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AN ANALYSIS OF THE EFFICACY OF FOUR ARTIFICIAL REEF DESIGNS IN TROPICAL WATERS

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ABSTRACT

Four artificial reef designs and a natural control reef were compared to determine their relative value as a fisheries enhancement tool in tropical waters. Reefs were comparably sized and designs ranged from haphazardly dumped scrap materials to carefully deployed, specifically designed concrete modules. All reefs were situated in the same biotope and depth, were similar sized and were located within 1 km of each other. Fish density, community structure and standing crop estimates on each reef type were made visually. Reefs composed of haphazardly dumped scrap materials (automobile shells and surplus concrete pipe) provided the poorest enhancement. These reefs were also highly unstable and exhibited low life expectancies. Reefs composed of modules of scrap automobile tires set in concrete bases and dumped haphazardly showed moderate enhancement that varied with the degree of module dispersion. Due to their high mass to volume ratio, modules of this design were relatively stable but the design precluded effective stacking, resulting in low relief structures. Significantly greater enhancement effects (e.g., mean standing crop, mean size per fish and mean number of species) were attained on a small reef constructed of 42 open framework concrete cube modules arranged to provide maximum refuge space for fishes. The open framework concrete cube module was engineered for a long life expectancy and stability in high energy environments. The data suggest that haphazard deployment of materials provided significantly poorer enhancement relative to a reef constructed of designed modules assembled into a specific configuration.

A paucity of information exists in the western fisheries literature on the role of reef design in habitat enhancement studies. Traditionally, artificial reefs in the United States have been built by dumping surplus "materials of opportunity." In many cases the primary justification for the construction of these artificial reefs was the disposal of wastes rather than resource enhancement (Buckley, 1982). However, when placed in areas of little or no topographical relief, these reefs served to attract and locally enhance fishery resources. In some cases, low-cost reefs have had large detrimental impacts on surrounding marine communities through pollution (automobiles, refrigerators), instability (tires, concrete pipes), or short life expectancies (automobiles). Not all of these problems have manifested themselves on a given reef or program, but examples exist in almost every U.S. reef program.

In the last several years western fisheries biologists have become aware of the habitat enhancement technology developed in the Far East and in particular, Japan (Buckley et al., 1985). However, documentation is lacking as to the effectiveness of designed artificial reefs relative to less costly reefs constructed of dumped materials (Bohnsack and Sutherland, 1985).

In Hawaii, construction of artificial reefs has been ongoing since the early 1960's. Early reefs were built of scrap automobiles, barges, ships and surplus concrete pipe (culvert) sunk in one of four designated sites around the islands (Kanayama and Onizuka, 1973). Because of the nature of the materials used and their haphazard deployment, there was little attempt to incorporate any design criteria into these reefs. These early efforts at establishing artificial reefs in Hawaii used the technology then available as did other reef programs in the U.S. Initially, these reefs worked well, but over a long period of time they have proved to be relatively poor fish attractants. There was insufficient planning from the standpoint of meeting biological needs of target fishes and engineering appropriate stability into the system. The resulting reefs had low profiles, little refuge space, poor stability (pipes roll and crush benthic organisms), and short life expectancies (Brock et al., 1985).

Perhaps the most significant factor affecting these reefs has been their instability due to occasional high surf. Physical disturbance from waves is also the most important parameter in determining the structure of Hawaiian coral communities (Dollar, 1982). Numerous studies have shown that occasional storm generated surf may keep coral reefs in a non-equilibrium or sub-climax state (Grigg and Maragos, 1974; Connell, 1978; Woodley et al., 1981; Grigg, 1983). Indeed, the large expanses of near-featureless limestone substratum present around much of the Hawaiian Islands at depths of 10 to 30 m attest to the force and frequency of these events (pers. obs.). These same wave forces also impinge and scatter deployed reef materials as well as impact their fish communities (Walsh, 1983).

