Coral Reef Mitigation and Restoration Techniques Employed in the Pacific Islands: I. Overview

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Abstract- In the past two decades numerous reef mitigation and restoration projects have been undertaken throughout the world. This article summarizes our experience with a wide range of projects in Hawaii and the U. S. - affiliated Pacific islands. The terms "mitigation" and "restoration" are often taken to mean reef repair, coral transplantation or construction of additional habitat (e.g. artificial reefs). However, other options are available and should be considered. In some situations removal of the anthropogenic factor causing the damage while allowing natural processes of recovery to occur is the best approach. Natural rates of reef recovery can be very rapid in such situations and direct human intervention on the reefs is unnecessary. In some instances a negotiated environmental settlement or financial penalties can be used to establish trust funds to offset environmental losses. Review of past attempts to mitigate reef damage and restore reefs suggests that managers must have a broad strategic plan and incorporate a wide range of approaches designed to fit each situation on a case by case basis. Although protection of the reefs must always be the top priority, there will inevitably be situations where damage will occur. In these situations restoration and mitigation measures will have to be considered.

I. INTRODUCTION

Reef coral communities are destroyed by storm waves [1], ship groundings [2], fresh water floods [3], crown-of-thorns starfish invasions [4], dredging [5], various forms of pollution [6,7,8,9,10], and coral mining [11]. In recent years there has been extensive damage to reefs on a worldwide basis due to bleaching and coral death that has been attributed to global warming [12].

A number of approaches have been employed in attempts to offset these losses. Over the past decade the authors of this article have been directly involved in a number of coral reef restoration and mitigation pilot projects in Hawaii and the U. S. - affiliated Pacific islands. For the most part the results of the projects have not been published in journals, so information is only available from various reports and through personal communication with individuals directly involved in the work. The purpose of this paper was two-fold. First, we describe and summarize examples of various types of mitigation and restoration projects from our region in order to demonstrate the types of problems encountered and the approaches previously used in various situations. Second, we synthesize and evaluate the usefulness of the techniques. Information contained in this paper also provided the basis for a companion paper on guidelines for the mitigation and restoration of coral reefs [13].

II. OVERVIEW OF MITIGATION/RESTORATION PROJECTS IN THE PACIFIC ISLANDS

For purposes of this discussion we group the various approaches used to mitigate reef damage and restore reefs into four main categories: A. Direct Action, B. Indirect Action, C. Negotiated Settlement and D. Establishment of Strategic Reserves.

A. Direct Action

Most of the mitigation/restoration projects undertaken in the past fall into this category [14-26]. Active intervention is generally directed at the reestablishment of reef coral populations and/or coral habitats in damaged areas. The focus generally is on re-establishing the reef corals because they form the reef framework, and their presence is a requisite for many other forms of reef biota. Techniques for active intervention include reef repair, coral transplant, coral seeding, or construction of artificial reefs.

1. Reef Repair

During 1992 a large naval vessel dragged its mooring chain across a submerged reef in Agana Harbor in Guam, damaging the corals over a wide area. The military claimed jurisdiction and argued that no mitigation was needed. The Guam Attorney General's office ruled that resources belonged to people and threatened lawsuit. In response a recovery effort was developed that included righting the overturned corals, stabilizing fragments and removing debris. The area was mapped and monitored. Many fragments did eventually reattach and survive. A major factor contributing to the recovery was that the site is protected from ocean storm waves and swell, so the broken and dislocated corals remained in place. Within five years there was considerable recovery of damaged corals and recruitment of new corals, but damage was still evident [27].

