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Vertical Artificial Structures as an Alternative Habitat for Coral Reef Fishes in Disturbed Environments

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ABSTRACT

The coral reefs of Eilat (Red Sea) have been heavily damaged as a result of extensive tourist activity. Artificial reefs have been demonstrated to be a potential tool for the restoration of marine habitats. We investigated the fish assemblage on pillars supporting the oil jetties in Eilat, studying the species composition on these vertical structures; and the relationships between fish community features and the structural characteristics of these artificial reefs over time, using multivariate regression analysis. The fish assemblage on these 25-year-old structures was shown to be abundant and diverse, comprising 146 species, distributed among 35 families. The 10 most abundant species were planktivores, accounting for 78% of all individuals; the most numerous fish was Neopomacentrus miryae *(*Pomacentridae*). Size and complexity of pillars were correlated with fish abundance, richness and diversity, and related to the availability of shelters. These community indices increased near the bottom, possibly due to behavioral preferences. High coefficient of variance (CV) values indicated high temporal variability, resulting from a pronounced recruitment of* N. miryae *and other common species during April 1993. We discuss the possible use of these artificial reefs as a model for the construction of artificial habitats aimed at the rehabilitation of fish assemblages in deteriorating natural coral reef areas. © 1998 Elsevier Science Ltd. All rights reserved*

Keywords: artificial reefs, coral reef, fish community, recruitment, Red Sea.

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INTRODUCTION

Various anthropogenic perturbations are known to impose stress on coral reef ecosystems world wide (Richmond, 1993; Sebens, 1994; Grigg, 1995). One major cause of stress is tourist activity and its associated development, which can bring about a deterioration in reef conditions (Kenchington, 1988; Sudara and Nateekarchanalap, 1988; Pendelton, 1994). Visitors to the reef break corals and resuspend sediment (Gittings *et al.*, 1988; Rogers *et al.*, 1988; Neil, 1990). Such damage may have a devastating impact on the environment by altering species composition, leading to communities dominated by opportunistic organisms (Chou, 1988; Rogers, 1990; Wittenberg and Hunte, 1992). The decrease in spatial complexity of the reef caused by the destruction of corals can lead to a reduction in both species richness and diversity of reef fishes (Sano *et al.*, 1984; Dennis and Bright, 1988; Dawson Shepherd *et al.*, 1992). Coral destruction may also be followed by a reduction in fish settlement, since shelter is known to be one of the limiting factors for recruitment of fish on reefs (Robertson *et al.*, 1981; Hixon and Beets, 1993).

In the 1970s it was noted that continuous disturbance to the coral reef in Eilat, Israel (Gulf of Eilat, Red Sea) caused by human activities, had altered the benthic species composition, leading to domination of benthic algae in some locations (Fishelson, 1977). In the past, the major anthropogenic stresses in Eilat were caused by oil spills and phosphate pollution (Fishelson, 1973; Loya and Rinkevich, 1980). Recently, however, the major cause of damage has been the accelerated tourism development and the hundreds of thousands of visitors to the reef annually (Diamant, 1996). In addition to restricting tourist activities and developing an educational programme, there is a need to apply other solutions in order to rehabilitate reefs, e.g. by offering alternative diving sites and enlarging the overall pool of reef organisms.

