface on which

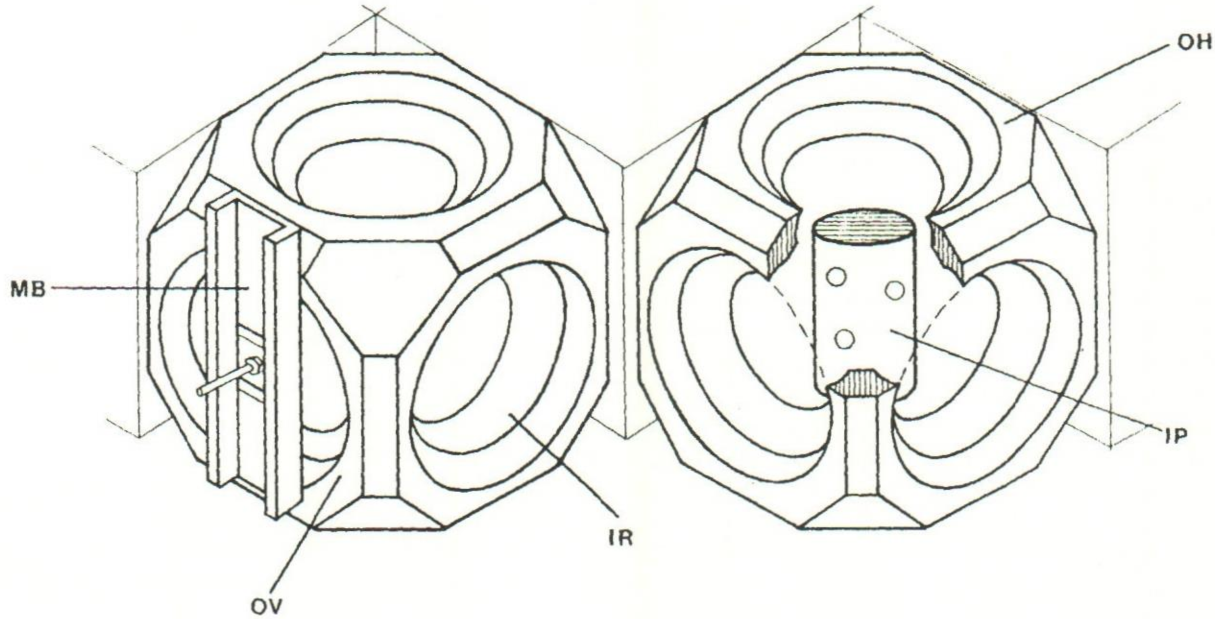

Figure 3. Different categories of surfaces distinguished on SHED surfaces to study coral recruitment patterns. OV, outer vertical; OH, outer horizontal; IR, inner ring (near-vertical); IP, inner pipe; MB, metal bar.

they had settled was recorded to allow mortality to be followed. Different categories of surface orientation were distinguished on the SHED structures (Figure 3) and the area of each category calculated to allow recruitment per unit area to be determined for each type of surface.

Coral cover and diversity on a relatively stable (less heavily mined) area of the reef flat were compared with that in the unconsolidated mined control areas within the study site to determine whether natural recovery was faster there.

Evaluation of coral transplantation

Corals for transplantation were collected by denuding three undegraded 50 m^2 areas of reef flat. Corals were transferred to the three Armorflex study sites submerged in seawater and the base of each colony was fixed into position with marine cement at the earliest opportunity to reduce stress. Once in position, photographs were taken of each study site to provide a baseline reference map of the coral positions on the concrete mattresses. Each colony was initially identified to genus level (species level if possible) and greatest and least diameters and heights were measured. Growth, survival and losses of transplants were monitored at 8–12 monthly intervals, and recovery of the artificially denuded areas monitored simultaneously. Coral recruits on both the transplanted and plain Armorflex areas were surveyed in detail 29 months after emplacement to determine whether transplantation aids recruitment.

Criteria to assess the effectiveness of the artificial reef structures

The full potential of these structures in terms of fulfilling the functions and services of the original reef may take 10–20 years to be fully revealed. We therefore adopted criteria that would provide realistic indicators of short-term recovery, as shown in Table 1.