2. Transplantation of corals.

During the construction of the Pacific Underwater Observatory, Piti Bay, Guam, USA, corals were moved to clear a path across the reef flat. The corridor was used to move pre-fabricated observatory components and support facilities (a jack-up barge and crane) across a reef flat and into a large sinkhole known locally as the Piti bomb hole [28]. The first phase (1990-1991) involved determination of a tow route across the reef that would impact the fewest numbers of corals and result in the least risk to the reef. The Piti reef flat in is frequently impacted by typhoon-generated waves and consists largely of unconsolidated sand and gravel resting on a carbonate framework that is strewn with large carbonate boulders. Reef corals and soft corals found on the reef flat generally are attached to these large blocks. The optimal tow path selected across the reef flat had a centerline distance of approximately 1500 ft. and varied in width from 100 to 130 ft. The edges of the tow path were marked with buoys. At its shallowest points the depth was approximately 2.5 ft below MLLW. During typical non-spring high tides the depth at these same locations averages approximately 5 ft. Only those carbonate boulders large enough to obstruct movement of the observatory components and support vessels were identified and tagged for transplantation. A total of 69 large blocks of with 400 attached coral colonies were moved the minimum horizontal distance (generally less than 30 feet) needed to clear the channel and were moved the minimum distance out of the channel to a location having the same depth. Care was taken to avoid coral damage during detachment and movement. Depending on the size of the feature various techniques were used including pry bars, airbags, buoys, skiffs, and a ring carriage. Transplant mortality did not occur, but 29 corals showed slight damage (less than 1% of tissue area damaged, with one coral showing more extensive damage (less than 50%). After six months these corals had healed, but predation by the starfish *Acanthaster* had killed 11 corals, about the same rate as for non-transplant corals. This project was successful because corals were moved short distances within their normal environment and did not experience severe changes in light, water motion and other factors. They were moved attached to large blocks of substrate, so did not need to be re-attached at their new site.

One of the major pitfalls of a transplant program lies in identifying a suitable site to receive transplanted corals. This problem was demonstrated during a project designed to salvage corals that would be destroyed during the construction of the West Rota Harbor in Saipan. Approximately 10,000 corals were transplanted out the area to be dredged during 1996 [29]. The selected receiving area was adjacent to a landfill site and to the main shipping channel. In November 1997 the tanker Shogun ran onto the coral transplant reef resulting in extensive damage. On December 16, 1997 storm surf from the Super Typhoon Paka further disturbed the area. The commonwealth Ports Authority now plans to dredge the area where the corals were transplanted in order to expand the harbor.

In 1994 a large-scale transplant pilot study was undertaken at Kawaihae Small Boat Harbor, Hawaii. The harbor development project was initiated in the early 1960s, but not completed. The entrance channel and turning basin had been blasted in 1969 and 1970 during "Operation Tugboat". Completion the harbor required extension of the existing breakwater and construction of a new mole and breakwater [30]. No additional dredging was required. However, the planned construction covered about 1.8 hectares (4.5 acres) of shallow reef habitat, some of which was occupied by corals and associated organisms [31]. A coral transplantation and monitoring plan was developed in order to evaluate the feasibility of this method as a tool to mitigate adverse impacts of harbor construction [32]. Corals that would eventually be buried under the breakwaters were moved to eight transplant sites that had low coral cover. These sites ranged from deep fore-reef to reef flats, channels, and within the harbor.

Divers first placed squares of wire (5 cm mesh) on the substrate adjacent to the collection site. A float was tied on one end of a 25 m line and a large spring clip tied to the opposite end. The line was clipped onto to one corner of the chicken wire mesh, serving as a visual marker for the divers. This line was used later to haul the corals off the bottom. Divers then moved corals and placed them on the chicken wire. Most corals were loosely attached to the substratum or rested on unconsolidated material and were easily moved. Occasionally, a sledgehammer was used to loosen corals that were too large or firmly attached. When the chicken wire was amply covered with coral, divers secured the four corners with the clip, forming a sling. The divers then returned to the boat and completed the operation with no personnel in the water. When all personnel were safely out of the water, the boat engines were started and the boat maneuvered alongside of the floats. The float was retrieved, and the two or more persons hauled the bags off the bottom. The bags were hoisted close to the surface, the lines were tied off on cleats. Generally four bags of corals were carried on each boat trip. The boat slowly transported the corals to the transplant sites. Bags were lowered to the bottom, and the floats thrown clear of the boat, after which time the boat was anchored and secured. Divers then entered the water to set up the transplant stations. Corals remained fully immersed in water throughout the operation. All of the corals moved in this operation were massive colonies typical of high water motion environments. These corals can be handled with little or no breakage. Much more care is required in transplanting delicate species.