Since 1983 Hawaiian artificial reef programs have utilized more specific planning and reef module designs. This paper examines the effectiveness of these designs in the development of fish communities and evalutes these experimental reefs relative to the older reefs constructed of dumped scrap materials.

MATERIALS AND METHODS

Artificial reefs examined in this study were situated in the state sanctioned Maunalua Bay Artificial Reef Site which is located in a 24 ha area about 2 km off the south shore of Oahu, Hawaii in waters 20 to 35 m deep. The substratum at this location is comprised of relatively barren reef limestone that is overlain by small patches of sand and rubble usually not exceeding 10 m in diameter and spaced 50 to 150 m apart. Occasional cover is encountered in the form of small ledges (to 40 cm high) that approximately parallel the shore. These ledges may run for 20 to 80 m in length and are spaced 50 to 250 m apart. Corals are found on the emergent hard substratum; dominant species are *Porites lobata* and *P. compressa,* the two most abundant coral species in the Hawaiian Islands (Maragos, 1977). Other coral species seen include *Pocillopora meandrina* and *Montipora verrucosa.* Overall, live coral is estimated to cover less than 5% of the substratum and the largest colonies (*Porites* spp.) rarely exceed 1.5 m in diameter and 1 m in height.

The Maunalua Bay Artificial Reef Site was initiated in 1961 and over a 12-year period received almost 1,600 stripped auto bodies and 2,116 metric tons of damaged (surplus) concrete pipe (Kanayama and Onizuka, 1973). Much of this older material has disintegrated or has been swept into deeper water by storm surf. However, one area was located where surplus concrete pipes are still situated in relative proximity to each other. More than 60 pipes ranging in diameter from 45 to 150 cm and up to 3.7 m in length are clustered in several groups over an approximate 1,200 m^2 area (Fig. 1). More recently, 2 derelict barges were scuttled in the artificial reef site and in 1985–1986 state aquatic biologists deployed approximately 550 auto tire modules in a 1 ha area within the site. These modules were comprised of 8 to 10 tires placed side by side to form a cylinder, the lower third of which was embedded into a 30 × 60 × 150 cm concrete base for stability (Fig. 2). These tire modules were dumped from a barge which resulted in a haphazard arrangement on the bottom. Approximately one-half of the units were scattered or dispersed (less than one unit per 10 m^2 of substratum), probably because the barge drifted during deployment; the other half were clumped (greater than one unit per 6 m^2 of substratum). Most of the aggregated tire modules occurred in a single elongate pile with a maximum height of approximately 3 m.

About 0.4 km away from the auto tire reef materials was a small experimental Japanese style artificial reef constructed in 1985 of 42 open framework concrete cubes each measuring 1.2 m on a side (Fig. 3). Fifteen of these cubes were outfitted with a horizontal shelf situated behind a center crossmember to provide additional cover for fishes. The concrete cubes were deployed using a winch and moved into proximity to each other using a lift bag. The reef was comprised of 38 cubes that formed a monolayer upon which 4 modules were placed to create a second level (Brock et al., 1985).

Fishes were visually censused on the above artificial reefs and the natural control reef using both line transects (20 × 4 m) and whole reef counts as outlined in Brock et al. (1979) and Brock (1982). The control reef was a randomly selected 60 m^2 area located within the same biotope as the artificial reefs. Data gathered from all reefs include species observed, numbers of individuals and their estimated