RESULTS

Re-establishment of the reef fish community

The re-establishment of the reef fish community was reported in detail by Edwards and Clark (1993); a summary follows. Immediately prior to emplacement of the artificial structures, the density of fish in the 50 m^2 study sites was, on average, less than 1 m^{-2} and most individuals seen on the degraded reef flat had a total length of less than 10 cm.

Colonisation of the artificial structures by fish was initially very rapid, with adults of species already present on the reef flat being attracted to the structures within hours of their deployment. On the SHED structures, within the first month there was a five-fold increase in the number of fish species and individuals compared with baseline surveys. On the Armorflex structures, there was a two- to three-fold increase in the numbers of individuals and a doubling of the numbers of species in the same period, while on the chain-link fencing areas changes were less pronounced (Figure 4). The primary effect was a marked increase in the numbers of herbivorous fish on the reef flat in the vicinity of the structures (notably surgeon fish and parrot fish) and the attraction of larger fish (> *ca.* 20 cm total length) including food fish such as groupers (Serranidae) and snappers (Lutjanidae), back onto the degraded faro.

The population sizes and numbers of species remained fairly stable on the artificial structures for about 1 year after emplacement. However, seasonal recruitment of large numbers of juvenile apogonids and pempheridids caused fluctuations in some areas.

Comparing censuses taken about 2.5–3.5 years after emplacement, the most topographically complex SHED areas were the most effective at attracting fish (Figure 4a). The progressively less topographically diverse areas supported progressively fewer fish, but considerably more than mined control areas.

SHED areas, plain and coral-transplanted Armorflex areas were not significantly different with respect to fish species richness (Figure 4b). However, these sites had significantly more species ($p < 0.01$) than the chain-link fencing sites, which in turn had significantly more species ($p < 0.01$) than the mined control sites. Pristine 50 m^2 reef flat areas on Feydhoo Finolhu supported on average 35 species, the number reached by SHED and Armorflex areas about 1 year after emplacement.

In summary, from 1–3.5 years after emplacement, the SHED and Armorflex sites had about the same species richness and similar or greater densities of reef fish than nearby 50 m^2 pristine reef flat sites. Meanwhile, the chain-link fencing sites maintained approximately 40% of the numbers of species and individuals observed on pristine sites.

When considered in terms of fish biomass, the rehabilitation of the fish community was even more striking (Figure 5). The degraded reef flat supported on average about 0.3 t ha^{-1} of fish, while a nearby pristine reef flat on Feydhoo Finolhu supported about 1.2 t ha^{-1}. The Armorflex areas compared favourably with pristine reef flat, supporting 1.5–2.2 t ha^{-1}, while the SHED areas markedly surpassed them, supporting 4.5 t ha^{-1}; this was primarily due to the shelter provided by the SHED blocks for larger fish.

Table 1. Description of criteria used to evaluate the effectiveness of artificial reef structures for reef recovery in the short- (<5 years) and long-term (>5 years) timescales

Short-term attributes	Long-term attributes
Increase in coral recruitment	Accumulation of mature coral colonies
Increase in percentage cover of corals	Increase in topography and reef framework
Increase in reef fish and invertebrate diversity and abundance	Increase in goods generated (e.g. fish, shell fish)
Increase in substrate stability	Improved capacity for sea defence

