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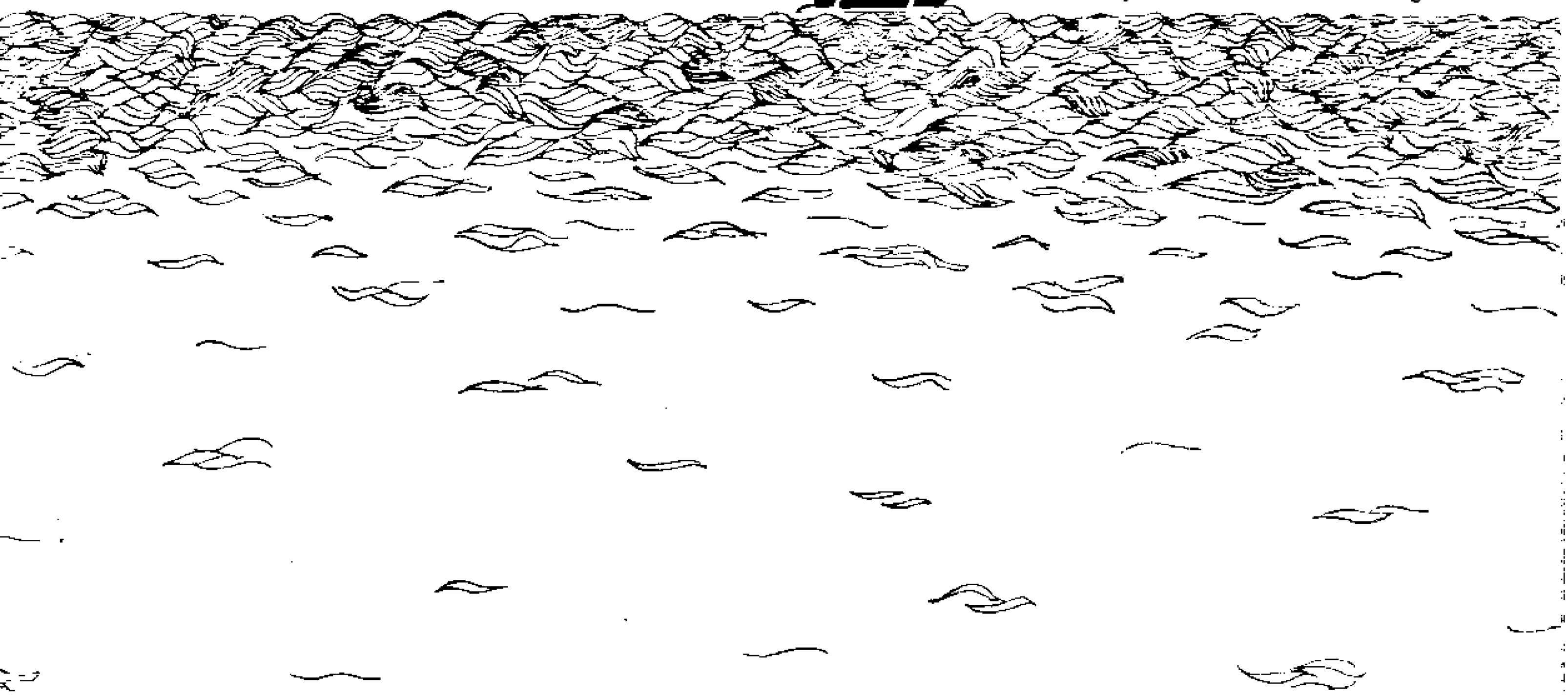

Coral Transplantation: A Method to Create, Preserve, and Manage Coral Reefs

James E. Maragos

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CORAL TRANSPLANTATION: A METHOD TO CREATE, PRESERVE, AND MANAGE CORAL REEFS

by

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Report on the Sea Grant project, Succession and Stimulation of Succession on Denuded Coral Reef Substrates (R/07-01); Keith E. Chave, Principal Investigator; Sea Grant Years 01-05.

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ABSTRACT

Coral reefs in Hawaii and other tropical areas are valuable economic and recreational resources. However, in recent years urbanization and other human activities have accelerated the destruction and pollution of reef resources. Past studies have indicated that reefs are very sensitive to man-made stresses and, once denuded, may take decades to recover. The feasibility of using transplanted corals as a method to shorten recovery time and to create new coral reefs is discussed in this report. Corals of two common Hawaiian species, Porites compressa *and* Montipora verrucosa, *were transplanted in three areas of Kaneohe Bay, Oahu and were monitored for growth and survival over an 18-month period. Natural rates of coral recovery over a period of 34 years in Kaneohe Bay were also studied to assess the importance and feasibility of the transplantation method. Results of the study showed that coral transplantation may be an effective procedure for preserving and creating coral reefs in Hawaii, especially in some environments where natural recovery is likely to fail.*

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INTRODUCTION

The coral reefs of Hawaii are an important natural resource. Reefs are composed of coral skeletons and other biogenic carbonate remains which have been cemented together to form rigid structures. Much of the city of Honolulu lies upon a fossil coral reef and many Hawaiian shorelines are surrounded by broad reefs. These formations act as natural breakwaters protecting land areas from large waves and storms and, at the same time, provide habitats for a large number of organisms including commercially exploited fish and other food organisms (shellfish, *limu*) which live within reefs. Coral reefs have also become increasingly important to man for recreational purposes such as skin and SCUBA diving, spearfishing, shell and coral collecting, surfing, and underwater photography. With time, skeletons of reef organisms including corals are broken down into small particles to form and replenish white sand beaches along many of Hawaii's shorelines. It is also used by the construction industry to make concrete.

The importance of corals to reefs may be compared to the value of trees to forests. Trees are the physical structure of forests. Without trees there would essentially be no forest. Similarly, without corals there would be no reefs. However, while the management of forests has been going on for centuries, the management of coral reefs is a new and unpracticed concept.

It has been established that coral reefs are sensitive to the modifications of the environment by man. In Hawaii the degradation of reef areas has increased at an alarming rate in recent years. Eutrophication associated with sewage discharge, dredging activities with channel and harbor construction, and sedimentation and flooding with poor land management practices have been identified as especially damaging stresses to reef environments. These stresses are more intensified where water exchange is restricted. Hence it is not surprising to find protected bays and lagoons among the first to be noticeably modified; for example, Palmyra lagoon (Dawson, 1959), Kaneohe Bay (Maragos and Chave, 1973), and Pearl Harbor (Evans, personal communication; Smith, personal communication). In some cases a decline in the amount of normal reef organisms coincides with an increase of other organisms, especially benthic algae, which may further displace or destroy the original communities (Banner and Bailey, 1970; Maragos, 1972a; Fischelson, 1973). It is also evident from other preliminary studies that once reef communities are destroyed, complete recovery may not occur for several decades or even longer.

It has become increasingly apparent that there is a need to develop a means to modify or to alleviate urban stresses on coral reefs. Other approaches could concentrate on the establishment of procedures which would enhance natural recovery of reef communities. A future goal may be to develop techniques to establish reef communities in areas where they normally do not occur.

There are two possible ways for reef communities to recover after favorable environmental conditions have been restored. Natural dispersal and colonization by larvae is the usual mode. The second way involves artificial stimulation through human activities.

The feasibility of transplanting reef corals as a method for hastening the recovery of degradated reefs as well as for creating new coral reef communities is discussed in this report. Other studies (Shinn, 1966; Maragos, 1972a) have shown that corals can be transplanted without damage and will grow normally if certain precautions are taken. This report concentrates on a further application of the method to determine under what conditions transplantation would be ecologically significant and economically feasible.

METHODS

Three reef sites in the lagoon of Kaneohe Bay were selected for study. Each site was subjected to a different set of environmental conditions. Naturally occurring corals, if they existed, were removed from the immediate vicinity of each transplant site prior to the experiments. Several hundred colonies of the two most important Hawaiian corals were transplanted from natural reef habitats to the study sites. Growth, survival, and losses of the transplants were monitored at frequent intervals over an 18-month period.

The second aspect of this study involved the investigation of natural coral colonization. In order to quantitatively assess the importance and feasibility of the transplantation method, it was necessary to acquire information on the patterns and rates of natural coral recovery. It was also necessary to determine under what conditions, if any, natural recovery rates would be sufficient to preclude the need for transplantation. Information obtained from earlier studies on the colonization of corals on dated surfaces was also consulted (Grigg and Maragos, in press; Maragos, 1971, 1972b). A series of artificial surfaces were established in the bay in order to monitor colonization of corals during time periods of 0 to 1.5 years.

TRANSPLANT STUDIES

Transplantation Site Selection

The three transplant sites are located from north to south in the lagoon of Kaneohe Bay. Open-ocean environments were not selected for two principle reasons: (1) reefs having good water circulation and exchange are less likely to be affected by urban stresses and (2) wave impact and surge currents in such environments create difficulties and increase cost factors.

An earlier transplant study (Maragos, 1972a) showed that corals transplanted in healthy reef communities grow and respond in a manner similar to naturally established corals in the same environments. It was therefore concluded that a control transplant station located on a healthy coral community was unnecessary for the present study.

The north bay transplant station

The north bay transplant station (Site A) is located on the western-facing (leeward) edge of a shallow, broad reef flat which extends eastward for 2 km (Figure 1). Water depth at the station varies between 1.0 and 2.0 m and horizontal water visibility is usually 8 m or more, making light and temperature conditions at the site optimal for coral growth. The substrate is composed of sand, rubble, and consolidated coral rock. About 20 m to the west of the station is a steep lagoon slope where flourishing fingercoral *(Porites compressa)* communities dominate the slope to depths of 10 m. A rippled sand channel is located immediately northwest of the station and has an average depth of 2 m. Waves break along the front edge of the broad reef about 1 km to the northeast and generate moderately strong surge currents as the waves pass over the station toward the lagoon. During exceptionally high tides and heavy surf, large waves break within 50 m of the station and produce strong surge currents. Sand-sized sediment is frequently in suspension due to water motion.

The mid-bay transplant station

The mid-bay transplant station (Site B) is located on top of a patch reef which was dredged to a depth of 3 m in 1939 (Figure 1). The station, situated approximately 0.5 km north of Coconut Island, is located 20 m west of the steep, eastern-facing slope of the patch reef. Although horizontal water visibility at the station, which varies between 4 and 6 m, is less than that found at the northern station, light and temperature conditions are nevertheless considered adequate for coral growth. Coarse sand, pebbles, and rubble dominate substrate cover at the station. Long-period swells and large waves do not strike this section of the reef and therefore do not produce noticeable surge currents. However, the station is subject to good circulation and wind chop. Coral communities are well developed along the slope but are not as flourishing as those reported near the northern station.