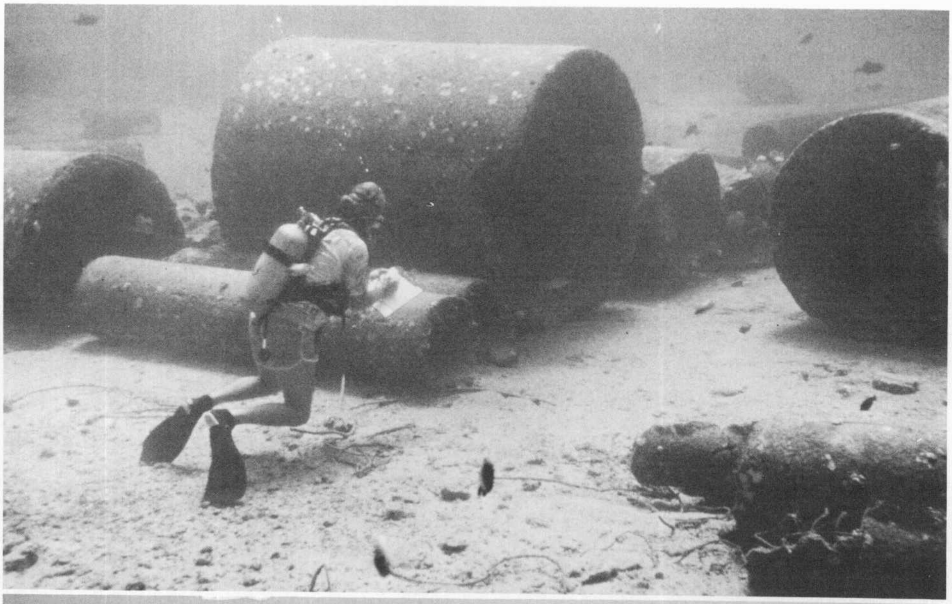

Figure 1 (left). One of the clusters of surplus concrete pipe censused in this study.

Figure 2 (right). Aggregated tire and concrete modules. Each module is approximately 1.5 m in length; this cluster covers approximately 158 m^2.

standard lengths. The estimated lengths of each species were used to compute standing crop (g/m^2) estimates using length-weight regression techniques. Regression parameters for the individual species were from unpublished data (Hawaii Cooperative Fishery Research Unit, University of Hawaii).

Problems associated with the use of the visual transect method for the assessment of fishes (Brock, 1954) have been dealt with elsewhere (Chave and Eckert, 1974; Jones and Chase, 1975; Sale and Douglas, 1981; Brock, 1982; Sale and Sharp, 1983; Thresher and Gunn, 1986). Despite its drawbacks,

Figure 3. Open framework concrete cube artificial reef comprised of 42 modules. Modules are 1.2 m on a side and weigh 1,150 kg.

the visual census technique remains one of the best non-destructive survey methods available for the assessment of diurnally active coral reef fishes (Brock, 1982).

Due to heterogeneity of variances the non-parametric Kruskal-Wallis ANOVA (Sokal and Rohlf, 1981) was used to discern statistically significant differences among ranked means for the number of species, the weight of individual fish and the standing crop of fishes censused on the 4 artificial reef types and the natural control reef. The a posteriori Student-Newman-Keuls multiple range test (SAS Institute, Inc., 1985) was used to elucidate differences between specific locations.

RESULTS

All study reefs were similar with respect to their maximum height, deployment depth, maximum hole diameters and bulk volume (Table 1). Bulk volume is defined as the space which envelopes a reef structure including its internal voids (Nakamura, 1985). Large differences in the area covered by each reef were apparent; the concrete cube reef occupied 60 m^2 while the concrete pipes covered almost 1,200 m^2. A measure of dispersion (defined here as the area covered in square meters divided by the bulk volume in cubic meters multiplied by the water depth in meters) shows the concrete cube reef to be much less dispersed than any of the other reefs (Table 1).

All reefs were deployed in one part of Maunalua Bay and were presumably exposed to similar immigration and recruitment processes. The composition of the fish communities on the various artificial reefs and control area were strikingly similar. In total, there were 137 species of fishes distributed among the reefs; the greatest number of species from a single location (N = 125) was recorded from the concrete cube reef. Ninety-two percent of these were also encountered on the natural reef (control area), 96% on the dispersed tire reef and 93% on the aggregated

Table 1. Summary of measured physical parameters and deployment methods for the artificial reefs examined in this study