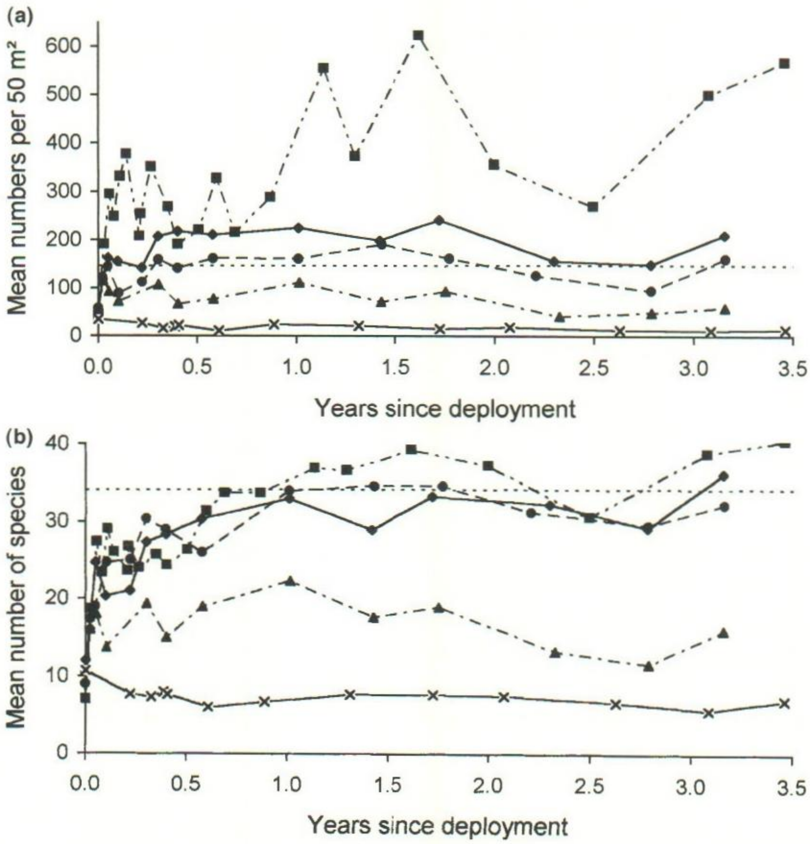

Figure 4. Summary of (a) numbers of fish and (b) numbers of fish species counted on different types of reef structures, compared with mined and unmined control sites. The ordinates are mean numbers of fish and fish species 50 m^{-2} on three replicates of each substratum type at each time. The dashed and straight lines indicate the mean number of fish observed in 50 m^2 unmined reef-flat areas at Feydhoo Finolhu and mined reef-flat areas at Galu Falhu, respectively; ■ indicates SHED areas; ◆ indicates transplanted Armoflex areas; ● indicates plain Armorflex areas, and ▲ indicates chain-link fencing areas.

Fish communities on the SHED and Armorflex areas have clearly developed well away from their initial state on the mined reef (Figure 6). However, they remain distinct from those on the natural reef flat on Feydhoo Finolhu. This difference seems to be largely due to the artificial reef structures attracting particular species, such as *Apogon apogonoides* onto the reef flat where they are normally uncommon.

Rehabilitation of the coral community

Patterns of coral recruitment

The first coral recruits belonged to a pioneer species *Pocillopora damicornis*. This species which elsewhere planulates monthly, was observed on the SHED areas 6.5 months after emplacement. Further settlement of corals with a branching growth form (pocilloporids and acroporids) were observed after 10 months on both the concrete surfaces and on the inside of the PVC pipe inserts. The first coral with a massive growth form (*Porites* sp.) settled at the same time. An average of 12.6 recruits m^{-2} were found on the SHEDs, with 3136 being recorded on the *ca.* 250 m^2 of surfaces studied in the three areas (Table 2). After 3.5 years, each SHED area supported *ca.* 500 coral colonies, some of which were approaching 25–30 cm in diameter, as shown in Figure 7.

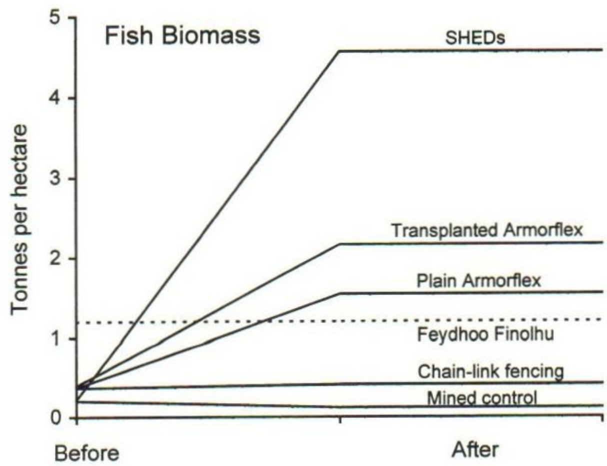

Figure 5. Mean fish biomass (t ha^{-1}) before and after emplacement of the artificial reef structures.