A few loose-lying colonies of *Montipora verrucosa* noted at the station were removed or incorporated as transplants prior to the experiment. The dominant benthic organism at Site B was the green algae *Dictyosphaeria cavernosa*, commonly referred to as "bubble algae." Naturally occurring coral colonies of both *Porites* and *Montipora* were being rapidly smothered by mat-like expanses of the algae during the course of the study.

The south bay transplant station

The south bay transplant station (Site C) is located on top of a predominantly sandy section of a patch reef which was dredged to a depth of 3 m in 1939 (Figure 1). The station is situated approximately 100 m south of Coconut Island reef. Municipal sewage is discharged into Kaneohe Bay lagoon approximately 3 km to the south. The sewage is a source of plant nutrient which greatly increases productivity levels in the south bay and results in decreased water transparency. Average horizontal visibility was between 2 and 3 m during the course of the study.

Several decades ago coral communities were very common in the south basin but they were almost absent at the time of the study. A few isolated colonies of *Montipora verrucosa* were noted near the station site. Bubble algae *(Dictyosphaeria)* was also common forming large, rounded masses which appeared to live unattached to most reef substrates near the station. Although coral development was greater on the adjacent slope located 35 m west, those

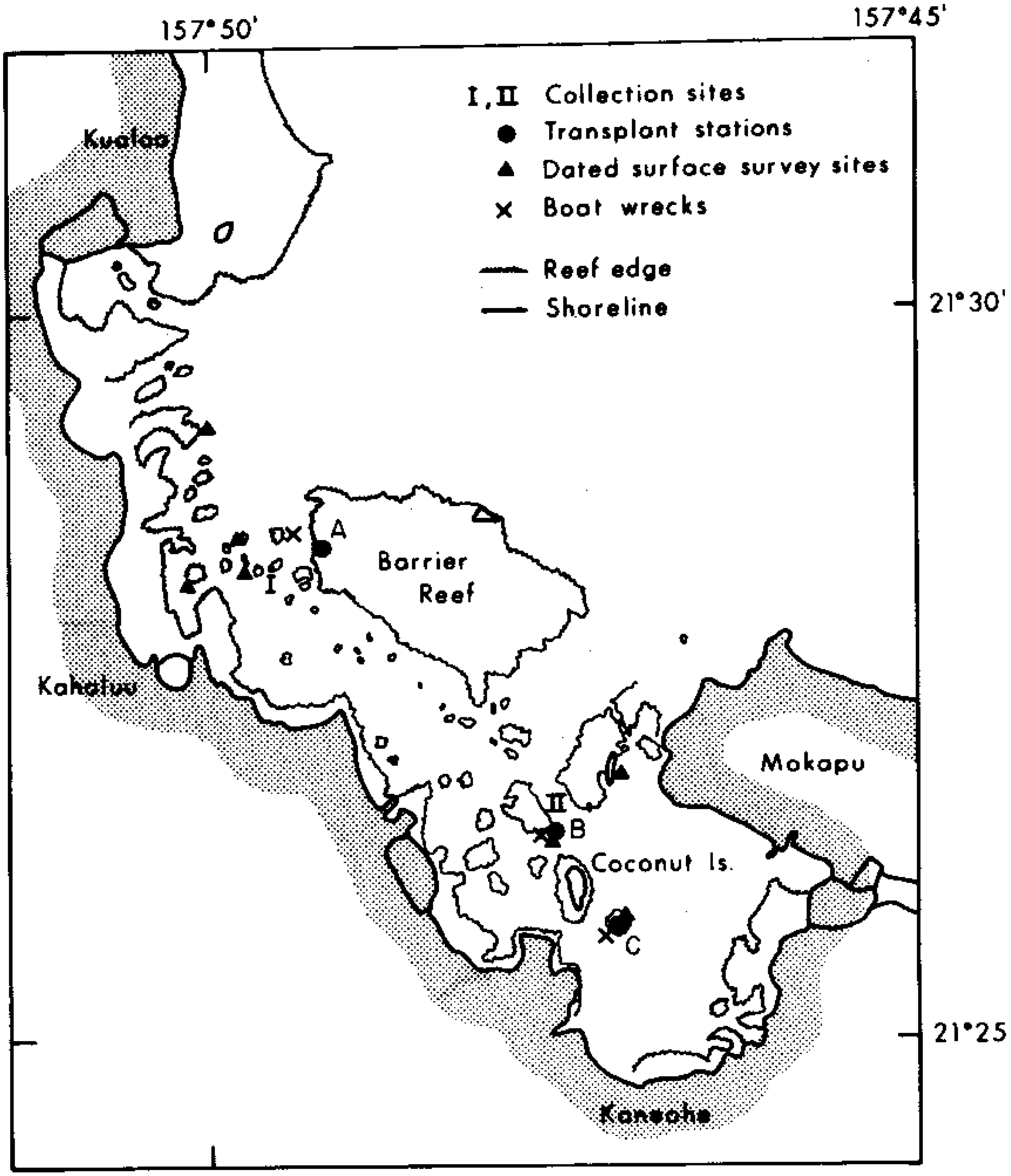

Figure 1. Map of Kaneohe Bay showing sites of coral collection, transplant stations, sites of dated surface surveys, and boat wrecks.

communities were more poorly developed than most reef slope communities in the middle and northern sections of the bay.

Transplant Species Selection

Past studies have indicated that *Porites compressa* and *Montipora verrucosa* are dominant reef corals in protected lagoon environments in Hawaii. *Porites compressa* accounts for 85 percent of the total coral cover in Kaneohe lagoon and *Montipora verrucosa* accounts for an additional 10 percent. These are among the fastest and largest growing of Hawaiian corals (Maragos, 1972a). They are common, easy to collect, and, because of their irregular or branching growth form, easy to attach by means of wires. Frequently, colonies lie loose on the substrate.

There are over 30 common species of Hawaiian reef corals but only the two species mentioned above were considered appropriate for use as transplants. The other species were not selected for one or more of the following reasons: (1) rare or confined distribution; (2) slow growth; (3) limited colony size; (4) colony form not conducive for removal or attachment; and (5) common only in open-ocean environments.

Establishment of the Stations

The establishment of the three transplant stations began in October 1971 when eight army surplus iron bedframes were positioned side by side at each of the chosen sites (Figures 2 and 3). The bedframes served as attachment platforms to which a number of insulated, nontoxic, telephone wire strands were tied. Later identification numbers were assigned to each platform.

Coral transplantation was carried out about one month after the bedframes were established. In November 1971 divers descended to the reef bottom to collect *Porites* from Site A and *Montipora* from Site B (Figure 1). The divers dislodged coral colonies and placed them in buckets which were then placed in skiffs and transported to the transplant sites where they were securely fastened to the platforms with the insulated wire strands. Precautions were taken so that colonies would not be damaged or exposed to air during transplantation. Total transplantation time averaged about three hours at each station. The diameters of the colonies ranged between 5 and 40 cm at the beginning of the study.

Montipora colonies were not established at the northern station because it was concluded that surge and scour conditions were suboptimal for the coral. However, both species were established at the other two stations.

Monitoring of the Stations

During an 18-month period, all stations were monitored at approximately two-month intervals. Records were kept on observations of the colonization and

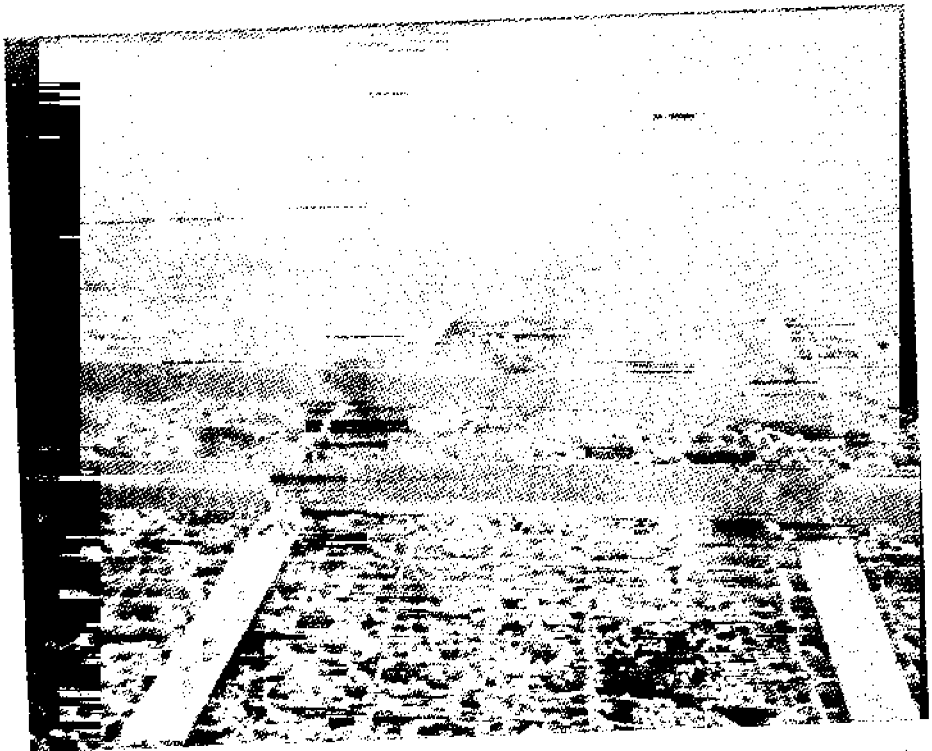

Figure 2. North bay transplant corals and bedframes at the beginning of the study.

Figure 3. Mid-bay transplant corals and bedframes at the beginning of the study.

fouling of the bedframes and corals by other organisms and changes in shifting sediment distribution. No colonizers were removed from the station and surrounding substrates except "bubble algae." Bubble algae was removed because it was not considered to be a natural stress to corals. The algae did not occur in abundance until after large amounts of sewage began to be discharged into the bay in the early 1960's. As sewage discharge increased, so did the biomass of the algae. To date, bubble algae has destroyed over 25 percent of the coral populations in Kaneohe Bay (Maragos, 1972a).

Changes in the size of the colonies between successive field-measuring operations provided estimates of the rate of growth by the transplants. Measuring operations were conducted during every other visit to each station or at approximately four-month intervals during the study. For each colony one diver measured the long diameter and the axis perpendicular to the long diameter with a meter stick; the other diver recorded the figures on underwater writing slates.

