BULLETIN OF MARINE SCIENCE, 78(1): 151–159, 2006

ARTIFICIAL REEFS VS CORAL TRANSPLANTATION AS RESTORATION TOOLS FOR MITIGATING CORAL REEF DETERIORATION: BENEFITS, CONCERNS, AND PROPOSED GUIDELINES

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ABSTRACT

Restoration of degraded reefs is considered one of the major reef management strategies to help remedy the negative effects of human activities on coral reef ecosystems. Degraded coral reefs may not respond readily to restoration efforts due to our incomplete understanding of various ecological dynamics such as loss of source sites, decline in species richness, shifts in species dominance, trophic interactions, and bioinvasion. Coral reef restoration techniques are at an experimental stage. There are two major approaches to reef restoration: coral transplantation and artificial reefs. Coral transplantation is appealing because it is an efficient means of turning a bare reef into a highly covered reef and there is a scientific basis for the technique. By contrast, artificial reef implementation is widely used and apparently accepted by the public and some resource managers, yet its scientific foundation is far from complete. Even so, there are major potential benefits of artificial reefs, which make them an essential tool in reef restoration. I suggest that the focus on artificial reefs and coral transplantation be shifted to combined approaches that use aspects of both in conjunction with other methods such as re-introduction of algal grazers. This review examines the advantages, disadvantages, and general guidelines for coral reef restoration.

Coral reefs are among the most complex and biodiverse ecosystems on earth, and together with associated tropical nearshore ecosystems are critically important to humankind for the ecosystem goods and services they provide (e.g., Costanza et al., 1997). Yet coral reefs are in serious deterioration —suffering massive, long-term declines in abundance, diversity, and habitat structure due to overfishing, pollution and other anthropogenic and natural disturbances (e.g., Birkeland, 1996; Wilkinson, 2002; Pandolfi et al., 2003, 2005).

The worldwide deterioration of reefs, particularly in the last decades, has directed more attention to the prospects of mitigation activities, notably coral reef restoration (e.g., Edwards, 1998; Edwards and Clark, 1998; Pickering et al., 1998; Clark and Edwards, 1999; Yap, 2000, 2003). The increased attention has led to worldwide initiatives, which aim to improve the state of impacted reefs. The variety of mitigation activities ranges from species reintroduction and coral transplantation to enhancement of recruitment potential and artificial reefs (Grove, 1982; Edwards, 1998; Edwards and Clark, 1998; Clark and Edwards, 1999; Yap, 2000, 2003; Epstein et al., 2003). The term mitigation refers to any deliberate action taken to alleviate adverse effects, whether by controlling the sources of impact, or the exposure of ecological receptors to them (Treweek, 1999). The U.S. Council on Environmental Quality (CEQ) suggests several approaches to mitigation (i.e., avoidance, reduction/moderation, restoration, compensation, and rescue), which should be implemented sequentially, with avoidance measures assuming priority (Canter, 1996). Thus, reef impact mitigation should not replace reef protection as the first management option. How-

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ever, the numerous deteriorating reefs and wide areas of degraded reefs make the use of restoration approaches inevitable.

Restoration is defined as the act of returning an ecosystem, as nearly as possible, to its original condition (Edwards, 1998). At present, however, the defined goals of various restoration programs extend beyond this term, to describe acts that "take" ecosystems, or their components, to a wide variety of states. These include returning the reef to a previous state, rescuing or promoting a given species, increasing live cover or biomass, increasing diversity, etc. At present, there is no evidence for the effectiveness of restoration efforts on large timescales (10–20 yrs or more), and even near-term benefits are not well documented. However, it is fairly clear that restoration actions will continue despite the slow progress of our scientific understanding of the processes involved or the related benefits. Therefore, it is of immense importance to illuminate concerns and guidelines, which should be considered by researchers and managers prior to and during implementation of restoration programs.

In coral reefs, the two major restoration approaches are coral transplantation and artificial reefs, which in many cases are applied regardless of the environmental conditions, causes of decline, or goals. The aim of the present synthesis is to review these two methods as restoration tools, consider their benefits and disadvantages, and to propose guidelines, which may help in improving their success by better selection of appropriate methods and implementation protocols.