About 10 months after emplacement, coral recruits were recorded on the vertical edges of the flooring slabs anchoring the Armorflex mats, and after 16 months recruits were observed on vertical surfaces of the concrete mats themselves (Figure 8). Over the study period, an average of four recruits m^{-2} were found on the Armorflex areas with and without transplants, while the vertical edges of the concrete mats supported an average of 18 recruits m^{-2} on both types. After 2.5 years, small numbers of acroporid and pocilloporid recruits were observed on the vertical edges of the paving slabs anchoring the chain-link

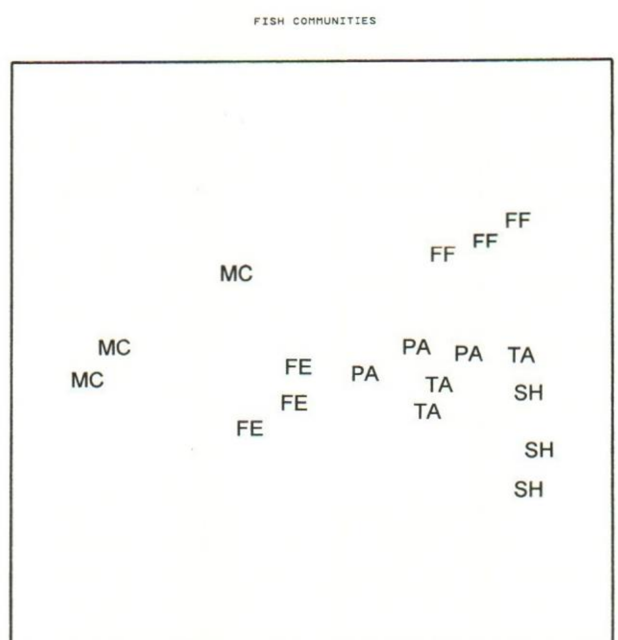

Figure 6. A two-dimensional representation of MDS ordination of the fish communities on the artificial structures (PA, TA, SH, FE) the unmined reef flat (Feydhoo Finolhu, FF) and mined control (MC) areas using the mean numbers of each species in the last three surveys (after 2.5–3.5 years).

Table 2. A summary of visible coral recruitment (all species) in the three SHED areas after 3.5 years, indicating the total numbers of recruits (m^{-2}) and their survival over the study period

SHED area	Total number of recruits	Number of recruits (m^{-2})	Number of recruits alive after 3.5 years	Percentage of recruits alive after 3.5 years
A5	988	11.9	526	53.2
B1	1062	12.8	558	52.5
C3	1086	13.0	505	46.5
Mean	1045	12.6	530	50.7
Total	3136	–	1589	–

The total area surveyed for coral recruitment was 83.27 m^2 (this does not represent the total area available for settlement, due to difficulties in accessing inner areas).

fencing. However, all recruits subsequently died due to their low elevation and the abrasive action of the mobile rubble and sediment. At the last survey, the first evidence of reef cementation was observed, where a small number of coral colonies had grown over the chain-link fencing (Figure 9).

Influence of structure design on coral recruitment

The density of branching species of coral recruits on the SHEDs was greatest on outer vertical surfaces (mean density, 31 m^{-2}) rather than on outer horizontal surfaces ($< 2\ m^{-2}$). Other surfaces particularly good at attracting coral recruits were the inner surfaces (27 m^{-2}) of the PVC pipe inserts. The density of