The species and health of the colonies were also recorded. Colonies were classified as "poor" if between 25 and 95 percent of its surface was not covered by living coral tissue. Colonies were regarded as "dead" if more than 95 percent of the coral was devoid of tissue. Originally all coral transplants showed living tissue covering 90 percent or more of the colony surfaces.

The number and size of colonies which had become detached or lost were also recorded.

Data on the growth rate of corals for each visit were later converted to projected surface-area estimates using the formula for an ellipse

$$A = \pi ab$$

where A = surface area
a = semi major axis (or ½ of the long diameter)
b = semi minor axis (or ½ of the axis normal to "a").

Correction factors for state of health were also introduced into the calculations. For colonies designated as "poor," the "A" value was multiplied by a factor ranging from 0.3 to 0.9, depending upon the health of the colony. For colonies designated as "dead," "A" was multiplied by a factor of zero. The living and dead surface area (cm^2) values were summed for all the transplants of a bedframe and later for all the frames at a station. Changes in the coral coverage between successive measurements presumably reflected net growth or decline of the transplants.

In a similar manner records were also kept on the size and number of detached and lost colonies.

Results of Transplant Studies

Results of the transplant studies are summarized in Figure 4 and Tables 1 and 2. At all stations corals which survived and maintained a healthy condition began to grow over attachment wires (Figure 5) and some even began to

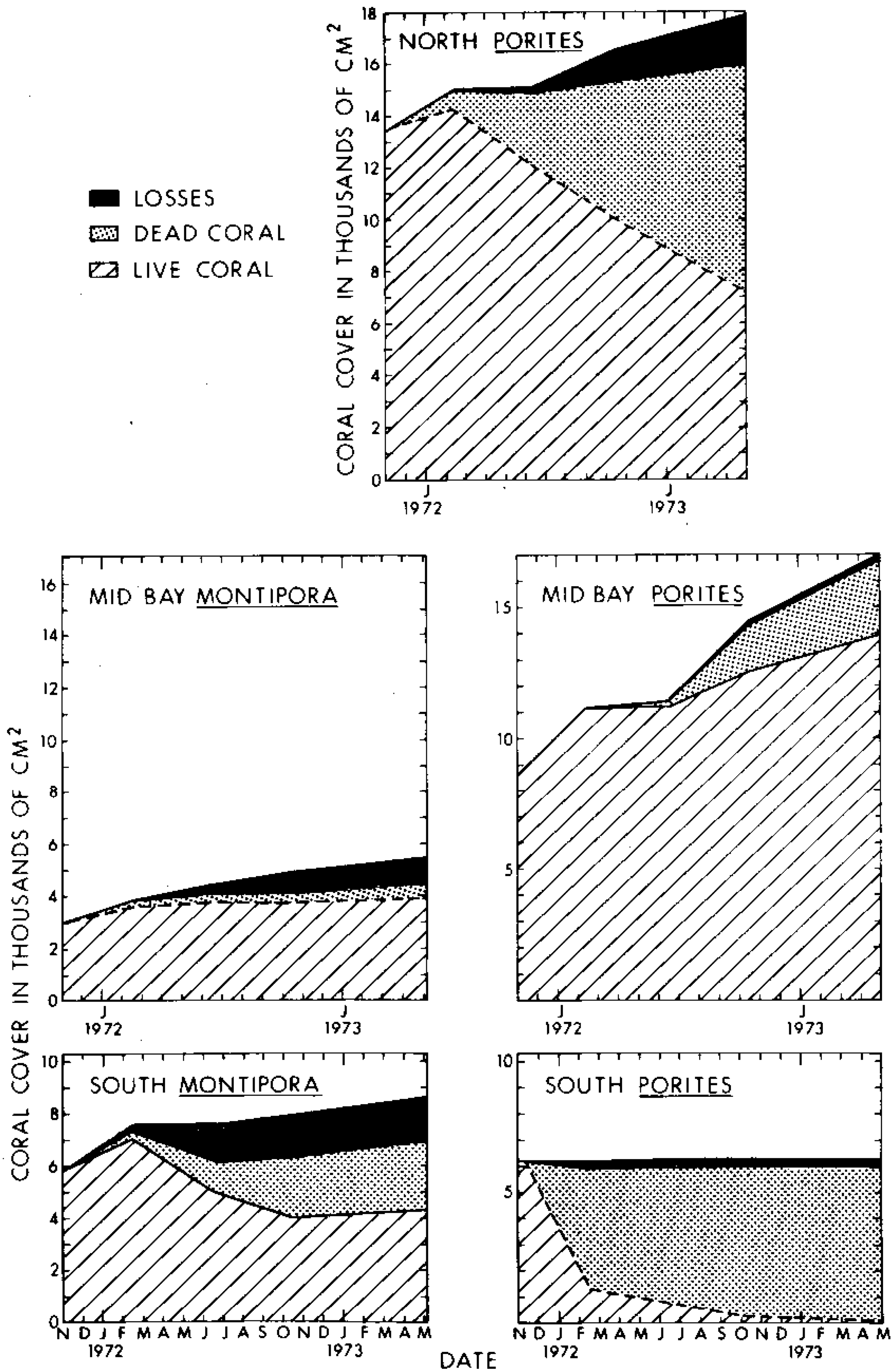

Figure 4. Summary of live, dead, and lost coral transplants at the three study sites in Kaneohe Bay.

TABLE 1. CORAL TRANSPLANT DATA ARRANGED TO SHOW THE EFFECT OF COLONY SIZE ON CORAL GROWTH RATE (increase in cm^2/18 months)

Only data from colonies still healthy at end of study are included.

Coral	Transplant Station	Colony Size	Number of Colonies	Mean growth rate per colony (cm^2)
Porites compressa	north bay	small	1	9
		medium	11	65
		large	1	264
	mid-bay	small	6	77
		medium	50	109
		large	5	132
Montipora verrucosa	mid-bay	small	3	98
		medium	8	84
		large	2	323
	south bay	small	3	39
		medium	9	114
		large	4	160

small = diameter less than 10 cm

medium = diameter 11 to 20 cm

large = diameter greater than 20 cm

TABLE 2. EFFECTS OF SIZE AND LOCATION ON THE SURVIVAL AND MAINTENANCE OF CORAL TRANSPLANTS AT THE END OF THE STUDY.

Porites data from south bay was omitted due to high mortality and poor health.

Coral	Transplant Station	Colony Size	Total number of colonies	Percentage of colonies "poor" & "dead"	Percentage of colonies "lost"
Montipora verrucosa	mid-bay	small	18	6	9
		medium	15	1	5
		large	3	1	0
	south bay	small	35	13	17
		medium	32	24	0
		large	7	4	0
Porites compressa	north bay	small	15	14	0
		medium	75	51	8
		large	21	17	2
	mid-bay	small	11	5	0
		medium	73	21	0
		large	6	1	0

encrust and cement to portions of the bedframes. These responses were noticeable two to three months after transplantation.

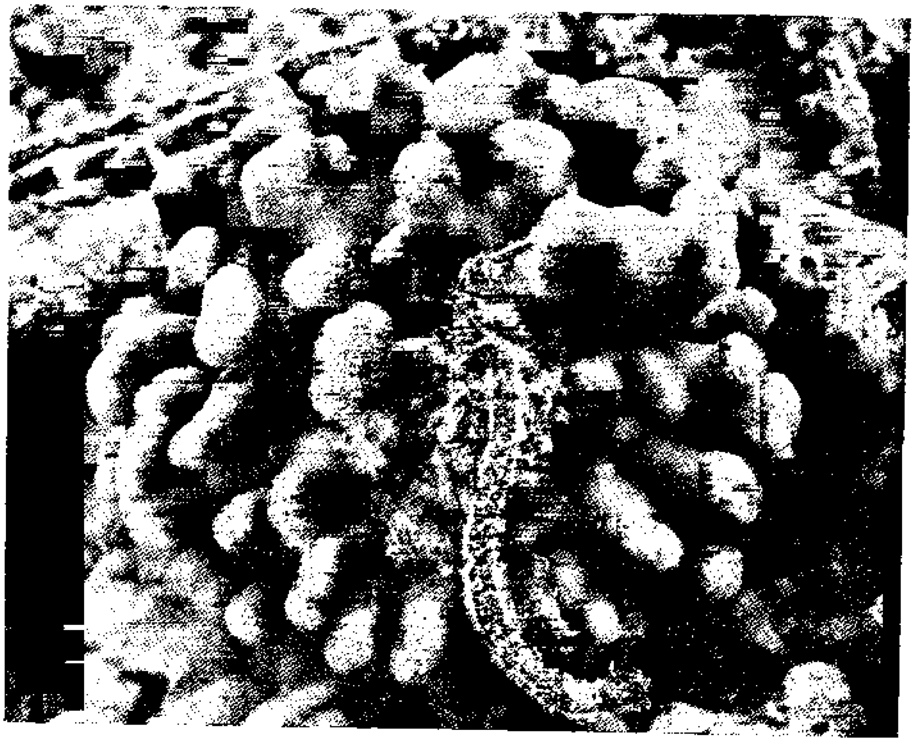

Figure 5. Close up of transplanted *Porites* colony. Growth over attachment wires indicates a healthy response by coral.

North bay transplants

All of the north bay station transplants were specimens of the fingercoral *Porites compressa*. After an initial net growth, the corals began to decline in health and growth (Figure 4). The total of live and dead coral increased slightly with time while the total living coral surface area decreased steadily. These observations indicated that although the corals were undergoing limited growth, the rate of mortality was much greater.

Some colonies were torn free of the attachment wires by surge currents and other unknown factors. None of the loose corals was subsequently found in the vicinity of the station during reconnaissance dives; the fate of these corals is unknown. The poor health and diminished growth of the remaining colonies were attributed to the combined scouring effect of sand in suspension and wave surge.

At the beginning of the study the transplants displayed the typical fingercoral form. The same colonies which survived to the end of the experiment displayed a more rounded form with living tissue prevalent only in protected crevices. Some of the modified transplants were almost undistinguishable in form from colonies of the common Hawaiian coral *Porites lobata* which is characteristic of surf-dominated marine environments. *Porites compressa*, on the other hand, is most common in surge-free environments. A previous transplant study (Maragos, 1972a) also indicated that *Porites* *compressa* is not well adapted to open-ocean environments subjected to excessive scour and wave action.