Artificial reefs have been demonstrated to be a potential tool for the restoration of marine habitats (Pratt, 1994). The creation of new, well-planned, artificial reefs, may offer alternative shelters, which would be expected to recruit juveniles, and thus enlarge the overall pool of fish (Campos and Gamboa, 1989; Alevizon and Gorham, 1989). To date, research into artificial reefs has focused primarily on examining the potential enhancement of fishing grounds (Buckley and Hueckel, 1985; Bell *et al.*, 1989; Relini and Relini, 1989; Bohnsack *et al.*, 1991; Liu *et al.*, 1991; Naito, 1990; Bombace *et al.*, 1994). Moreover, most studies have been conducted in temperate seas and the Mediterranean (reviewed in Seaman *et al.*, 1989; Jensen, 1997). One recent application for artificial reefs has been to use them for mitigation of environmental damage, as demonstrated along temperate Pacific coasts in the United States (Seaman and Sprague, 1994). In tropical waters, artificial reefs have mainly been used to study fish community structure, recruitment dynamics and settling preferences (e.g. Beets and Hixon, 1994; Cummings, 1994). Only a few artificial reefs have been used to study their management potential as tools for nature conservation (e.g. Campos and Gamboa, 1989); and most of these studies used low-relief structures. Bohnsack *et al.* (1991) noted that high reefs may not be effective for demersal fish species, while Hair *et al.* (1994) showed no difference in abundance and richness between near bottom and near surface flat artificial reefs units in Botany Bay, Australia. Beets (1989) and Brock and Kam (1994) demonstrated, however, that floating 'Fish Aggregating Devices' (FADs) can enhance recruitment of coral reef fishes to benthic low-relief structures. Size, relief, surface area, complexity and location were all demonstrated to be important factors influencing the success of an artificial reef as an attractor of targeted species, and as a means for general enhancement of the fish community (Bohnsack *et al.*, 1991; Kim *et al.*, 1994).

Artificial reef design developments have led to the deployment of specifically designed reef modules of various structures and materials, but predominately concrete (Lin and Sue, 1994; Bohnsack *et al.*, 1994; Grove *et al.*, 1994). In some countries, notably the USA, artificial reefs have been used as an option for solid waste disposal and enhancing benthic communities (Waldichuk, 1988). Modular artificial reefs have been demonstrated to support more diverse fish assemblages than reefs constructed of scrap materials (Brock and Norris, 1989).

This study examines the feasibility of using the vertical pillars supporting the oil jetties constructed in the early 1970s at Eilat (Red Sea, Israel) as a model for construction of future artificial reefs. In preliminary observations the fish community at the site seemed rich and diverse as compared to nearby natural reefs; however, none of the local natural reefs has the extent of vertical relief of these jetties. In order to study the relation between structural characteristics and fish community features at the jetties, the following objectives were set: (1) to study the species composition of the fish assemblage that settles on such vertical structures; (2) to examine the relationship between pillar size, structural complexity and fish abundance, species richness and diversity; (3) to study the effect of bottom proximity on the fish assemblage; and (4) to analyze temporal features of the fish assemblage on a short time scale (10 months).

MATERIALS AND METHODS

Study site

The study was conducted at the jetties of the oil terminals located 5 km south of Eilat, Israel (Fig. 1(a),(b)). The site is closed to the public, and since oil pollution is strictly controlled, the area is almost undisturbed. The two jetties are supported by steel pillars, each 1 m in diameter, and located on a moderate sandy slope. Most of the pillars are partially surrounded by barbed wire, which adds much to the structural complexity of the site. The northern jetty is 150 m long with pillars 15 m apart (Fig. 1(c)). The southern jetty is 250 m long with extensions to the north and south. Most of the pillars at the southern jetty are arranged in triplicates; two pillars adjacent (one diagonal) and a third one based 10 m away (Fig. 1(d)). The triplicates are arranged 20 m apart, down to 30 m depth. The sixth group of pillars from the shore comprises two triplicates, 3 m apart. Pillars of different sizes, with and without wire, were chosen for the study and numbered (Table 1). Pairs of pillars enclosed by wire were regarded as one structure (Fig. 1(d)). A group of six pillars without wire, at the end of the southern extension of the southern jetty (indicated in Fig. 1(b)), was considered as a single large, vertical, non-complex structure, and was censused once. The height of the wire from the bottom (Fig. 1(d)) was measured at each pillar. Wire coverage (%) = (wire's height/pillar's height) × 100.