Parameter	Concrete cube	Aggregated tires	Dispersed tires	Surplus pipe
Maximum height (m)	2.4	3.0	0.75	1.5
Deployment depth (m)	20	21	21	21
Maximum hole diam. (m)	0.75	0.6	0.4	1.8
Area covered (m^2)	60	527	473	1,176
Bulk volume (m^3)	78	245	188	102
Dispersion*	0.065	0.023	0.020	0.004
Deployment method	placed	dumped	dumped	dumped
Dates deployed	11/85	7/85–6/86	7/85	1972

$$* \text{Dispersion} = \frac{\text{bulk volume } (m^3)}{\text{area covered } (m^2) \times \text{water depth } (m)}$$

tire reef. The lowest species commonality (90%) occurred between the reef constructed of surplus concrete pipes and the concrete cube reef. Although fishing activities were not quantified (e.g., creel censuses, etc.) our qualitative observations suggested that fishing pressure on the various reefs was similar during the period of this study.

The open framework concrete cube artificial reef had a greater mean number of species (49 ± 8), a larger standing crop (1,266 ± 612 $g \cdot m^{-2}$) and larger fish (137 ± 41 $g \cdot fish^{-1}$) than any other location we sampled (SNK test, Table 2, $P < 0.05$). Among the other locations, no differences were found in the mean number of species between the aggregated tire reef (28 ± 9) dispersed tire reef (22 ± 10) and the concrete pipe reef (29 ± 8, $P > 0.05$). The control reef, however, had significantly fewer species (21 ± 4, $P < 0.05$) than all other reef types except the dispersed tire reef.

Fishes on the concrete pipe reef (53 ± 25 $g \cdot fish^{-1}$) and the dispersed tire reef (46 ± 19 $g \cdot fish^{-1}$) were larger than those from the control area (29 ± 15 $g \cdot fish^{-1}$, Table 2, $P < 0.05$) while those on the control, dispersed tire and concrete pipe reefs were smaller than fishes censused on the aggregated tire reef (92 ± 28 g·fish). Standing crop estimates from the concrete pipe reef (264 ± 220 $g \cdot m^{-2}$), aggregated tire reef (123 ± 74 $g \cdot m^{-2}$) and the dispersed tire reef (95 ± 57 $g \cdot m^{-2}$) were statistically indistinguishable from each other ($P > 0.05$), while standing crop from the control reef (46 ± 25 $g \cdot m^{-2}$) was significantly smaller than from any of the artificial reefs (Table 2, $P < 0.05$).

DISCUSSION

Fish communities on natural undisturbed substratum in the Maunalua Bay Artificial Reef Site are characterized by low standing crops and small-sized individuals. The natural bottom affords little cover and most resident fishes are either small as adults or are juveniles of larger species that emigrate with growth. Two pre-deployment baseline censuses conducted on the site where the concrete cube reef was subsequently placed exhibited a mean standing crop of 61 ± 39 $g \cdot m^{-2}$; this estimated standing crop is comparable to the natural reef control area (45 ± 25 $g \cdot m^{-2}$, N = 47).

Some authors (Risk, 1972; Gladfelter and Gladfelter, 1978; Brock et al., 1979; Ogden and Ebersole, 1981; Anderson et al., 1981; Shulman et al., 1983; Shulman, 1984; Eckert, 1985; Walsh, 1985; Alevizon et al., 1985b) have viewed reef structure as an important factor in determining the community structure of coral reef fishes. Others have suggested that recruitment processes are more important than

Table 2. Mean number of species, weight and standing crop of fish (±SD) from four types of artificial reef and a natural reef control area. Horizontal lines separate reef types that show a significant difference ($P < 0.05$) for each variable (using the Student-Newman-Keuls multiple range test on ranked values of each variable)