Selection of Restoration Methods

There are two levels of decision-making in the implementation process of restoration programs. First, the selection of a suitable restoration approach (i.e., artificial reefs, coral transplantation, combined artificial reef–coral transplantation, etc.) should consider the restoration goals (e.g., Table 1), degradation causes, the reef state, and present environmental conditions because these factors have significant influence on the consequences (benefits and drawbacks) of each restoration approach. Second, once the restoration approach has been selected, an appropriate implementation procedure should be tailored (Tables 2, 3). It should be kept in mind that the benefits of each program are conditioned by its appropriate implementation.

Despite the careful selection of a restoration program and its sound implementation, our present knowledge of restoration techniques is still limited, which can lead to significant shifts from the expected goals. In addition, our inability to predict future environmental conditions can contribute to unexpected consequences of the restoration actions. These two impediments may lead to the failure of the restoration program.

Another possible pitfall is an inattentive, fast-response approach. In cases where the sources of stress are persistent and reef deterioration continues, poorly conceived restoration measures may cause further adverse effects. For instance, coral transplantation aimed to replace dead corals of different species, may lead to drastic changes in community composition, especially if the donor corals for transplantation are of a limited species list. Algal blooms are also an example, where coral transplants may inhibit the grazing activity of sea urchins and other grazers, and discourage additional natural coral recruitment. Therefore, the presence of environmental stressors should be considered prior to the implementation of any restoration

Table 1. Possible coral-reef restoration goals.

1. Rescue/promotion of given species.
2. Increase diversity of sessile and/or mobile organisms.
3. Increase biomass of sessile and/or mobile organisms.
4. Increase live cover of sessile organisms.
5. Change demography (e.g., age structure) of given populations.
6. Increase genetic variability of given populations.
7. Re-modify the reef state following ecosystem shift.
8. Return the reef community to a given state (e.g., prior to a significant disturbance event).
9. Reverse habitat loss.

measure. In cases where the stressor persists, restoration efforts will probably not succeed as expected.

Critical Steps in Selecting and Applying the Restoration Program.—In order to avoid irreversible restoration-related adverse effects, the adoption of a careful "monitoring-restoration-control" protocol, which will allow step-by-step progress of the restoration program (Fig. 1), is recommended. The first step, prior to any implementation of a restoration program, is to assess the state of coral reef by biomonitoring at various biological levels (i.e., cellular to community; Bresler et al., 2001; Ben-Tzvi et al., 2004). The next step, to be applied by repeated monitoring, is to determine whether the stress sources are still effective and causing the reef further deterioration, or whether the process has stopped. In the first case, the mitigation program should commence with approaches other than restoration (i.e., avoidance, reduction, minimization, etc.) to halt the adverse effects on the reef. These can then be followed by a restoration program. In the latter case, a restoration program should be applied immediately. In both cases, the initial stages of the restoration program should consist of preliminary restoration actions (Fig. 1), which will be characterized by a relatively limited scale, location in less sensitive sites, and careful monitoring. During the preliminary restoration stage, various actions should be carried out to refine the exact restoration goals, understand the environmental conditions in the area, follow further changes in the state of the reef community and recognize possible adverse effects of natural and anthropogenic disturbance sources. The information obtained during the preliminary restoration stage is expected to provide the scientific basis for a full-scale restoration program and the exact restoration approach. Two such restoration approaches are examined and discussed below: coral transplantation and artificial reefs, as well as the combination of both.

Table 2. General guidelines for appropriate use of coral transplantation as a restoration approach.

1. Follow ecological principles rather than convenience considerations when selecting transplant species.
2. Avoid any significant damage to donor sites or colonies.
3. Attach transplants by efficient methods to improve their survival under extreme weather conditions.
4. Adopt various known methods (including lab treatment during early stages) to increase the survival of transplants.
5. Avoid changes in population genetic structure (notably promotion of resistant over susceptible genotypes).
6. Consider the use of artificial reefs as potential substrates in cases of limited natural substrates.

Table 3. General guidelines for appropriate use of artificial reefs as a restoration approach.

1. Site selection: select the site based on deployment assessment of environmental conditions in various candidate sites.
2. Site selection: avoid deployment of artificial reefs in proximity to natural reefs (yet, not too far).
3. Site selection: coordinate with other maritime activities, such as navigation and fishing.
4. Reef structure: follow accepted recommendations for reef structure materials (e.g., Christian, 1998).
5. Reef structure: fit shape-related outcomes of community development to restoration goals.
6. Reef structure: select resistant designs in terms of shape, size, weight, and materials to withstand extreme wave energies and avoid movement and breakup.
7. Reef structure: include notable traits in the restoration goals; e.g., shelter and refuge habitats for mobile organisms, appropriate surfaces for optimal settlement, and recruitment of sessile organisms.