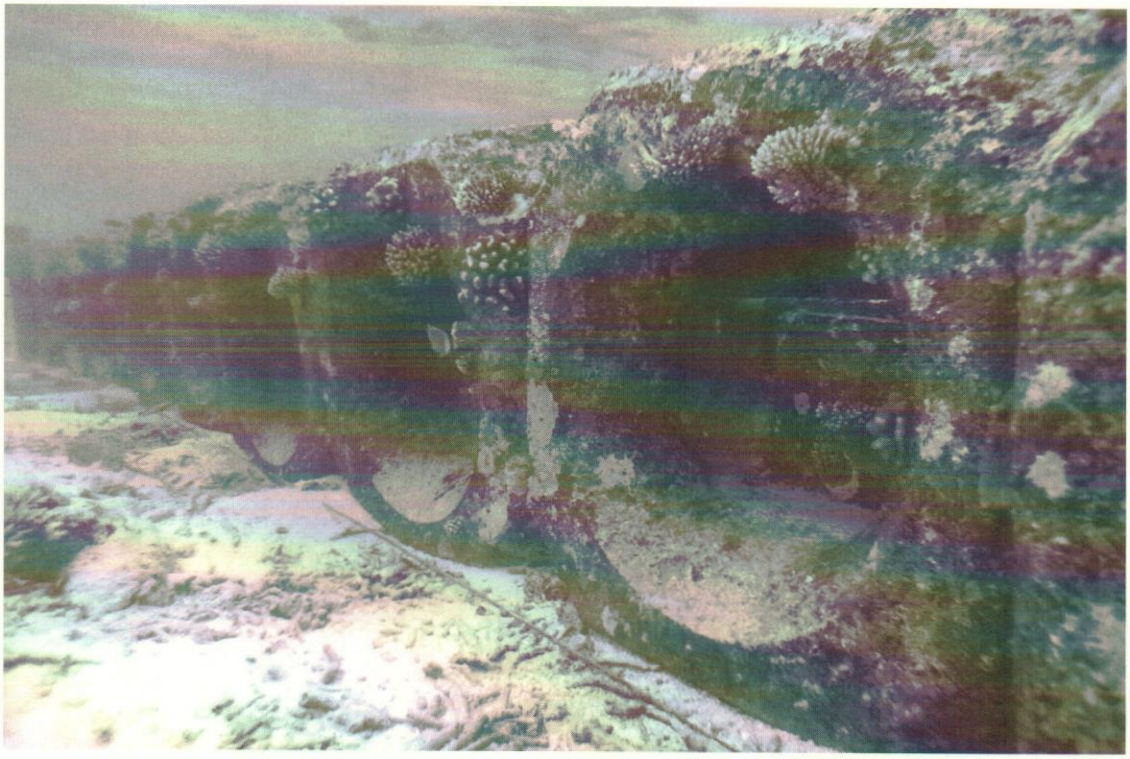

Figure 7. Coral growth on the SHED blocks 3.5 years after the first 'visible' coral recruits were recorded.