The average spatial complexity of the barbed wire areas was determined by counting the number of wire lines passing within an imaginary 25×25×50 cm volume-unit, obtained by using a 25×25 cm quadrat and a 50 cm plastic rod (Goren, 1992). Spatial complexity was divided into the four following wire density categories: (1) 1–2, (2) 3–5, (3) 6–8, and (4) > 8 wires ($n = 110$ quadrats). It was found that the average density of wire

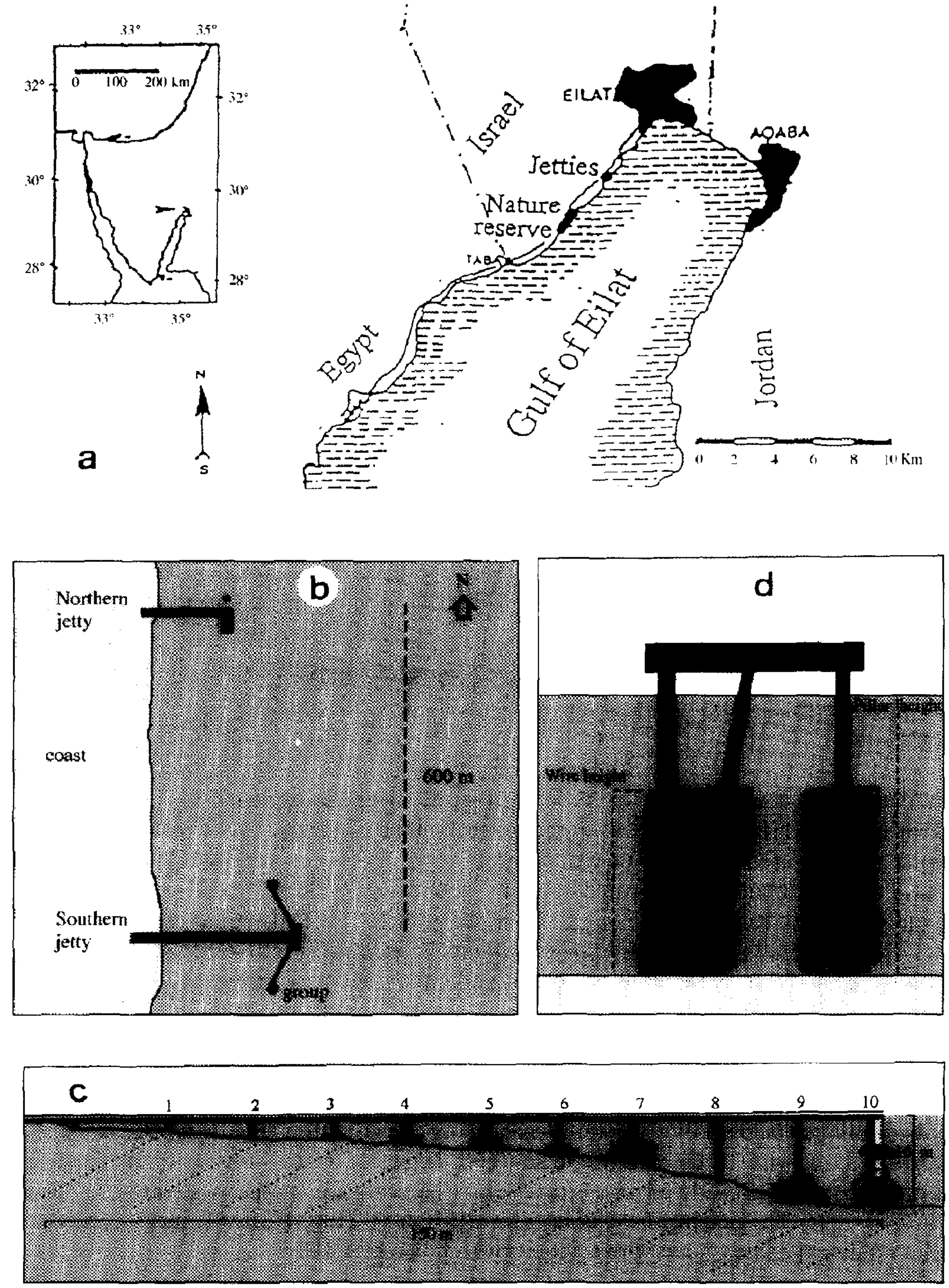

Fig. 1. A schematic description of the jetties at the Eilat oil terminal. (a) Geographical location of the study site. (b) The relative position of each jetty and their general shape. (c) A side view of the northern jetty. The 11th studied pillar is located under a perpendicular pier at the end of the jetty. (d) A side view of a triplicate of pillars at the southern jetty.