Coral Transplantation as a Restoration Tool

Coral transplantation seems to be the most widely accepted coral reef restoration approach. This is reflected by the relatively wide range of studies dealing with coral reef restoration and remediation, in general, and with coral transplantation in particular (Rinkevich, 1995; Clark and Edwards, 1995; Edwards and Clark, 1998; Yap, 2000, 2003; Epstein et al., 2001, 2003; Sabater and Yap, 2002). The primary justification for coral reef restoration involving coral transplantation is if the affected area would otherwise fail to recover naturally, usually indicated by the absence of coral recruitment (Edwards and Clark, 1998). Coral reef restoration by means of coral transplantation may bear some clear benefits, especially in cases of promotion of a particular species or fish community restoration (Table 4). Such benefits include: immediate increase in coral cover and diversity; increased recruitment of coral larvae as a result of the presence of transplants; survival of locally rare and threatened species when their primary habitat is destroyed; reintroduction of corals to areas where larval supply is limited, or where post-settlement mortality is high; and instant increase in topographic complexity, and hence, shelter for various associated organisms. However, an inattentive or ill-conceived implementation of coral transplantation may lead to several possible adverse effects on the reef (Edwards and Clark, 1998; Table 4).

Potential drawbacks associated with coral transplantation include: loss of colonies from donor areas; high mortality rates of transplanted corals; reduced growth rates of transplanted corals; failure of attachment of transplants, and their subsequent loss due to wave action; and reduced fecundity of transplants due to stress. These drawbacks are related mainly to technical aspects. However, there are ecological aspects, which in many cases are overlooked, but should be carefully considered for their role in determining the reef community development following transplantation actions. For example, transplantation of certain coral species (usually from a very limited species list) can exclude sensitive species, which have been eliminated by the disturbance and will not recruit because of the transplanted corals. Therefore, by implementing coral transplantation, one determines to a large extent the community structure. Likewise, dense transplantation of numerous fragments may put constraints on grazing activity. It should be noted that the above drawbacks of coral transplantation are largely irreversible, disabling "retreat" in cases of failure of the restoration program.