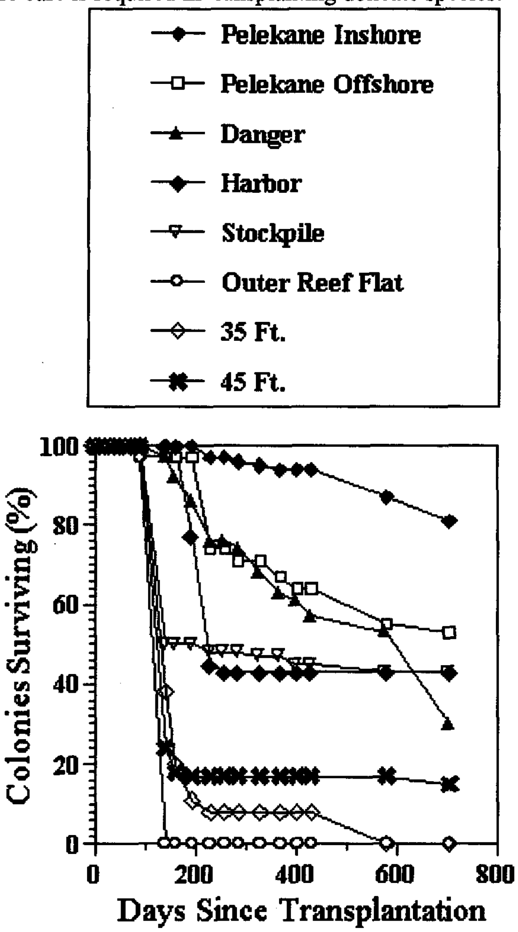

Fig. 1. Colony survival over a 2 year period following transplantation of corals at Kawaihae, Hawaii at eight transplant habitats ranging from fore-reef, reef flat, inshore, offshore channels and within the harbor [32].

At each experimental transplant site, a 2.5 m x 2.5 m square of wire mesh was firmly attached to the bottom using stakes cut from steel reinforcing rod and large nails. Corals were then placed and secured to the grid with wire. Four sediment traps were attached to stakes at each site. Photographs and video were taken and used to compile detailed maps of the corals located at each transplant site. These maps were subsequently used by divers to monitor survivorship of corals. A total of 47 bags of coral were moved. Bags are estimated to weigh between 45 and 70 kg buoyant weight. Taking an average of 58 kg, an estimated 2,700 kg buoyant weight were moved. The ratio between buoyant weight and wet weight for the dominant species in the area, was calculated to be 2.76. Thus approximately 7,500 kg (16,000 lbs) wet weight were moved. A total of 43 person days were spent in the process.

Results of the transplant effort are shown in Fig. 1. The transplant was conducted during the calm summer months and initial mortality was non-existent. The winter following the transplant effort produced some of the largest swell seen at Kawaihae in 10 years, damaging many of the plots by burial or physical removal of the corals. Corals not damaged by wave action continued to show decline over time due to various local factors such as overgrowth by algae, fish grazing on coral tissue or high sedimentation. Additional corals were transplanted into several of the areas showing highest survival, but these corals also gradually declined over the course of a year.

The overall conclusions of the study were:

- Reef corals can be transplanted successfully in large numbers with little or no initial mortality.
- Receiving areas available are generally marginal habitats, which cannot support high coral coverage over the long run.
- Corals transplanted into marginal areas will eventually decline due to a variety of factors including wave damage, sedimentation and eutrophication.

A more successful pilot transplant project was conducted at Kaneohe Yacht Club, Oahu using modified methods developed at Kawaihae [33]. Luxuriant coral growth in portions of this harbor reduced the depth and impaired navigation. A transplant project was undertaken to move the obstructing live corals from the harbor area to a nearby dredged fringing reef north of the harbor. The transplant receiving area selected is outside of navigable areas used by boats. The receiving reef had been dredged for seaplane runways circa 1940 and never recovered due to the presence of a thin layer of sand and silt which prevented coral larval settlement. The area is well suited to coral growth, if colonies could be established. The receiving area is not subject to ocean swell, so delicate colonies moved into the area would not be moved and damaged by wave action.

Three 6 square meter plots and one control plot were established at a depth of approximately 3 m. The corals in the harbor were gently pried from the bottom and moved into large plastic trays. The trays were kept submerged and hung from lines to a skiff, which moved the material at slow speed to the transplant site. The corals were removed from the trays and placed within the marked plots. A total volume of 5.2 cubic meters of coral was moved in five trips within a three-day period and resulted in roughly 20 square meters of bare substratum. Transplant occurred in June 1996 with little initial mortality. The transplant plots have been resurveyed and continue to thrive 5 years after the transplant effort.

3. Provide additional habitat

Reef damage can be partially offset by providing additional habitat in the form of artificial reefs or sunken wrecks. Artificial structures are not natural reefs. However, such habitats can serve a beneficial and useful purpose as excellent sites for recreational diving and fishing and thereby take pressure off of natural reefs.