TABLE 1
The Studied Pillars at the Northern and Southern Oil Jetties and Their Structural Features

Pillar	*Distance from shore (m)*	*Pillar height (m)*	*Wire height from bottom (m)*	*Wire coverage (%)*	*Calculated volume around a pillar (m^3)*	*Number of censuses*
Northern jetty						
2	20	3	0	0	11	4
3	35	4	0·3	8	16	4
4	50	4	0·4	10	26	4
5	65	6	1·5	25	23	4
6	80	7	0·7	10	22	4
7	95	8	3	37	59	4
8	110	12	0	0	33	4
9	125	16	4	25	72	4
10[a]	140	16	7	44	264	4
11	140	16	6	38	112	3
Southern jetty						
6a	100	7	3	43	33	3
6b	100	7	3	43	40	3
6c	100	7	3	43	40	3
6d	103	7	3	43	35	3
6e	103	7	3	43	40	3
6f	103	7	3	43	35	3
9a	160	16	9	56	117	4
9b[a]	160	16	9	56	117	4
10a	180	20	11	55	115	5
10b[a]	180	20	11	55	224	5
Group[b]	220	20	0	0	774	1

Pillars 6a–f belong to one group of six adjacent pillars.
[a] Two adjacent pillars surrounded together by wire and regarded as one.
[b] A group of six adjacent pillars also regarded as one.

lines per the above volume-unit was 6·1, corresponding to density category 3, but in many areas wire lines were even denser (category 4).

Census techniques

Visual fish censuses around the pillars, using SCUBA, were conducted during the period of July 1992 to April 1993. This technique is non-destructive and useful for most fish species, albeit resulting in a certain underestimation of both the cryptic and most abundant species (Brock, 1982). The barbed wire was encircled with horizontal nylon lines spaced at intervals of 3 m along the pillars from the upper wire sections to the bottom. In this way we created permanent belt transects (Cole and Tarr, 1990), 3 m wide and 10–15 m long (depending on the wire's perimeter around the pillars), marked on both sides (Sale and Sharp, 1983; Sale, 1997). At the tallest pillars censused (9–11 in the northern jetty, and 9a, 9b, 10a and 10b in the southern jetty), the upper part of the pillar, varying in width from 7 to 9 m, was not surrounded by wire, and was regarded as a single wide transect. While circling around the pillar, we monitored the fish assemblage at each transect depth. First, the more conspicuous fish were counted from a distance of 2–3 m, and the size of large schools was estimated to the nearest 50 individuals. Next, the diver approached the wire, and the space within the wire was closely examined for more crepuscular species, or small and cryptic ones, using a flashlight if necessary. In most cases, the fish were identified underwater to the species level. Appearance of juveniles was noted during censuses, though they were not distinguished in the counts. Only resident and visitor (transient) species (see Bohnsack *et al.*, 1994) with a clear association with the artificial structures were included in the counts, omitting transient pelagic species.

Community parameters

Species composition

The abundance of each species is described in this study by two indices: relative abundance (RA) and frequency of appearance (FA) in all censuses (Alevizon and Brooks, 1975). A census was defined as a single count of fish around a pillar at a given date ($n=75$). The indices were calculated as follows:

$$\mathrm{RA} = (\text{the pooled number of individuals of the } i \text{ species from all censuses/ the total number of all individuals in all censuses}) \times 100$$

$$\mathrm{FA} = (\text{number of censuses in which the } i \text{ species was noted/ total number of censuses}) \times 100.$$

Fish assemblage, size and complexity

Average values of absolute fish abundance (all species pooled), species richness (number of species) and diversity (H', Shannon and Weaver, 1964) were calculated for entire pillars and for the different sections (transects) along the tallest pillars censused. Multiple regression analysis (Draper and Smith, 1981) was performed on the entire data in order to examine the relationships between the community characteristics and spatial variables (pillar height, wire height, wire coverage). After examining the distribution of the dependent variables, root transformation was performed when needed.