There was a marked variation in the response of the transplants from one bedframe to another even though all frames were positioned near one another. Corals attached to the two frames located in slightly deeper water (2 m) generally showed better health and growth even though shifting sand partially buried some of the colonies (Figure 6). Corals attached to the four frames located at shallowest depths (1 m) on hard substrate showed the greatest decline and mortality. It appears that the effects of surge scour may vary considerably over small reef dimensions.

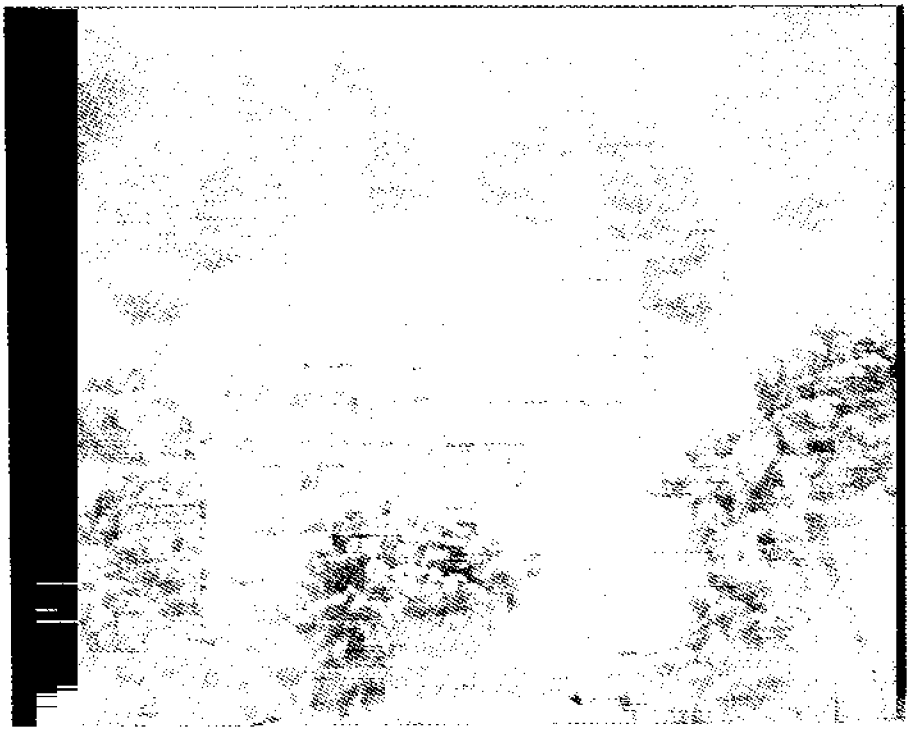

Figure 6. North bay transplant corals at end of study (May 1973). Most all of the *Porites* colonies in the picture are still alive even though shifting sediment partially buried many of the corals during the course of the study.

Mid-bay transplants

The coral transplants at the mid-bay station were specimens of both *Porites* and *Montipora*. Both showed vigorous growth, reduced mortality, and net gains in living tissue, with *Porites* almost doubling its total cover during the 18-month period (Figures 7 and 8). The average diameter increase for both species during the 18-month period was 4 cm.

Several colonies of each species died from unknown causes. A number of other colonies were smothered or partially smothered by growths of the bubble algae *Dictyosphaeria* in spite of attempts to control its growth. If these removal operations had not been conducted, it is likely that all of the corals at the station would have been covered by the algae.

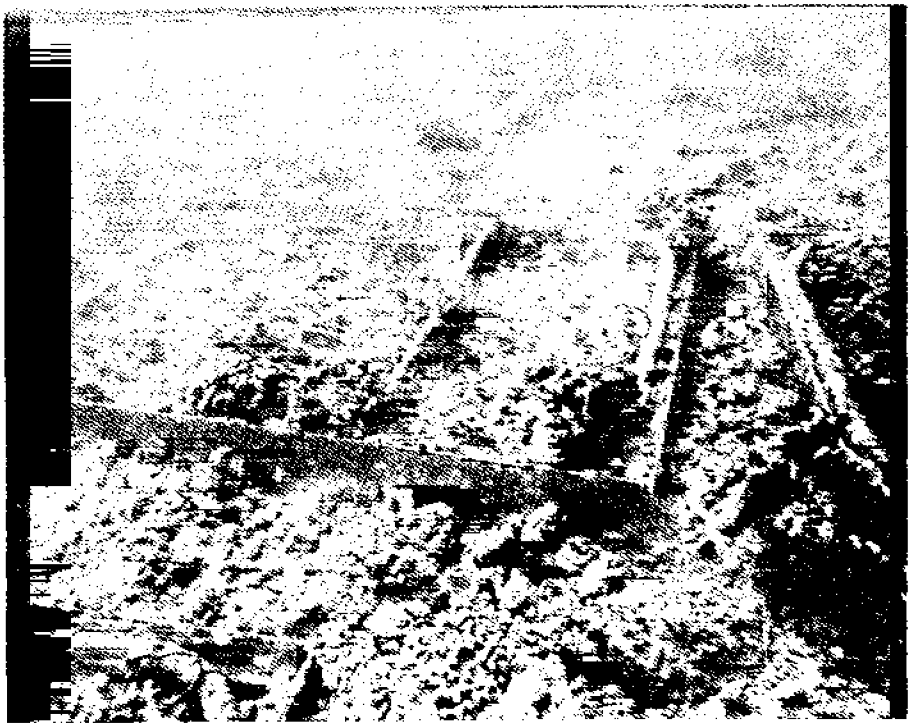

Figure 7. Mid-bay transplant corals at end of study (May 1973). Most of the coral colonies are still alive and many of the bedframe wires have dissolved.

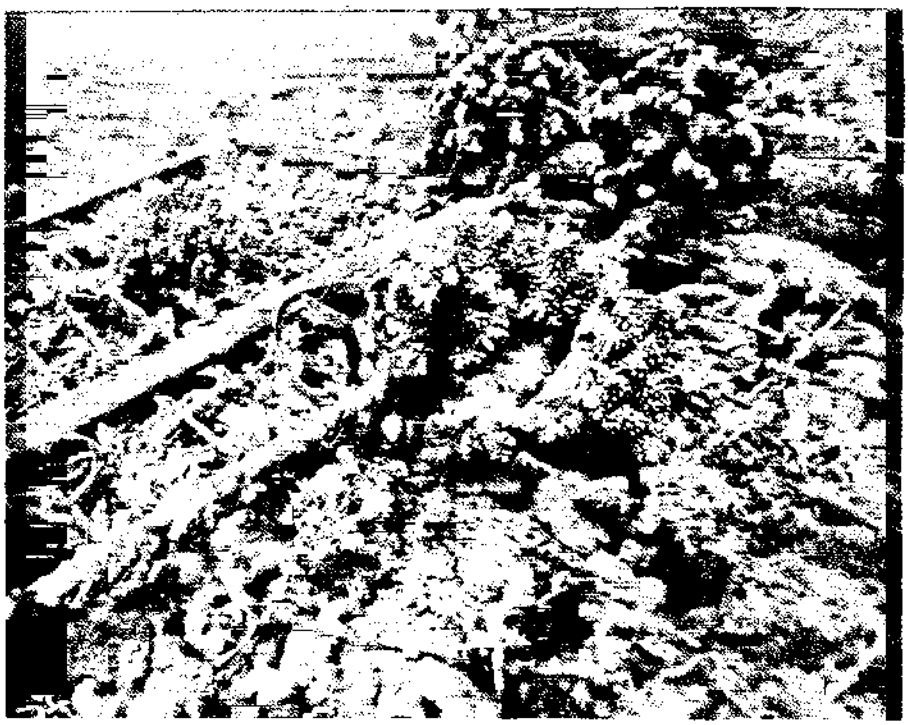

Figure 8. Living corals at mid-bay station 18 months after transplantation in November 1971. Colonies in foreground are *Montipora verrucosa* and those in background are *Porites compressa.*

During the course of the study a number of small colonies or portions of colonies of *Montipora* became detached from the bedframes but remained in the vicinity of the station. The number and size of these fragments increased with time. In Figure 4 this is designated as the "lost" portion of the population. At the end of the study these loose colonies comprised 20 percent of the total *Montipora* population at this station making the growth more pronounced when the "live" and "lost" categories are combined.

Only 5 percent of the *Porites* colonies experienced a similar fate at the mid-bay station. The lack of strong currents (surge or otherwise) at the station may explain the presence of the detached colonies in proximity to the bedframes. This is in contrast to what was noted for the north bay station where, presumably, surge currents carried loose fragments of colonies away from the station. It is possible that the production and dispersal of live coral fragments may be a common and natural phenomenon and may contribute significantly to the recovery and colonization of reefs by corals (Shinn, 1972).

South bay transplants

Both *Porites* and *Montipora* were also transplanted in south bay. *Porites* suffered rapid and catastrophic decline during the initial phase of the study (Figure 9). Only two colonies out of ninety were still alive by the end of the study and there was no sign of growth by *Porites* at any stage of the study. Although *Montipora* colonies fared much better, the population still suffered declining growth and considerable mortality. These colonies did not respond nearly as successfully as the *Montipora* transplants at the mid-bay station.

These observations substantiate earlier transplant observations by Maragos (1972a) who indicated that *Porites* was very sensitive to conditions in the south bay while *Montipora* displayed greater resistance. On the other hand, other studies have indicated *Montipora* to be more susceptible to the attacks of bacteria and coral eating flatworms (Jokiel and Townsley, in press). These and other factors may explain the reduced survival rate of *Montipora* at the south station.

Dictyosphaeria was again common at the station but did not attach to or damage any of the colonies. Sediment drifts may have buried some of the smaller *Montipora* colonies during the course of the study but almost all of the *Porites* colonies had died before sediment accumulation was noticeable (Figures 9 and 10).

The south station is located within 3 km of the outfall where municipal sewage is discharged into Kaneohe Bay. Anoxic conditions in the substrates resulting from organic loading and high productivity from water column organisms were suspected as being extremely toxic to corals (Sorokin, 1970; Maragos, 1972a). These may have caused much of the *Porites* mortality at the south station.

Effect of size on growth and mortality

At the end of the study it was apparent that the larger colonies of both species were expanding their living surfaces at a much greater rate than the medium and smaller colonies (Table 1). Another study showed that corals appeared to increase their linear dimensions at a constant rate with time

Figure 9. South bay transplant corals six months after beginning of study (June 1972). Bedframes are partially covered with sand. All *Porites* colonies are dead and all *Montipora* are still alive.