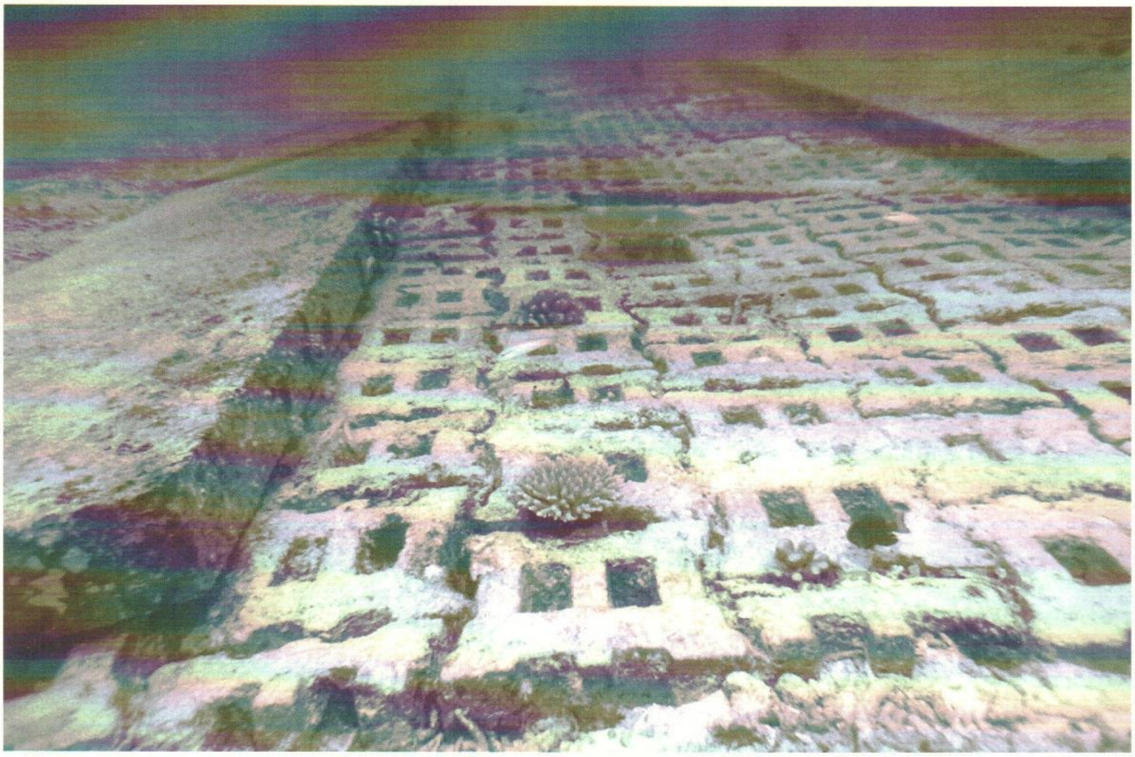

Figure 8. Coral recruitment on the plain Armorflex mattresses over the 29-month study period. Note the location of the coral recruits on the vertical edges of the paving slabs anchoring the Armorflex.

recruits on near-vertical surfaces such as inner rings was less (mean density, 6 m^{-2}) than on vertical surfaces, but greater than that on horizontal surfaces. In summary, any structures designed to attract coral settlement require as few horizontal surfaces as possible.

Development of coral community structure

The coral community which developed on the SHED areas was dominated by acroporids (50%) and pocilloporids (45%), with very few massive colonies (5%). The reef flat at the unmined control area at Feydhoo Finolhu was also dominated by acroporids (77%), followed by pocilloporids (9%), with massive species in the genera *Porites*, *Pavona* and *Favites* making up the remaining 14%. This compares with other shallow reef flat areas close to Malé, where massive colonies constitute up to 20% of the population. Similarly, the dominant coral recruits on both transplanted and plain Armorflex areas were branching species, with *Acropora* and *Pocillopora* species being equally abundant at all sites.

Evaluation of coral transplantation

A summary of the findings of the transplantation studies is given below. For a full description see Clark and Edwards (1995).

Twenty-nine months after transplantation, 41–59% of corals still survived on the concrete mattresses. Mortality rates of corals which remained attached were between 23–31% over the study period. During the initial 8 months, a large number of colonies were detached and swept off the transplant areas by strong wave action; however, from 8–29 months, there was little loss of colonies. Overall, 19–37% of the transplanted colonies were swept off the mats by wave action. In addition to those colonies lost from the transplanted areas, between 18–29% of colonies became loosened (i.e. unattached but still present within the transplant area) during the early part of the study.

Natural reef recovery

Coral cover in mined control areas showed a slight reduction from 0.8% (S.D. 1.2) in 1991 to 0.19% (S.D. 0.2) in 1993. The less heavily mined site at the south-east of Galu Falhu showed only a slight change in coral cover over 2.5 years from 5.6% (S.D. 4.86) in 1991 to 6.4% (S.D. 1.7) in 1993. These data confirm that the natural recovery rates of a mechanically damaged reef are very slow. After 2.5 years, coral cover in the denuded donor areas was 0.40% (S.D. 0.27) on average, with 9–12 genera present. This was similar to mined control areas which have had decades to recover. However, the areas mined by local coral miners suffer considerably more framework destruction than the artificially denuded sites in our study, where donor corals for transplantation were carefully removed with a minimum of collateral disturbance.