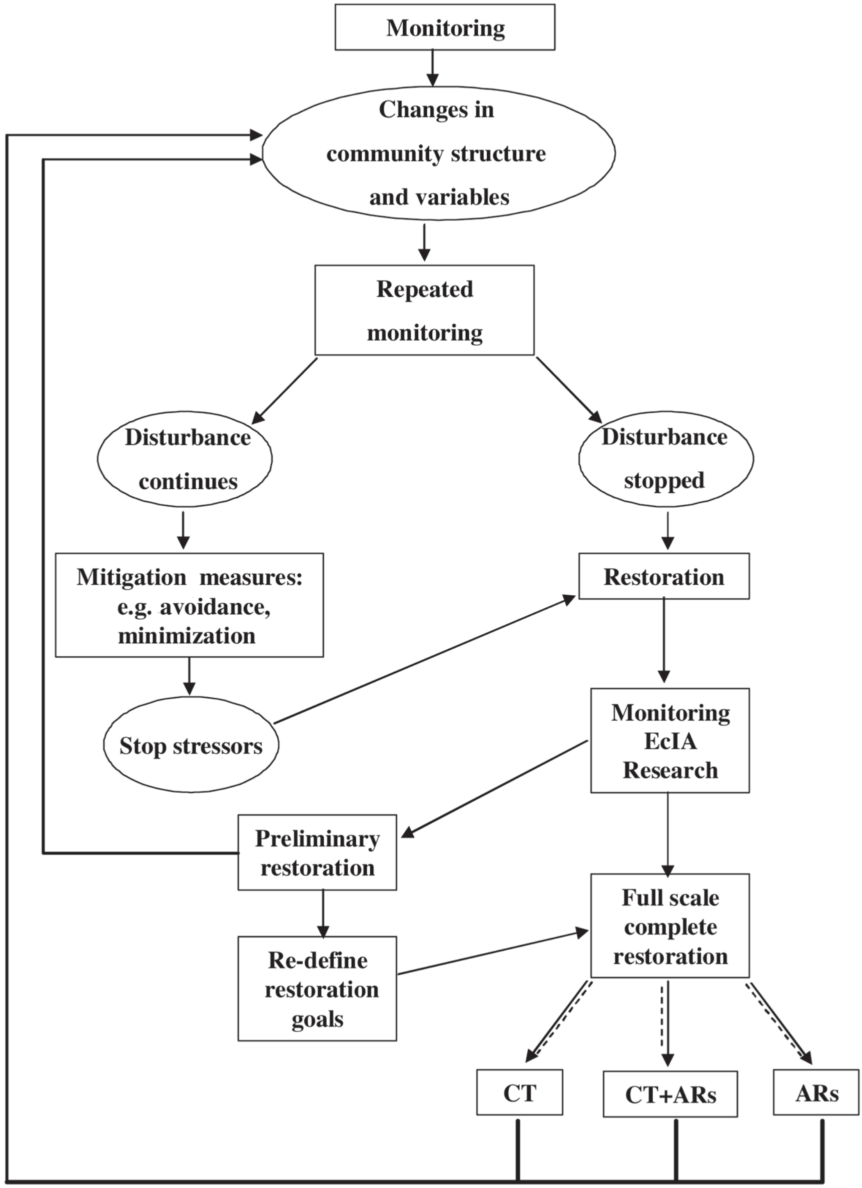

Figure 1. A conceptual flowchart of coral reef restoration. The critical decision steps of selection and applying preliminary and full-scale restoration programs are described as part of a "monitoring-restoration-control" protocol. Coral transplantation (CT), artificial reefs (ARs). The dashed lines indicate the three major alternative choices of coral reef restoration of which only one should be selected. *Further mitigation approaches are described in Treweek, 1999. EcIA = Ecological Impact Assessment.

Overall, it seems like the main appeal of coral transplantation as a restoration tool lies in its fast and prominent "achievement" in switching a bare reef into a lively, highly covered reef. However, at present, the "success" of coral transplantation programs is poorly supported by scientific knowledge, based on fairly limited spatial and

Table 4. Potential benefits and disadvantages related to coral transplantation as a restoration tool (following Edwards and Clark, 1998).

Potential benefits	Potential disadvantages
Increase coral live cover.	Promotion of common/dominant species.
Increase diversity of fishes.	Higher mortality rates of transplanted corals.
Increase recruitment.	Loss of transplanted corals due to attachment failure.
Promotion or rescue of rare and threatened species.	Reduced fecundity of transplants due to stress.
Enhancement of recruitment sites with limited populations.	Human-mediated selection of resistant genotypes.
Immediate improvement in aesthetics of physically destroyed sites.	Change in community structure.
Instant increase in structural complexity and recruitment immigration of diverse reef-dwelling species.	Limited knowledge and prediction ability.
Attractive projects that help promote public awareness.	Loss of coral colonies from donor sites inhibition of herbivore grazing activities.
	Reduction in substrates available for natural recruitment.

temporal experimental scales. Moreover, in most cases no controls were established to provide a comparative perspective of the restoration effectiveness.

Artificial Reefs as a Restoration Tool.—Artificial reefs are considered an efficient tool in enhancement of fishery and mitigation of marine ecosystems deterioration (e.g., Bohnsack and Sutherland, 1985; Seaman and Sprague, 1991; Collins and Jensen, 1999; Jensen et al., 2000). There are several environmental benefits expected from artificial reefs. First, they are expected to contribute to the conservation of natural reefs by diverting human activities from them. Second, artificial reefs can offer refuge for rare and endangered species of invertebrates and fish. Third, artificial reefs may provide nursery grounds for young stages of reef species (Collins and Jensen, 1999).

However, while the artificial reef method is widely used (in some cases over-used) by non-scientific bodies (i.e., for fishing interests, resource management, and public use), artificial reefs are not considered a promising restoration and remediation approach by coral reef restoration ecologists (for drawbacks of artificial reefs, see Table 5). Although this attitude is often not directly and explicitly stated, it is reflected by the poor attention to artificial reefs in publications dealing with coral reef restoration. This attitude is well reflected by a profile of the working group on coral reef remediation and restoration of The Coral Reef Targeted Research & Capacity Building for Management Project (GEFCORAL, 2004), according to which: "…Early initiatives focused more on artificial reefs where reefs or more accurately, fish-aggregating devices, are created on non-reef platforms, mainly to enhance fisheries production. While this approach is still being expanded, more recent activities are directed specifically at restoring degraded reefs."