Extensive damage and loss of a valuable dive site resulted at Sasanhaya Bay, Rota, CNMI when action was taken to eliminate a perceived danger from explosive depth charges aboard a sunken WWII Japanese warship. In May and June of 1996 an explosive ordinance demolition team detonated the explosives, which destroyed the historic wreck and caused extensive damage to the surrounding coral reef. A reef dominated by the coral *Porites rus* was reduced from 60% to 1% within approximately 150 m of the blast. Public outrage from divers, dive tour operators, fishermen, and environmentalists led to the development of a mediation plan. Two derelict vessels were cleaned of all contaminants and sunk in the area to provide additional dive sites and to provide fish habitat [34].

A major re-design and expansion of Maalaea Harbor, Maui, Hawaii has was proposed over 20 years ago, but has been blocked by environmental concerns. The proposed harbor development project has been designed and re-designed due to public concerns. Under the most recent proposals, alternative mitigation measures were included. Opportunities for mitigation of reef damage through use of coral transplant method do not exist at Maalaea due to lack of suitable receiving environments in the area [35]. The major factors preventing reef development along the Maalaea coastline are: 1). Lack of suitable hard substratum in the area and 2.) Severe wave impact and low tide exposure in the shallows.

However, lush coral reef communities have developed on all modified hard surfaces (dredged faces and rip-rap surfaces) at Maalaea in the 10 foot to 20 foot depth range [35]. Most of the coral habitat areas that will be impacted by proposed modification of the harbor at Maalaea are areas that were previously modified during the original construction of the harbor. Therefore, the proposed mitigation project involves modification of existing altered habitats with other altered habitats.

An interesting mitigation method has been proposed for the Maalaea project [36]. The plan calls for modification of the proposed sea wall design to include extension of boulder rip-rap along the groins to depths of 20 feet to 30 feet. This would create a rich coral reef in areas where only shifting rubble and sand exist today. Engineers involved in planning the project see this option as being cost-effective and well within the scope of the engineering plan. Creation of this additional habitat would increase the fisheries resource (fish, octopus, lobsters, etc.) immediately adjacent to the sea walls of Maalaea Harbor. This area is easily accessible to the public and would offset the loss of habitat caused by development of the harbor. Essentially, this modification would replace an unstable sand-gravel substrate with a complex hard-substratum environment that is suitable for coral reef development. Engineering design of the sea wall extension farther is not a difficult task, but the design must withstand the largest storm waves experienced at this site. Large riprap boulders set in the same manner as on the sea wall would be suitable. Such high-relief boulder riprap areas are rapidly colonized by corals, fish and invertebrates as shown by observations off the seaward channel at Kawaihae Harbor [37].

The engineering characteristics of this proposed modification are similar to requirements for other artificial coral reef habitats:

- Hard surfaces (basalt, carbonate, concrete) suitable for coral recruitment.
- Stability and permanence (able to withstand maximum storm surf without movement or damage, resists corrosion and erosion).
- High substrate complexity (high bottom relief, high rugosity, many holes and crevices for fish refuge).

An additional method that is under development involves seeding a reef with coral larvae. This method is appropriate when there are insufficient natural sources of larvae to establish colonies and where the substratum is suitable for initial coral settlement. It is a desirable method for establishment of some corals that do not transplant readily such as the large table *Acropora*. To date, a number of studies are showing some promise.

B. Indirect Action

One of the most effective and widespread actions leading to the restoration of reefs is seldom discussed. A powerful means of mitigation and restoration is to reduce or eliminate anthropogenic impact and allow natural processes to restore the reef. In such instances the emphasis is on eliminating the problem, which in any event must be accomplished before any restoration can begin. Once an anthropomorphic stress has been removed, rapid natural recovery of a reef system often occurs rapidly without further action. Numerous examples can be cited:

- Removal of sewage outfalls in Kaneohe Bay led to rapid recovery of coral reefs [38,39].
- The reefs off the former target island of Kahoolawe, Hawaii, were under tremendous sediment stress due to erosion caused by poor land management. Removal of 20,000 feral goats, termination of bombing, and efforts to reestablish vegetation and stabilize the soil is having a dramatic impact on the reefs. Sediment is now being winnowed away from the shallows faster than it is being delivered from the land. As a result, corals are rapidly colonizing the hard substratum that is gradually being uncovered by natural wave processes [40].
- Hurricane damage in 1992 decimated coral reefs along the south coast of Kauai, which are recovering rapidly. In many areas coral coverage and diversity is as high as found on undamaged reefs [41].
- Discharge of silt-laden was water and bagasse from sugar mills along Hawaii's Hamakua coastline caused

extensive damage to coral reefs [42]. Termination of discharges led to a rapid clearing of sediment and waste by wave action and subsequent regeneration of coral reefs in the former discharge zones [43,44].