Cost-effectiveness of artificial reef structures in promoting reef recovery

The relative success of the artificial reef structures was evaluated in terms of their effectiveness in restoring reef fish species and populations and in increasing coral recruitment. Data from the measured parameters (fish species richness, densities and biomass, and coral recruitment) were converted to a ranked scale (0–5) which represents an index of change, where 0 represents no change and 5 a high magnitude of change. Data from the experimental reef structures are compared with the unmined control reefs to

Figure 9. Chain-link fencing anchored with concrete paving slabs showing the first signs of coral growth.

provide a standard by which to judge former conditions. The costs of the various artificial structures include the deployment but not the costs in shipping. The success of the artificial reef structures appears to be proportional to both their cost and complexity (Table 3). The most structurally complex and expensive SHED units at £210 m^{-2} were more successful than the Armorflex mats (plain at £66 m^{-2} and transplanted at £97 m^{-2}), which in turn were more effective than the chain-link fencing at £26 m^{-2}. However, in the long-term the Armorflex mattresses may be as effective as the SHED units, provided that sedimentation is not a problem. In terms of stability, there was evidence that reef cementation and consolidation was starting to occur on the chain-link fencing after 3.5 years, suggesting that in the even longer-term this low cost option may have an application in areas where sediment mobility is not too severe. Finally, a significant part of the costs associated with the Armorflex and the chain-link fencing lay in the large concrete paving slabs used as anchors. If a cheaper means of fixing, such as large staples, could be used then the costs of these options would be significantly reduced.

CONCLUSIONS

Within 1 year of deployment, fish numbers, biomass and species richness had been restored to levels similar to, or greater than, those on unmined reef flats on all reef structures except the chain-link fencing. Although there has been successful re-establishment of the reef fish populations on the larger reef structures, their community structure is still significantly different to that of unmined reef flats. Certain design features of the larger reef structures have created shaded habitats akin to crevices and small caves which are very attractive to *Myripristis vittata*, *Pempheris vanicolensis*, *Chromis viridis* and *A. apogonoides*, which are not usually common in the reef-flat environment (Edwards and Clark, 1993).

Substantial coral recruitment had occurred within 3.5 years on the SHED blocks (12.6 recruits m^{-2}) and to a lesser extent on the Armorflex mats (3 recruits m^{-2}), demonstrating that the degraded area is not recruitment-limited. The lack of coral recruitment on the chain-link fencing areas suggests that the most critical factor preventing natural recovery is the lack of stable, sediment-free surfaces for recruitment of corals and other calcareous organisms. The coral community on all structures was dominated by branching corals, with few massive corals present. Given the relatively poor recruitment and slow growth rates of the massive species, it may be decades before a typical reef flat community can be restored, although levels of coral cover typical of undegraded reefs are likely to be reached much sooner.

Although previous studies (e.g. Schuhmacher, 1977) have suggested that a conditioning period of *ca.* 1 year is required before coral recruits can settle on new surfaces, coral recruits were observed 6.5 months after emplacement. Conditioning is thought to be necessary, partly to leach toxic substances from the concrete and partly to allow calcareous red algal communities (Morse and Morse, 1991) which favour coral settlement to develop. If conditioning is a prerequisite for settlement, it occurred within a few months at the shallow, high energy, clear water study site. The rate of coral recruitment is also influenced by the time of year when the structures are deployed in relation to the local spawning patterns of the corals. No data were available on coral reproduction in the Maldives before this project, but parallel studies by Sier and Olive (1994) and Sier (personal communication) have shown that three of the most common reef-flat corals, *Pocillopora verrucosa*, *Acropora hyacinthus* and *Acropora digitifera*, have annual reproductive cycles with broadcast spawning around March–April each year. Consequently, the larvae from these species were in the plankton approximately 6–7 months after emplacement, allowing considerable time for the new surfaces to be conditioned.

Coral transplantation was a costly and time-consuming activity of doubtful efficacy. Within 2.5 years, 40–60% of the transplanted corals had died or been lost due to wave action. The initial high losses during the first few weeks after transplantation were due to the difficulty of firmly attaching large massive corals to the Armorflex mats. The presence of transplanted corals did not enhance natural recruitment (Clark

Table 3. An evaluation of the cost-effectiveness of the different artificial reef structures in restoring coral recruitment and reef fish populations

Reef type	Design features	Stability	Cost (£ m^{-2})	Effectiveness in restoring:			
				Fish (A)	Fish (R)	Fish (B)	Coral recruits
Mined control	None	None	0	0	0	0	0
SHED blocks	High	High	210	4	4	5	4
Armorflex mats (plain)	Medium	High	66	4	4	4	3
Armorflex mats (with transplanted corals)	Medium	High	97	4	4	4	3
Chain-link fencing	Low	Low	26	2	2	1	1

(A) represents the increase in mean numbers of individuals, (R) the increase in mean numbers of species and (B) the mean biomass. The ranked scale (0–5) represents the index of change—see results for further details.

and Edwards, 1995). Given the above, the damage to other reef areas necessary to obtain the donor corals and the high rates of natural recruitment and growth on the artificial structures, it would appear that transplantation should only be undertaken under special circumstances (e.g. if natural recruitment is unlikely).