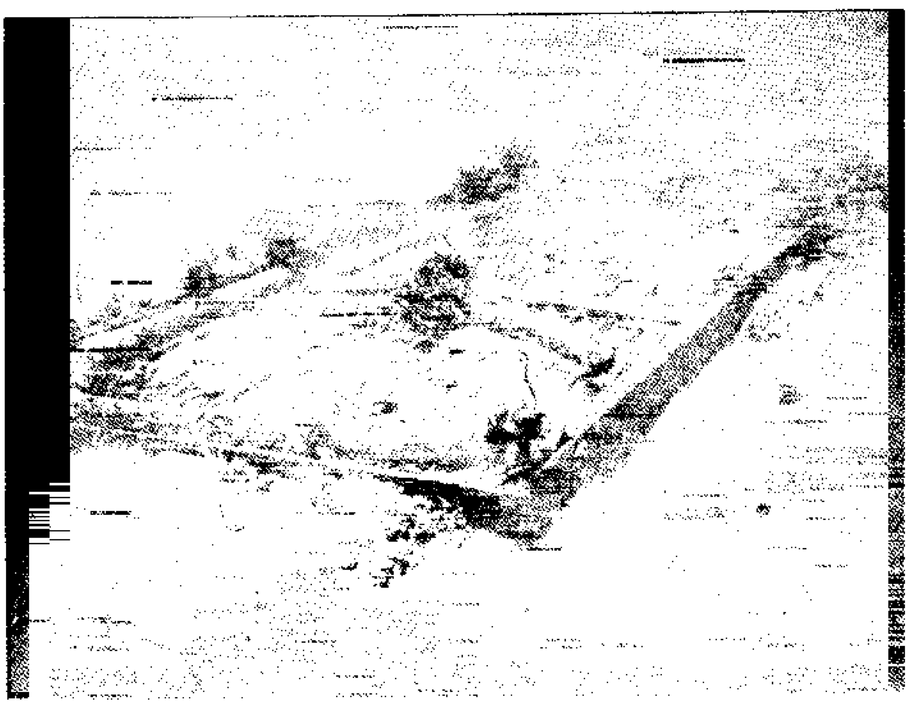

Figure 10. South bay transplant corals on a bedframe at end of study (May 1973). All *Porites* colonies are dead.

(Maragos, 1972a). This implies that corals would increase their surface area (second dimension) at a square of the rate of their linear increase (first dimension). Thus, the results of the present study are consistent with the theory that coral growth accelerates with time when expressed as a surface-area increase.

Other data (Table 2) also suggest that the largest corals show less tendency to become lost or die compared with the small and medium-sized transplants. However, the medium-sized corals appeared to fare worse than the smallest colonies indicating that the trend between size and survival may not be consistent. In any case the above findings suggest that larger corals are potentially better transplant risks.

NATURAL CORAL RECOVERY STUDIES

The conditions for the successful application of coral transplantation methods largely depend upon the rates and conditions under which natural coral recovery occurs. Thus it was necessary to acquire information on the nature of coral colonization with respect to time, substrate type, and distance from healthy reefs.

During historically documented time (1790-1973), lava flows have entered the ocean off the island of Hawaii on a number of occasions. The submerged lava substrates offer natural sites for coral settlement and colonization. By studying the state of colonization of corals on a number of flows of different ages, reconstruction of the history of coral development for periods up to 200 years under a variety of environmental conditions can be made. Preliminary results of these studies have been reported in Grigg and Maragos (in press). Data from these studies were used for the present investigation.

It should be emphasized, however, that environmental conditions within the confined lagoon of Kaneohe Bay differ considerably from those of the open-ocean, wave-exposed coastlines off the island of Hawaii. The structure and composition of open-ocean coral assemblages are much different from those of protected environments. Since a basic goal of this investigation is to determine transplantation feasibility in confined areas--those most likely to be degraded by urbanization--then it is also important to acquire information on natural colonization rates in confined environments.

Kaneohe Bay lagoon contains several reef substrates which have been denuded of corals during the past 34 years. In 1939 the US Navy dredged about 20 percent of the lagoon reefs in order to eliminate navigational hazards to boats and seaplanes. New surfaces were also created after the 1965 torrential rainfall which resulted in floods and a massive freshwater kill of marine organisms in Kaneohe Bay. Many coral communities, especially near Kahaluu Stream, were destroyed (Banner, 1968). In 1969 artificial surfaces were created when over 20 platforms were established for an earlier transplant study. These surfaces and those denuded by dredging and floods were surveyed for coral colonization (Figure 1).

In order to acquire information on coral colonization on substrates less than three years old, it was necessary to establish some artificial surfaces at the beginning of this study. Several large (2 m x 4 m x 10 m), aluminum-hulled, military-surplus, pontoon barges were scuttled in the bay near the survey sites in November 1971 (Figure 1). The size of the vessels provided a large surface area on which to study the initial phases of coral colonization. The southern and mid-bay wrecks eventually lay to rest on the reef bottom approximately 3 m below sea level. The northern wreck accidentally slipped off the shallow reef of similar depth and eventually came to rest at a depth of 8 m below the sea surface. The hulls were checked at six-month intervals to determine the progress of colonization by corals and other organisms. At the same time, the iron bedframes (transplant platforms) were observed for coral settlement. Thus, dated surfaces in Kaneohe Bay ranging from 0 to 35 years were surveyed for coral colonization.

Effect of Distance on Settlement Rates

An important aspect of coral colonization is the effective dispersal distance of coral larvae from adult corals. There has been no information previously available to assess the nature and importance of this factor. However, such a factor may have immense bearing on the possible application of the transplantation method. If dispersal and settlement of coral larvae are confined to small distances from parent colonies, then denuded reefs which are far removed from healthy reefs would presumably have slower colonization rates compared with those in close proximity to the healthy reefs and their larvae. Under such conditions coral transplantation could provide local sources of coral larvae (developing in adults) by establishing adult colonies upon remote denuded reefs. In order to determine the reef dimensions over which such a possible factor would operate, it was necessary to survey very large substrate areas entirely denuded of corals which lay adjacent to healthy flourishing coral communities. Surveys at a number of sites on the denuded substrates, each at a progressively greater distance from the established communities, may determine the importance of this factor.

The possible occurrence of a gregarious coral settlement effect was investigated on a patch reef near the mouth of Kahaluu Stream. During the 1965 floods, the reef slope facing the stream mouth was completely denuded of live coral while the reef slope facing away from the stream only suffered damage above depths of 2 m (Figure 11). A series of ten stations were surveyed on the side of the patch reef denuded of corals; these stations were positioned at progressively greater distances from the healthy reefs along the reef slope (Figure 11). The closest stations (1 and 10) were located within 5 m of the undamaged reef boundary while the furthest stations (5 and 6) were located over 100 m from the nearest healthy coral communities. Depth, reef slope, and substrate composition were nearly identical for all stations. Coral colonization at each site was estimated using a quadrat technique. The size, number, and species of coral lying within a one-meter-square frame (quadrat) were measured and recorded. A vertical series of six contiguous quadrats were analyzed at each site. The upper quadrat was positioned at the upper edge of the reef slope at a depth of 0.5 m while the deepest quadrat was usually positioned in mud at the bottom of the slope at a depth of

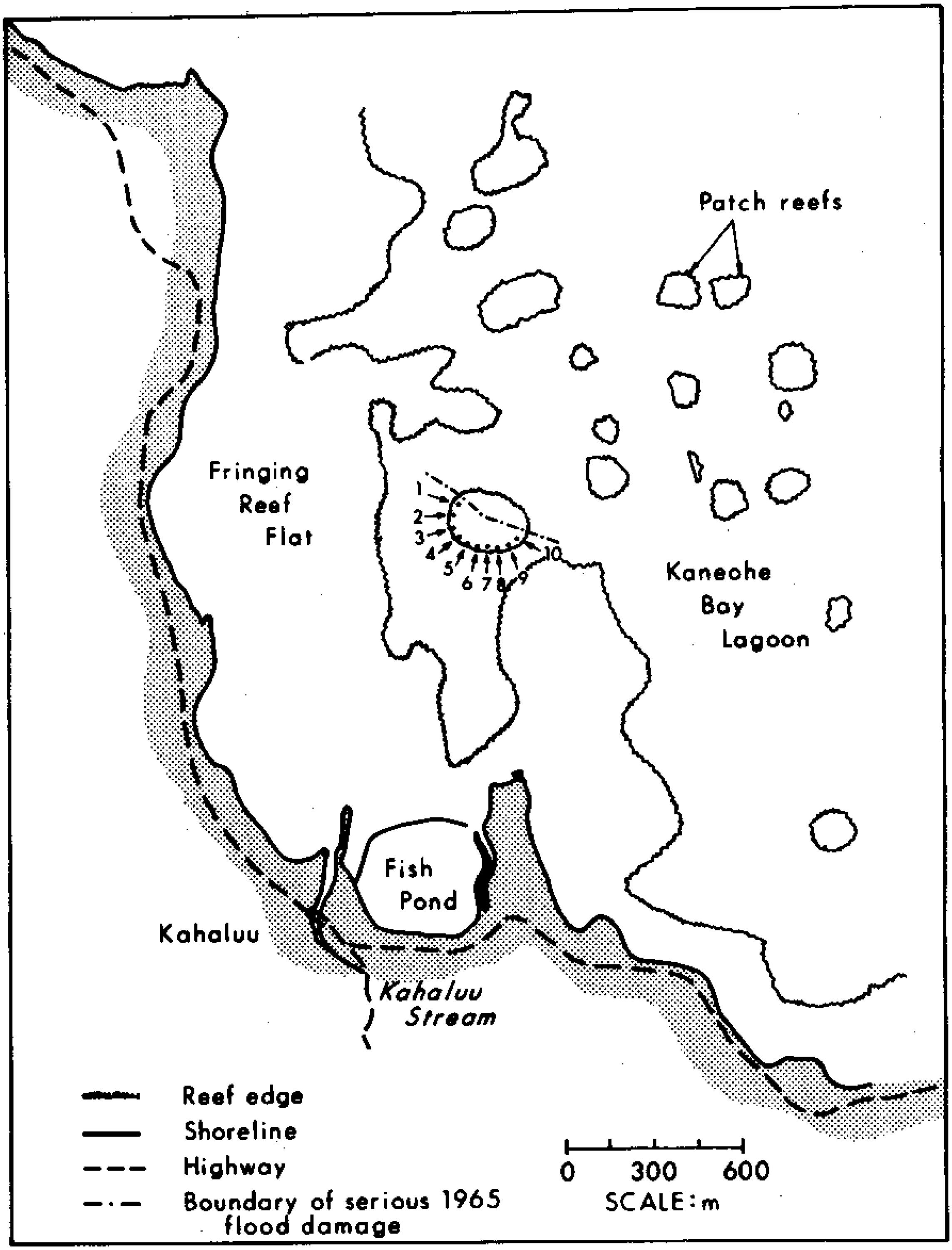

Figure 11. Location of a patch reef near Kahaluu Stream where a series of 10 surveys were conducted along a reef face denuded of corals during the 1965 freshwater kill.

approximately 3.0 m. Corals did not exist below these depths because sediment from the nearby stream had buried the deeper reef slopes. Thus at each site a vertical strip of the reef 1 m x 6 m was surveyed for coral colonization.