Fish assemblage and proximity to the bottom

The division of the pillars into separated horizontal sections, performed by the belt transects, allowed us to study the relationship between fish community features and depth and proximity to the bottom. In order to estimate the fish density per cubic meter at the belt transects around the pillar, we calculated the volume (in m^3) of living space and shelter available for fish in each transect by measuring the perimeter of the wire at three depths in the transect. The perimeter of the wire was measured every meter along the pillar. The total volume (available space) was calculated by multiplying the average area by the height of the wire. For the pillar areas with no wire the available space was calculated for a distance of 1 m around the pillar, this resulted in an imaginary cylinder with a radius of 1·5 m, and its volume was calculated and added to the above. From this volume we subtracted the volume occupied by the pillar itself, thus obtaining the total living space within the wire. The total volume around a pillar (Table 1) was derived from the individual volumes of the transects. Data from the four tallest pillars censused at the southern jetty were used for calculating the multiple regressions to examine the relationships between community indices and depth, distance from the bottom, and presence/absence of wire along the pillars. The presence or absence of the wire was a categorical variable and treated in the analysis as a dummy variable. The values produced for this variable should be added to the regression equation if proven significant.

Fish assemblage and temporal variability

In order to detect temporal variability in the fish assemblage, most pillars were censused three to five times during the 10-month study period. The coefficient of variation (CV) was calculated for all measurements as an indication of the extent of temporal variation of the fish assemblage (Sale *et al.*, 1994). CV expresses the standard deviation of a set of values as a percentage of the average, and is useful when comparing variability in datasets with different means. The multiple regression analysis also included the temporal (the month of census) variables which were treated as categorical (dummy) variables ($n = 82$). The regression analysis thus resulted in equations which included the coefficients of the continuous variables (pillar or wire height, depths, etc.), and the values of the categorical variables (presence of wire and month of sampling) which should be added to the equation, if proven significant. These equations are presented in tabular format (see Results).

RESULTS

Species composition

A total of 146 fish species (Table 2) from 35 families (Table 3) was recorded. The relative abundance (RA) and frequency of appearance (FA) of the species are shown in Table 2. The damselfish *Neopomacentrus miryae* (= *azysron*) (Pomacentridae) was the most abundant fish (RA = 43·8%), and recorded in almost all censuses (FA = 96·2%). This species appeared in large aggregations, which in April 1993 reached hundreds to thousands of individuals, composed mostly of juveniles. *Cheilodipterus quinquelineateus* (Apogonidae) was second in relative abundance (RA = 8·0%). This fish was also most abundant in April 1993, when many juveniles were found hiding among the spines of the sea urchin *Diadema setosum*. Of the 10 most abundant species, damselfishes accounted for 61·3% of all fishes and apogonids for 15·4%.

Amphiprion bicinctus (Pomacentridae) which dwells in association with sea anemones, was frequently observed at the oil jetties (FA = 61·5%). Pomacentrids, such as *Dascyllus marginatus* and *D. aruanus*, that are known to inhabit branching corals (Randell, 1983) were rare, with relative frequencies of around 20%. Herbivores such as scarids and siganids accounted for less than 1% of all fishes. Carnivores were relatively rare: scorpionids accounted for less than 0·9%, but *Pterois miles* was encountered often, and appeared in 57·7% of the censuses. Only five species of groupers were observed out of 46 known from the Red Sea (Randell and Ben-Tuvia, 1983; Goren, 1993), and all were counted in low numbers (few individuals); only *Epinephelus fasciatus* and *Cephalopholis miniata* were relatively frequent (FA = 40·4 and 21·2%, respectively). Four butterflyfish species, though having low RA values, were relatively frequent in the censuses (FA = 19–50%, Table 2), as was the emperor fish *Pomacanthus imperator* (FA = 40·4%). These territorial species appeared only around pillar sections surrounded by wire.