Corals are long-lived species, and therefore, the development of a coral reef ecosystem from the first settlement of coral larvae will take decades. Even under the most optimistic scenario we could not expect to see the first indicators of reef recovery before 5 years following emplacement. The preliminary results have provided information on the biological and physical conditions conducive to reef rehabilitation. For example, it is possible to influence the type of fish attracted to the artificial structures by altering the design. Inclusion of spaces which mimic caves and crevices attracts large numbers of Holocentridae (food fish), Apogonidae (baitfish) and Pempheridae. Monitoring and analysis of recruitment patterns and subsequent survival of juvenile corals suggest that desirable features on concrete surfaces include predominance of vertical or near-vertical surfaces and internal void spaces of varying sizes to provide shelter for fish. Sediment-free, vertical surfaces were most favoured for settlement by all species of corals recorded, while very little recruitment was observed on horizontal surfaces, a finding consistent with other studies (Harriot, 1985; Wallace, 1985). The potential advantages and disadvantages associated with the use of artificial reef structures for reef rehabilitation are given in Table 4.

Table 4. The potential advantages and disadvantages associated with the use of artificial reef structures for reef rehabilitation

Advantages	Disadvantages
Provides stability in high-energy environments	Risk of break-up leading to pollution
Provides a variety of surfaces for settlement of sessile organisms	Site selection and placement problems
Provides shelter, refuge and cryptic habitats to attract reef fish	May cause problems for navigation
Can function as a breeding ground	Rarely provides the aesthetic qualities of natural reefs
Rapid colonisation of juvenile corals on certain reef substrates (i.e. concrete)	Construction and deployment are costly and time consuming
Enhances productivity by providing new habitats	Difficulty of simulating natural reef topography and complexity

Socio-economic implications

Failure to appreciate the value of natural resources is a major factor behind coral reef degradation. Although regulatory measures to protect reefs already exist in many regions, lack of enforcement and support from the community means that these policies can remain largely ineffective. In the Maldives, alternatives to coral mining for the construction industry already exist in the form of a hollow (concrete) block manufacturing industry which uses imported cement and coral sand extracted from lagoons. Although these blocks are cheaper than coral rock, they are not the preferred option. One of the most common objections to these blocks is that they are not as strong as coral rock. The reason for the poor quality lies in the lack of quality control, which is in the hands of the manufacturers who cut costs by using low cement:sand ratios and do not properly cure the blocks (i.e. allow them to dry too quickly). In 1992, the government of the Maldives introduced legislation to control coral mining. These regulations are currently under review and it is likely that mining activities will be restricted to designated sites with the introduction of permits to collect corals.

Preliminary results indicate that concrete artificial reef structures can satisfy the critical biological requirements (i.e. provide substrate for the settlement and growth of corals and habitat to restore reef fish populations) associated with reef rehabilitation. However, this study has demonstrated that artificial reef structures are costly, time consuming and unlikely to simulate natural reefs for decades. Therefore, given the large areas of degraded reefs in need of rehabilitation, it would be impractical to recommend the use of artificial reef structures because of the expense and effort required to ensure their success. If the degraded area has a high value (e.g. for shore protection) the cost/investment could be justified. Where the sea defence functions of reef flats have been impaired or lost, the usual solution is to attempt to replace their roles by civil engineering. This can be extremely expensive, as already witnessed in Malé. Using artificial reef structures as the initial impetus to stimulate natural recovery and restore the protective function of coral reef flats may, in the long-term, be a much cheaper approach. Although results to date are encouraging, it will be a few years before we can properly judge their effectiveness at re-establishing coral growth and hence their sea defence function on severely degraded reef-flat areas.

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