There are various potential benefits of artificial reefs as a restoration tool (Table 5), with the most significant being that: artificial reefs are easy to remove, in case they fail to achieve their goals, offering easier "retreat" than the coral transplantation approach; artificial reefs can improve connectivity between sites, and therefore can assist in recruitment to natural reefs; artificial reefs provide extra substrate surfaces,

Table 5. Potential benefits and disadvantages related to artificial reefs as a restoration tool.

Potential benefits	Potential disadvantages
Increase in available substrates for reef organisms.	Slow development.
Increase in structural complexity.	Poor control of the community development.
Increase in settlement and recruitment.	Limited knowledge and prediction ability.
Increase in species diversity.	Reduction of larval supply from natural reefs.
Improving connectivity between sites.	Attraction of organisms from natural reefs rather than production.
Relatively easy removal in case of failure.	Possible adverse effects on neighboring natural reefs.
Instant increase in immigration of diverse reef-dwelling species.	Promotion of common/dominant species.
Attractive projects that help promote public awareness.	

and therefore, can serve as an ideal platform for restoration research and preliminary restoration actions. For these benefits alone, artificial reefs should be considered an essential tool in coral reef restoration and remediation.

Nevertheless, for artificial reefs to serve as an efficient restoration tool, the artificial reef design, deployment, and maintenance should follow basic guidelines, which are related to structure, shape, materials, size, location, etc. (e.g., Bohnsack and Sutherland, 1985; Seaman and Sprague, 1991; Christian, 1998; Jensen et al., 2000; Abelson and Shlesinger, 2002; Shemla, 2002). The guidelines are especially important to avoid damage to natural reefs and special attention should be given to site selection (Table 3). The artificial reef site should be selected based on pre-deployment assessments of environmental conditions in various candidate sites (Shemla, 2002). A notable consideration is the distance from natural reefs. If located in proximity to natural reefs, artificial reefs may exert adverse effects on fish and coral communities, especially so if serving as diving and/or fishing sites (Einbinder, 2003).

Conclusions

Conservation efforts over the past decade have been shifting from a focus on the preservation and protection of intact systems to the restoration of degraded systems. A major challenge to these efforts is that degraded communities often do not respond predictably to restoration efforts, producing inconsistent and sometimes unexpected results (Suding et al., 2004). Strong feedbacks between biotic factors and the physical environment can alter the efficacy of these restoration efforts. In this regard, degraded reefs may be resistant to such efforts due to various ecological changes, such as loss of source sites, loss of species richness, shifts in species dominance, trophic interactions, connectivity, and species invasion. To avoid failure of applied restoration measures, careful monitoring programs, which accompany the restoration process, are essential. Monitoring-based control procedures should actively respond to shifts from the expected progress of the restoration measures and their consequential recovery process.

Competent approaches and methodologies of coral reef restoration are in their early development stages, and therefore, are difficult to implement on large spatial scales. Furthermore, there are significant gaps in the scientific understanding of the complex processes of natural recovery that impede the success of restoration programs. These problems are true for all currently known restoration approaches, including coral transplantation and artificial reefs, but more so when dealing with other, much less studied approaches, such as species reintroduction (e.g., reintroduction of grazers to control algal cover; GEFCORAL, 2004) and recruitment enhancement (e.g., Heyward et al., 2002).

The present focus on coral transplantation and artificial reefs should be shifted to include combined approaches. This combined restoration approach should consider the use of artificial reefs with coral transplantation, as well as relatively neglected restoration methods, such as reintroduction of species (e.g., pre-disturbance dominant grazers) and settlement and recruitment enhancement. The idea of combined tools is to gain benefits from the different restoration methods, while reducing the disadvantages of each. artificial reefs can and should function as a major platform of such combined methods, especially at the research and preliminary restoration stages.

Acknowledgements

This study was funded by the U.S.-Israel Bi-National Science Foundation (BSF) and the MERC program of US-AID. The author thanks the Director and staff of the Marine Biology Laboratory at Eilat for their hospitality and the use of lab facilities. Thanks are also due to O. Mokady and N. Paz for their review of the article.

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