Natural Rates of Coral Recovery on Denuded Substrates

Results of surveys of the younger-dated surfaces (transplant platforms, bedframes, and boat wrecks) indicate that coral colonization is initially very slow or postponed for periods ranging from several months to over a year. For example, no colonies settled on the boat wrecks before a 12-month period. During this time, a succession of algae and invertebrates settled, grew, and sometimes disappeared at later intervals. Initially, green filamentous algae and worm tubes (*Spirorbis, Hydroides*) were most common; surgeon fish (*Acanthurus*) were also present. At the nine-month stage, bryzoans, tunicates, sponges, barnacles, alpheid shrimp, and crabs were found on the boat wrecks. At the end of 12 months a heavy layer of fouling organisms was found on the wrecks of the three stations and two small coral colonies of *Pocillopora* had settled on the mid-bay wreck. After 12 months, oysters and barnacles continued to increase in numbers. At the end of 18 months only six *Pocillopora* colonies had settled on the mid-bay wreck (Figure 12). The lack of coral settlement at the north bay station may have been due to the greater depth of the wreck. Pollution or associated factors may have inhibited coral settlement on the south bay wreck. Fish were common around the wrecks from the beginning of the study. A very large population of maomao (*Abudefduf*) was noted on several occasions around the south bay wreck during the last 12 months of the study.

A greater concentration of coral colonies settled upon the iron bedframes as compared with settlement upon the pontoon wrecks of the same age and location. The smooth surface, the aluminum composition, or the antifouling paint of the boat wrecks may have inhibited greater settlement by corals. Settlement on the bedframes occurred after six months. At the end of the study, approximately 1.5 and 4.0 colonies per bedframe had settled on the north bay and mid-bay frames, respectively; no corals had settled on the south bay bedframes. Most all were colonies of *Pocillopora damicornis* with a few colonies of *Porites lobata* settling on the north bay frames and *Porites compressa* on the mid-bay frames.

The above observations are consistent with those of Maragos (1971, 1972b) and Grigg and Maragos (in press) which indicate that coral colonization is very slow during initial stages and that *Pocillopora* is the most common of the early colonizers. It has been postulated by Harrigan (1972) that the young larvae of *Pocillopora* postpone settlement on clean, hard substrates until certain kinds of algae settle and create a surface film. The proper "conditioning" of substrates may also involve other organisms and processes. The large power of dispersal which characterizes *Pocillopora* was a primary reason why the coral was not selected as a potential transplant species. It can apparently colonize on new surfaces at a sufficient rate to preclude the need for artificial enhancement.

Surveys of dated surfaces older than three or four years indicate coral recovery proceeds more rapidly after the initial conditioning stages. Since

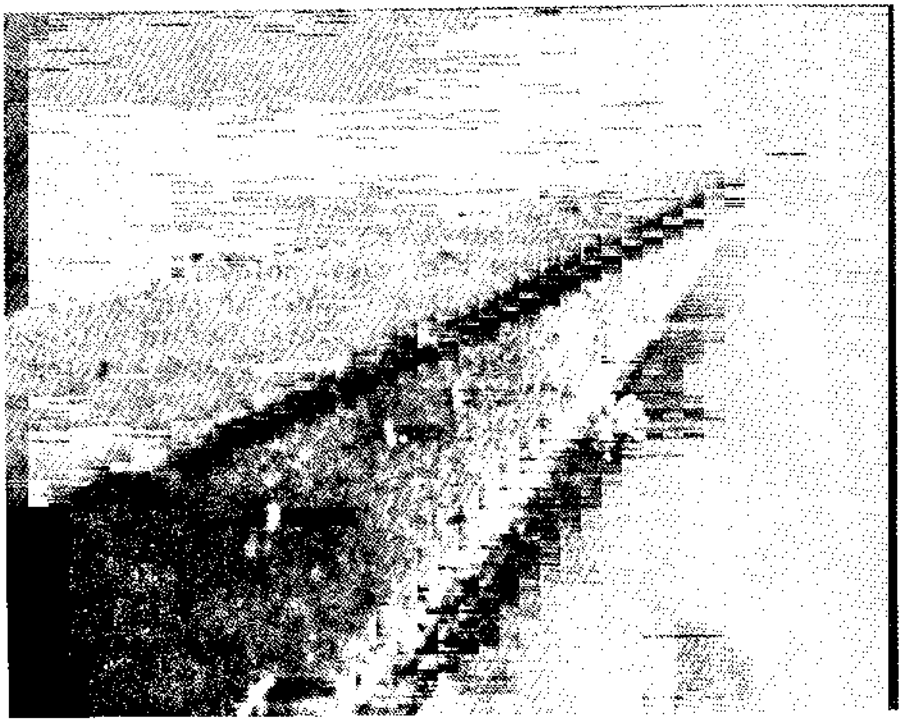

Figure 12. Close up of the side of the mid-bay wreck showing young coral colony of *Pocillopora damicornis*. Photo taken 18 months after scuttling of the wrecks in November 1971.

1968, the author has continually observed the colonization of reef corals on surfaces completely denuded of living corals during the 1965 floods in Kaneohe Bay (Figure 11). At the Kahaluu site during late 1969 and early 1970, coral colonization appeared to proceed more rapidly. In May 1973, some colonies at the Kahaluu reef site measured over 30 cm in diameter and colonies with diameters greater than 10 cm averaged $10/m^2$ (Figure 13). This seems surprising considering water quality and substrates at the station appear suboptimal. A fine sediment film covers all hard substrates while sediment loading and freshwater discharge from nearby Kahuluu Stream significantly reduces light penetration and salinity (Figure 11). In deeper water, coral colonization appears to have been inhibited altogether by thick deposits of fine sediments. At shallow depths colonization is now only beginning to occur; only small, young colonies are found on these substrates. This may be an effect of suboptimal salinity and/or temperature conditions. Extrapolating present trends, it appears that the Kahaluu study reef will be fully recovered within another 10 years (Figure 14). This would give a total recovery time of approximately 15 to 20 years. Results of surveys of submerged lava flows off the island of Hawaii (Grigg and Maragos, in press) indicate that coral recovery may be complete in some areas by 15 years.

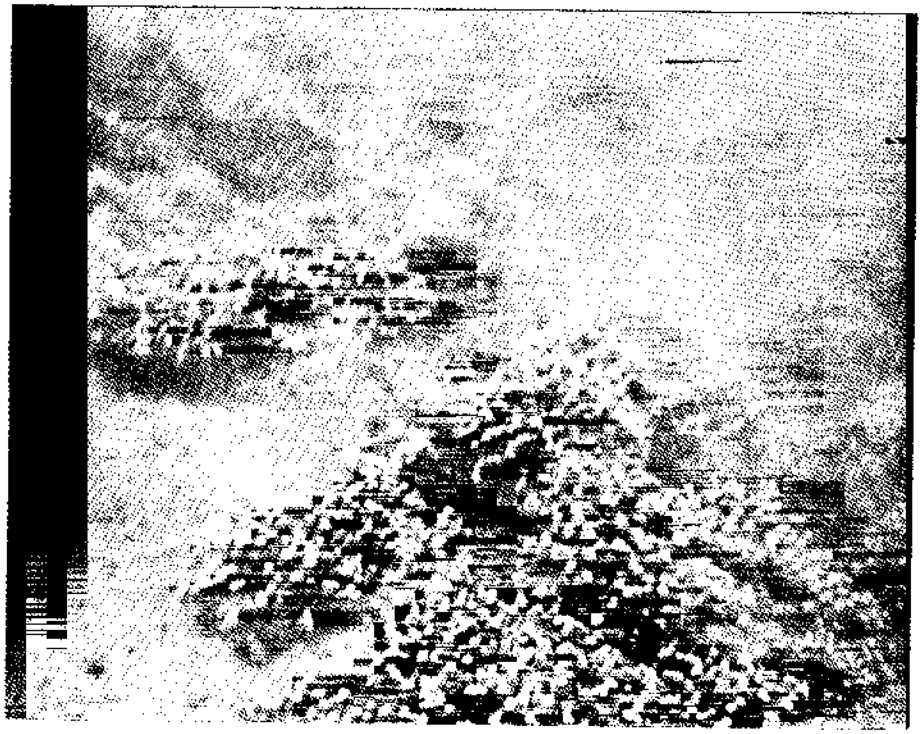

Figure 13. Coral colonization on a reef slope denuded of live corals during freshwater floods in 1965. *Porites* colonies of about 25 cm in diameter have settled on substrates partially covered by mud.