	Concrete cube (N = 47)	Aggregated tires (N = 11)	Surplus pipes (N = 5)	Dispersed tires (N = 10)	Control (N = 47)
Mean number of species	49 ± 8	28 ± 9	29 ± 8	22 ± 10	21 ± 4
Mean wt ($g \cdot fish^{-1}$)	137 ± 41	92 ± 28	53 ± 25	46 ± 19	29 ± 15
Standing crop ($g \cdot m^{-2}$)	1,266 ± 612	123 ± 74	264 ± 220	95 ± 57	45 ± 25

reef structure per se in determining the species composition of these communities (Russell et al., 1974; Sale and Dybdahl, 1975; Sale, 1978; 1979; Sale and Douglas, 1984; Sale et al., 1984a; 1984b). However as noted by Alevizon et al., (1985b), the spatial scale at which one samples fish community structure is central to the result and subsequent interpretation. Siting (i.e., nature and distance of the major recruitment sources) may also be an important factor in determining coral reef fish community structure on a given reef (Alevizon et al., 1985a). Since the reefs used in this study were all relatively large, of comparable size and located in the same depth and habitat (within a radius of 1 km), they were probably served by a common recruitment source.

The rationale for construction of the artificial reefs investigated in this study was to locally increase species that have commercial and recreational importance. Each reef design showed some enhancement effect for both targeted fishery and non-fishery species. However, regardless of species the most effective design for the parameters we measured was the concrete cube reef. Although the aggregated tire, dispersed tire and surplus pipe designs supported similar amounts of fish, the aggregated tire reef attracted larger individuals. This suggests an inverse relationship between reef material dispersion and the mean size of resident fish.

The standing crops we estimated on the aggregated tire, dispersed tire and concrete pipe reefs are consonant with those made on older reef materials (scrap automobile bodies and concrete pipes) in the same general area before the older materials disintegrated or were scattered by storm surf. Kanayama and Onizuka (1973) conducted 18 visual censuses on auto bodies and concrete pipe in the Maunalua Bay Artificial Reef Site from 1961 to 1973 and reported a mean standing crop of 92 ± 52 $g \cdot m^{-2}$. Their results seem to typify the low to moderate enhancement capabilities this study has described for reefs that were constructed of scrap materials dumped haphazardly. In contrast, the mean standing crop of fishes on the concrete cube reef (1,266 $g \cdot m^{-2}$) was relatively high compared to estimates made on natural and artifical reefs in other localities. Stone et al. (1979) reviewed published standing crop estimates and reported ranges of 27 to 158 $g \cdot m^{-2}$ on natural reefs and 26 to 698 $g \cdot m^{-2}$ on artificial reefs. Downing et al. (1985) reported a mean standing crop of 3,300 $g \cdot m^{-2}$ from three small auto tire reefs (approximate bulk volumes from 18 to 38 m^3 using his fig. 2) deployed as modules assembled into structured reefs in shallow waters off the coast of Kuwait. These authors however, noted that the small size of their reefs precluded extrapolation of their results to larger reefs, hence comparison of their results to the present study seem inappropriate.

A possible explanation for the greater enhancement characteristics of the concrete cube reef versus the other Hawaiian artificial reefs might be the deployment method. The concrete cube reef was constructed of specifically designed modules which were carefully assembled on the seafloor into a reef; the aggregated and dispersed tire reefs were built using designed modules (concrete and tires) and the concrete pipe reef was constructed of non-uniform surplus pipe. However, the tire and pipe reefs were deployed by dumping from a barge. As a result, these modules were haphazardly scattered across the substratum. The data also suggest that although newer modules constructed from scrap tires cast into a concrete base may prove more stable than auto bodies and surplus concrete pipe, the extra effort expended in producing such modules is not reflected in greater aggregating properties because of their final haphazard arrangement.

In conclusion, results suggest a hierarchy of artificial reef effectiveness at this Hawaiian locality: least effective are reefs built of haphazardly dumped unmodified scrap materials; more effective are reefs using specifically designed modules deployed by dumping and the most effective are modules assembled into specifically designed reefs. Thus, insofar as shelter is concerned, a specifically designed set of shelter spaces appears to be more effective than the highly variable shelter that results from the haphazard deployment of materials.

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