C. Negotiated financial settlement or "trade offs".

In some cases the primary options are not available and environmentalists must make the best of a bad situation by obtaining some sort of settlement in order to achieve environmental or social benefit as compensation for the damage. For example, the bulk carrier Oceanus grounded on Satawol on March 18, 1994. The ship cut a large trench in the reef and pulverized the coral. More damage resulted as the ship was pulled off the reef. Subsequent shifting of coral rubble created by grounding destroyed other habitats. The impacted area was the prime fishing and gathering site for the residents of Satawol. The remoteness of the island and high wave exposure of the site severely limited the options available for repair and restoration. The residents went to court and were eventually awarded a settlement for approximately $2 million, a large portion of which went into a trust fund that is being used to offset the socioeconomic and environmental impact of the grounding [45, 46].

During 1988, the U.S. Department of Defense proposed a project to dredge one of the richest reefs in Agana Harbor (Guam) in order to build an ammunition wharf. This site was the only location suitable because of the explosive hazard [47]. Environmental managers in the responsible agencies concluded that it would be impossible to block the action because of the national defense provision. To oppose the action would be futile so alternative action to mitigate the damage was undertaken. In exchange for damage to the reef, the federal government agreed to create two permanent reef reserves. The Haputo Ecological Reserve and the Orote Peninsula Ecological Reserve were established. Enforcement provisions in the reserves led to the end of dynamite fishing in the area. Certainly no one would recommend the "trade-off" course of action except in cases where there is no chance of preventing habitat loss.

D. Strategic Reserve Network.

We are entering a new era of mitigation and restoration. There is increasing evidence of global reef decline due to global warming, global nutrification, over-exploitation and various other factors. Recently, the concept of developing strategic global coral reserves has emerged as a means of offsetting global decline in reef systems [48]. During the January 2001 meeting of the American Association for the Advancement of Science (AAAS) in San Francisco, past president Dr. Jane Lubchenco released a scientific consensus statement signed by 150 of the world's leading marine scientists declaring that there is now compelling scientific evidence that marine reserves conserve both biodiversity and fisheries, and could help to replenish the seas. Completed 3 year studies sponsored by AAAS demonstrate that networks of fully protected marine reserves linked ecologically (through larval dispersal) and physically (through currents) are much more likely to achieve the full array of benefits that marine resource managers are being called upon to deliver. A meeting of experts in May 2001 that was organized by the Nature Conservancy is in the process of establishing guidelines for development of an interconnected coral reef reserve network for the future [49]. Thus the terms mitigation and restoration are taking on a global meaning in a time of global coral reef decline.

III. Conclusions

Our experience with reef restoration and mitigation projects in the U.S. affiliated Pacific Islands is consistent with studies from other parts of the world and lead us to the following conclusions:

- Given the documented global decline in coral reefs, restoration and mitigation must be viewed from a broad global strategic perspective rather than from a limited local point of view.
- Protection of reefs from environmental degradation must be given highest priority, because mitigation and restoration efforts are expensive and often ineffective. If damage does occur, managers have a wide variety of mitigation/restoration tools at their disposal. These tools includes removing anthropogenic stress, reef repair, coral transplantation, construction of artificial habitat (artificial reefs, sunken wrecks), establishment of compensatory environmental trust funds and creation of protected area networks.
- Mitigation and restoration focus must be on coral habitat rather than coral colonies.
- Transplantation of coral heads is feasible but has many limitations. Initial transplantation of corals is generally highly successful, with no mortality associated with the transplantation process itself. Gentle handling and keeping the corals submerged in baskets during transport is important to transplantation success. Initial mortality is low if factors that stress corals are minimized and transplanted corals are secured to the substratum. However, transplanting corals into a marginal habitat leads to their eventual demise.
- Favorable transplant sites are generally limited to wave-protected lagoon areas. Infrequent wave events along exposed coastlines (intervals of 10 years or more) have major impacts on the structure of coral reefs. These events are devastating to transplant sites due to the difficulty of securing transplanted corals properly to substrate. These events can dislodge, bury, abrade or break corals.
- Emphasis in the future will increasingly be on the establishment of coral reef reserve networks. Such reserve networks will serve as a primary tool in the restoration of reefs throughout the world.

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