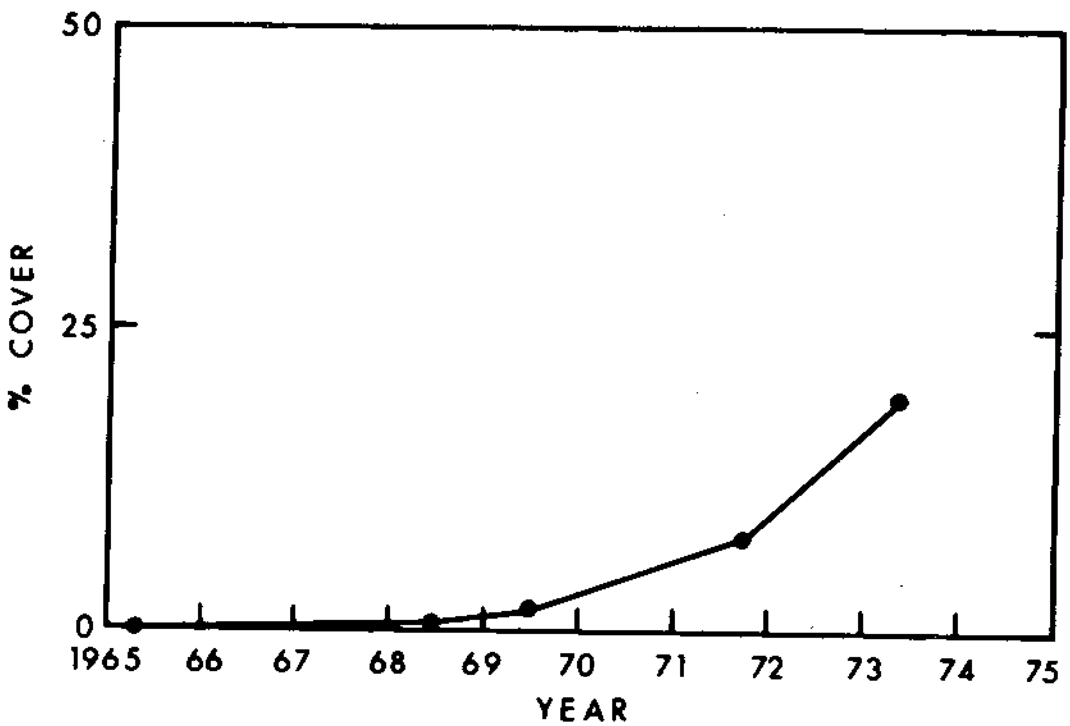

Figure 14. Recovery rate of live corals on a reef slope denuded of corals during floods in 1965.

Surveys of some of the reef substrates in Kaneohe Bay which were denuded of corals by dredging activities in 1939 showed variable rates of recolonizations. A number of reefs were dredged to uniform depths of 3 m while other reefs were dredged to depths of 9 m. Surveys indicated that coral colonization on the deeper reefs have not occurred--with one exception--and that sediment accumulation is more pronounced on deeper slopes. The greatest colonization has occurred on the shallow upper steep edges of the dredged reefs. Reefs in the south basin show very limited signs of coral recovery. Where sediments have accumulated on level or flat areas of the reefs (shallow or deep), coral recovery has been either slow or non-existent. The greatest coral recovery--100 percent cover--occurred on a few partially dredged patch reefs in the north lagoon. These reefs appear to have been vertically sliced so that it is probable that proportions of the original coral communities were not destroyed. Surveys of the dredged faces of these reefs in 1969 showed that recovery was complete in less than 30 years (Figure 15). It is not unreasonable to hypothesize that encroachment or greater larval recruitment from the undamaged sections of these patch reefs contributed to the rapid and total recovery of the dredged sections.

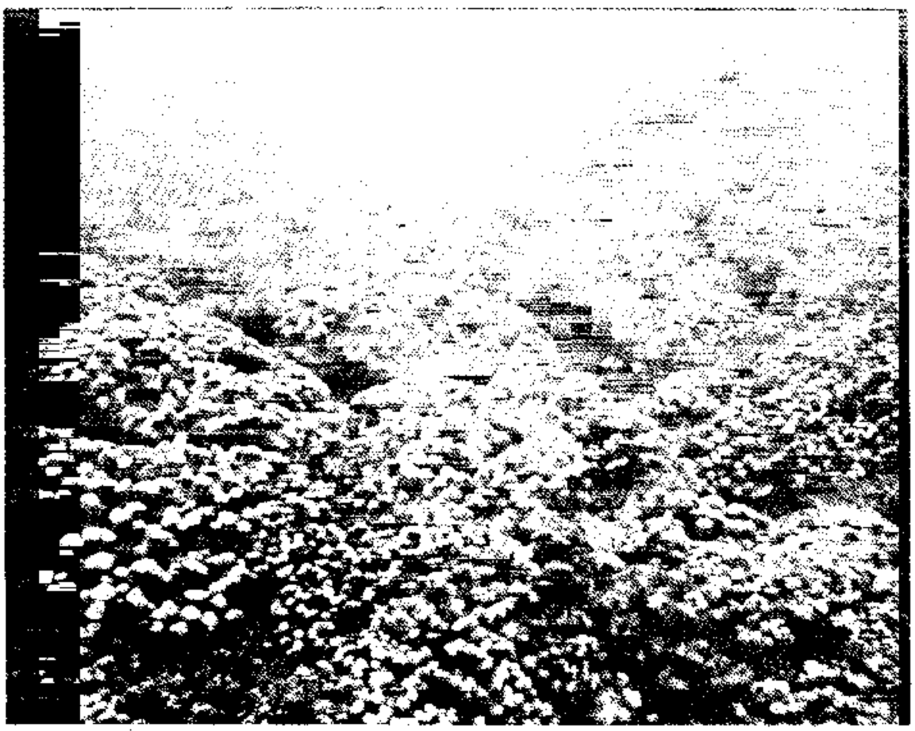

Figure 15. Coral community which has completely recolonized a north bay patch reef dredged completely of corals by the Navy in 1939.

In terms of coral coverage, complete recovery of reef corals on lava flows off the island of Hawaii may occur within 15 to over 50 years depending upon environmental factors. In exposed environments, recovery takes less time because, to begin with, coral communities are less developed on normal reef substrates next to the flows. Where coral development was previously high--along leeward coasts--recovery time takes longer. The present study indicates that protected environmental conditions and other factors may result in complete recolonization within 30 years.

Results of Studies to Determine the Effect of Distance on Settlement Rates

As mentioned earlier, it is important to determine over what distances dispersal and settlement of corals may be significantly reduced or limited. If these distances are small, then remote, denuded reefs should require more time to recover than those adjacent healthy reefs. Under these conditions coral transplantation could be a valuable aid in supplying larvae from adult transplants to remote reefs. In order to test for this gregarious effect a survey of the patch reef at Kahaluu was made (Figures 11 and 16). It indicated that coral colonization does not show any consistent variations or gradients on previously denuded reef sites along a horizontal axis between 0 and 100 m from healthy, flourishing reefs. Generalizations of these results are limited since the distance effect was not analyzed for reef dimensions greater than 100 m and because analysis was possible on only one particular type of reef environment--protected shallow reef slope. Further surveys being conducted on some of the wider lava flows surrounded by healthy reefs off the island of Hawaii should provide more information regarding this question.

In summarizing the above results, coral colonization appears to proceed slowly during the initial months and years and is inhibited almost completely on substrates covered with fine or loose sediment. Where substrates and other conditions are suitable, corals preferentially settle on steeper slopes at intermediate depths. Although coral composition and environmental conditions vary considerably in Hawaii, coral colonization is generally very rapid and may be complete in 15 to 50 years. *Pocillopora* appears to be well adapted to settling earlier on new substrates. Other corals such as *Porites* and *Montipora* may be able to rely upon accessory dispersal phenomena such as encroachment and fragmentation to aid in the colonization process.

DISCUSSION

Success and Feasibility of Coral Transplantation

Results of this study show that corals transplanted from one habitat to another will attach, grow, and survive, if environmental conditions are favorable. Excessive surge scour may limit the use of dominant calm-water corals in some environments. However, application of the transplantation technique will be most successful where reef coral communities are most likely to succumb to urbanization stresses, especially in protected or confined areas where reduced water circulation and exchange have magnified the effect of man-made stresses. Eutrophication-related stresses appear to be quite detrimental to the dominant calm-water reef coral, *Porites compressa*. In any case, factors which caused the destruction of coral communities in the first place must be alleviated before application of the transplantation technique is possible. This applies particularly to sewage discharge in Kaneohe Bay which has directly killed many coral communities in the south basin and has probably caused the explosion of "bubble algae" which has smothered most coral communities in the mid-bay section. It appears that coral settlement on sediment-covered and dredged environments has been inhibited. Transplanted adult colonies, however, can survive and grow well in these environments and point to a possible future application of the technique. Coral transplantation is not recommended where natural coral colonization is likely; the only beneficial effect of transplantation would be to reduce the time of total recovery by a few years.

If future-planned surveys reveal that coral colonization is effectively reduced on reef substrates remote from healthy reefs, then coral transplantation may offer yet another means by which reefs can be stimulated to recover. Transplantation of adult colonies to remote reefs will place a steady supply of developing coral larvae in close contact with denuded substrates.

The success of coral transplantation may be gauged in several ways. Increase in the amount of living coral tissue offers the most simple index. The production and growth of dead coral should also be considered a benefit, provided the amount of living tissue does not decrease. Dead coral cover is a common feature on coral reefs and the skeletons of many dead corals eventually become cemented to one another to form a reef. Dead skeletons are also homes for a number of other reef organisms including fish, rock borers, and crabs. Coral larvae may settle on the dead portions of corals and eventually grow into large living colonies.

In a similar manner corals which have become detached from anchoring platforms may also provide recovery potential. This study has shown that these corals, particularly *Montipora*, may continue to survive, grow, and act as dispersal agents during the colonization process. Hence, the attachment of coral transplants to frames or other stationary objects may not be necessary, especially where currents are weak.

Introduction of New Forms to Hawaii

Porites compressa and *Montipora verrucosa* appeared to be the only two Hawaiian species acceptable for use as transplants. However, *Porites compressa* appears to be very sensitive to the effects of sewage discharge while *Montipora* appears to grow more erratically and may also be susceptible to predation by flatworms and other organisms (Jokiel and Twonsley, in press). In addition, Hawaiian reef corals do not appear to grow as fast as corals to the west and south of Hawaii (Maragos, 1972a).

There is now considerable evidence to suggest that environmental conditions may be suboptimal for reef coral growth in Hawaii (Maragos, 1972a; Coles, 1973). However, other evidence suggests that the poor coral fauna of the Hawaiian Islands may, in part, be due to its geographic isolation from other island groups (Vaughan, 1907; Dana, 1971; Maragos, 1972a; Grigg and Maragos, in press; Maragos, in press).

Among the many coral genera missing from Hawaii is *Acropora*, one of the most common and geologically important reef types in both the Atlantic and Pacific Oceans. *Acropora* occupies a great variety of habitats on the reef and occurs in a variety of forms; to date over 200 species of *Acropora* have been described. Some species are capable of very rapid growth--up to 10 cm or more per year--and grow over three times as fast as the fastest of Hawaiian corals.

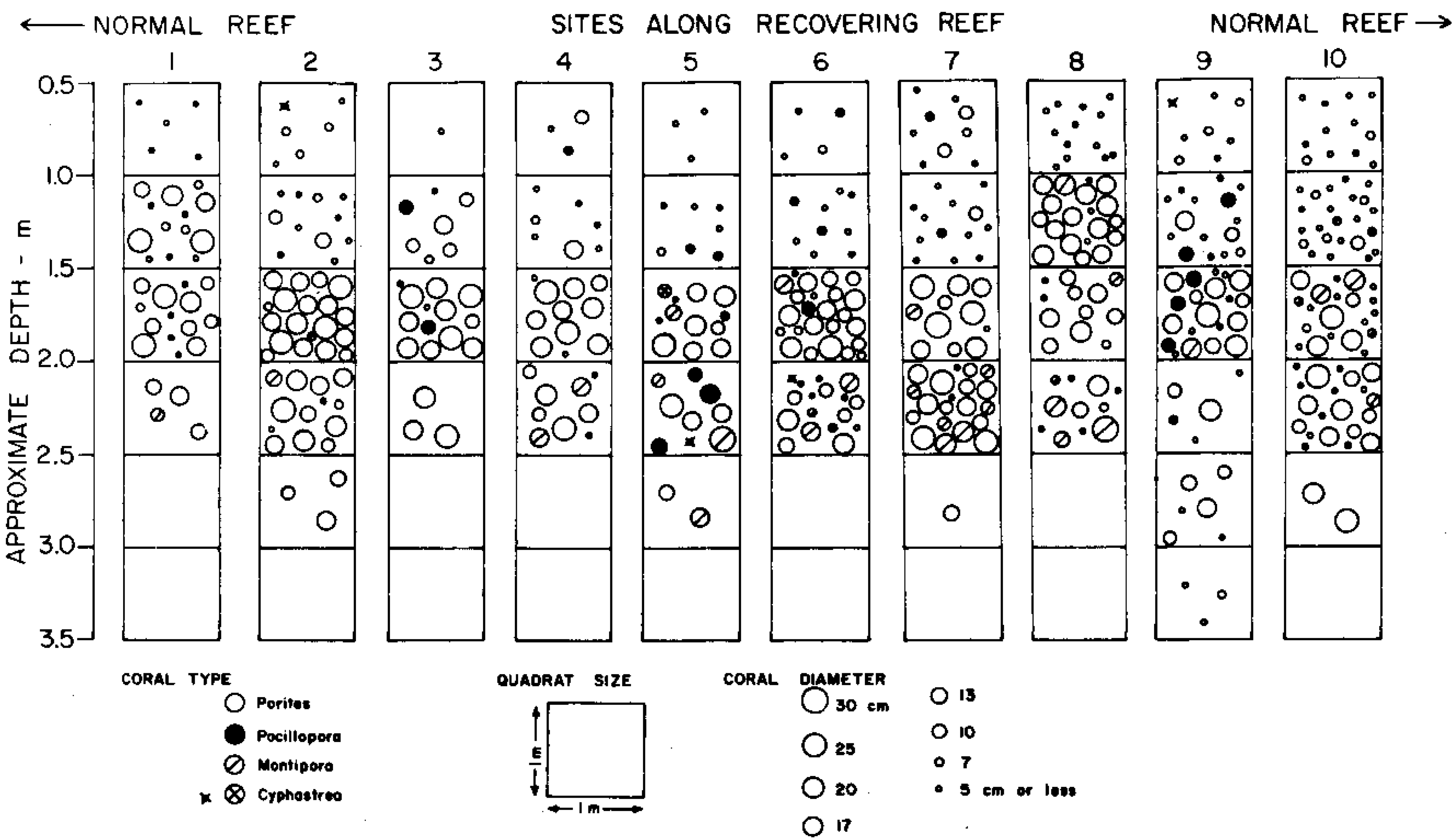

Figure 16. Graphical presentation of coral recovery at 10 sites along a reef face denuded of corals during the 1965 freshwater kill. Quadrat size and coral colony size are drawn to scale. The spatial arrangement of colonies is drawn for convenience and does not correspond to the actual orientation of the colonies in the field. However, the size, number, and species composition of corals within each individual square corresponds to observed conditions. For purposes of convenience the profiles were crowded together; they were separated by distances of 15 m on the reef. Normal undamaged coral communities were present at the perimeter of the sampled reef slope (damaged reef) and extended continuously around the remainder of the patch reef.

Acropora corals are also capable of rapid recovery. In one instance, tracts of staghorn *Acropora* demolished by a hurricane in Florida were found to be completely recovered within two to three years (Shinn, 1972). Another observation by the author in polluted Pago Pago Bay, American Samoa indicates that some species of *Acropora* appear to resist municipal sewage, tuna cannery waste, oil spills, sediment loading, and rainwater dilution and continue to grow. Hence, it seems reasonable to speculate that of the many types of *Acropora* known to exist, a few may find conditions in Hawaii favorable.

The full potential of the coral transplantation technique to hasten the recovery or development of coral communities in Hawaii may not be realized until non-Hawaiian forms such as *Acropora* are considered as transplants. The introduction of exotic corals, however, is not without problems. Precautions including careful collection and temporary isolation must insure that unwanted diseases, predators, and parasites do not accompany the corals.

Economic Assessment of Coral Transplants

It should be realized that the economical benefits derived from coral transplantation are difficult to assess. Although this study has shown that transplants will grow noticeably; nevertheless, corals do not grow quickly. Coral communities may take decades to recover even if the transplant technique were used.

Rates of reef recovery aided by transplantation methods largely depend upon the density at which individual colonies are established at reef sites. At considerably more cost, coral transplants could be placed in close proximity to each other to reduce recovery time. However, it seems more likely that densities between one and five colonies per square meter should be achieved instead. Based upon extensive diving experience, corals showing densities within the above range appear conspicuous and predominant on reef substrates. Densities of coral much less than this may not produce significant ecological stimulation of the environment and densities much greater than $5/m^2$ may reduce the advantage of using the long-lived and large-sized corals of *Porites* and *Montipora*.

Corals offer little direct marketable value to the Hawaiian economic community--except for a number of *Pocillopora* colonies (tree coral, rose coral) and *Fungia* (mushroom coral) which are illegally harvested and sold to tourists as souvenirs. The economic importance of reef corals is based upon their ecological and geological significance to reefs. The presence of corals in some environments provides a necessary foundation for commercial and recreational fishing and food harvesting. Coral skeletons are a principal component of sand which forms white sand beaches along Hawaiian shorelines. Beaches are utilized by residents and visitors alike and are exploited and mined for beach construction and cement production by the building industry. Reefs, composed largely of coral skeletons, provide recreational sites for surfers and divers and also protect island shores from storms and large waves. These indirect values should be considered when calculating the cost-benefit ratios for proposed programs designed to help create, preserve, revive, and manage reefs using the transplantation method.

Collection

Moderately large coral colonies (20 to 40 cm in diameter) grow faster and perhaps survive longer than smaller corals of the same species. If the most expensive and time consuming aspect of the transplant operation is the collection of coral heads, then it would be more economical to collect larger colonies since these are more likely to survive and grow. Also larger colonies are more likely to be reproductively mature and hence supply greater numbers of larvae than smaller colonies. However, colonies which are too large may increase transportation costs due to greater bulk and weight and may be more difficult to detach and manipulate during diving operations. In this respect collection of a greater number of moderate-sized colonies having the same combined mass as a few larger colonies may be more economical.

Attachment

Attachment of coral transplants to stationary objects is also a time consuming and costly process. However, attachment may not be necessary on level, flat reef tracts where currents are not strong enough to move corals and where water movement is less likely to move corals around. The natural fragmentation and dispersal of small unattached coral fragments may indirectly offer additional benefits of transplantation without increased cost.

Upkeep and maintenance

If upkeep and maintenance of the transplants are necessary at regular and frequent intervals, then the cost of such operations should be added to total cost estimates. Maintenance operations are very likely where algal growths of *Dictyosphaeria* are prolific. Other forms of algae did not appear to be destructive to the corals even when algae settled in concentrated numbers on the frames and dead portions of the coral skeletons. Maintenance operations may also be necessary for another reason. If a transplant station were set up where surge currents are strong, divers would have to periodically check the station to insure that the platforms or frames have not been toppled over or carried out of the station area.

Future Research

As mentioned earlier, important avenues for future research include determining the effect of isolation distance on coral settlement and the feasibility of introducing non-Hawaiian corals as transplants. In addition, scientists will need more information in order to predict with greater accuracy the conditions and time under which coral colonization will or will not occur. More studies will need to be conducted on the settlement behavior and density of settlement of coral larvae. Long-term transplant studies should also be conducted in order to assess with greater accuracy the value of such methods; tentative plans are being made to maintain the present transplant stations.

SUMMARY

Under certain conditions coral transplantation may be an effective means to enhance recovery of damaged reefs or to establish new coral communities. The stresses which destroyed pre-existing communities should be removed prior to the application of the method. Coral reef tracts which have been disrupted by man's recent activities would be those most likely to benefit by transplantation; these include confined areas where reduced circulation has magnified the stresses and their effects. Establishment of transplant stations near excessive wave action and surge presents logistical and economic problems. Sediment appears to inhibit coral larval settlement but does not affect the growth and survival of larger transplants. Hence, transplantation may be particularly valuable in establishing coral communities in sediment-dominated environments.

Natural colonization rates of corals on hard suitable substrates are more rapid than generally thought; reef communities may totally recover (in terms of coral cover) from catastrophies including floods and dredging activities within 30 to 50 years. These coral recovery rates are comparable with those calculated on lava flows which have entered the ocean off the island of Hawaii on a number of occasions. Corals appear to postpone settlement on new substrates for periods up to a year or more and proper conditioning of the substrates by algae or other substances may be a necessary prerequisite. Where natural colonization is likely, coral transplantation may serve to hasten the recovery of reef tracts.

Larger colonies appear to grow more rapidly (surface area increase) and survive longer than smaller forms of the same species. However, very large colonies may be too heavy and expensive to transplant. The dispersal of coral fragments by water movement may be another possible advantage resulting from the application of transplantation. Results of this study also revealed that coral transplants need not be attached to stationary objects under some conditions; this could significantly reduce the cost of transplant operations. Reconnaissance surveys of potential transplant sites should be conducted in order to estimate the frequency, if any, of maintenance operations.

Future research should include acquisition of more data to determine under what physical conditions, time spans, and distances natural coral recovery will occur. The possibility of introducing new corals to Hawaii should also be considered.

Because corals grow slowly and recovery may take decades, recognizable dividends in the application of transplant methods may not be apparent for years. However, corals directly and indirectly affect many other organisms and the accretion of reef and sand deposits. They also considerably affect the recreational and economic potential of many Hawaiian marine preserves. Thus it becomes essential for man to acquire the knowledge and technology to preserve existing reefs, revive destroyed reefs, and perhaps establish new reefs.

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