TABLE 2
Relative Abundance (RA) and Frequency of Appearance (FA) of the Fish Species During the Censuses at the Oil Jetties

Species	*RA*	*FA*	*Species*	*RA*	*FA*
Neopomacentrus miryae	43·84	96·2	*Chromis pembae*	0·06	5·8
Cheilodipterus quinquelineatus	8·00	71·2	*Cephalopholis miniata*	0·05	21·2
Dascyllus trimaculatus	5·63	98·1	*Scarus viridescens*	0·05	21·2
Amblyglyphidodon flavilatus	4·14	73·1	*Pseudocheilinus hexataenia*	0·05	15·4
Amblyglyphidodon leucogaster	4·13	88·5	*Chaetodon melannotus*	0·05	9·6
Pseudanthias squamipinnis	3·92	78·8	*Scarus sordidus*	0·04	19·2
Pomacentrus trichourus	3·58	90·4	*Cheilinus abudjubbe*	0·04	15·4
Apogon cyanosoma	3·58	67·3	*Coris variegata*	0·04	15·4
Apogon aureus	3·29	55·8	*Pseudocheilinus evanidus*	0·04	15·4
Paracheilinus octotaenia	1·56	32·7	*Zebrasoma veliferum*	0·04	15·4
Stethojulis sp. 1	1·43	86·5	*Plagiotremus tapeinosoma*	0·04	7·7
Adioryx diadema	1·21	76·9	*Pomacentrus albicaudatus*	0·04	1·9
Chromis dimidiata	0·87	55·8	*Pseudobalistes fuscus*	0·04	1·9
Caesio lunaris	0·78	1·9	*Cirrhitchthys oxycephalus*	0·03	13·5
Chromis pelloura	0·72	25·0	*Pomacanthus maculosus*	0·03	13·5
Pterois miles	0·69	57·7	*Bodianus diana*	0·03	11·5
Holacanthus xanthotis	0·65	76·9	*Scorpaenopsis barbatus*	0·03	11·5
Cheilodipterus lachneri	0·58	48·1	*Pygoplites diacanthus*	0·03	11·5
Thalassoma klunzingeri	0·55	67·3	*Antennarius coccineus*	0·03	11·5
Bodianus anthioides	0·50	61·5	*Coris caudimacula*	0·03	11·5
Myripristis murdjan	0·50	55·8	*Ostracion cyanurus*	0·03	11·5
Ostracion cubicus	0·48	69·2	Gobiidae sp. 2	0·03	5·8
Abudefduf saxatilis	0·45	36·5	*Plectroglyphidodon leucozona*	0·03	3·8
Acanthurus nigrofuscus	0·43	55·8	*Pseudochromis springeri*	0·02	23·1
Labridae juvenile 1	0·42	9·6	*Chilomycterus spilostylus*	0·02	11·5
Labroides dimidiatus	0·40	53·8	*Larabicus quadrilineatus*	0·02	7·7
Siganus rivulatus	0·37	25·0	*Chromis trialpha*	0·02	3·8
Sphyraena sp.1	0·35	1·9	Blanniidae sp. 2	0·02	1·9
Priacanthus hamrur	0·35	26·9	*Cantherhines pardalis*	0·01	7·7
Amphiprion bicinctus	0·30	61·5	*Arothron diadematus*	0·01	5·8
Pteragogus cryptus	0·29	44·2	*Cephalopholis argus*	0·01	5·8
Heniochus diphreutes	0·28	32·7	*Cheilinus lunulatus*	0·01	5·8
Cheilinus digrammus	0·27	42·3	*Chrysiptera annulata*	0·01	5·8
Chromis ternatensis	0·25	17·3	*Genicanthus caudovittatus*	0·01	5·8
Chromis weberi	0·24	11·5	*Scarus ghobban*	0·01	5·8
Chaetodon paucifasciatus	0·23	50·0	*Synodus variegatus*	0·01	5·8
Parapeneus forsskali	0·22	28·8	*Istiblennius periophthalmus*	0·01	3·8
Carangoides fulvoguttatus	0·22	3·8	*Diplodus noct*	0·01	3·8
Centropyge multispinis	0·21	48·1	*Scorpaenopsis diabolus*	0·01	3·8
Scolopsis ghanam	0·21	40·4	*Acanthopagrus bifasciatus*	0·01	1·9
Scarus fuscopurpureus	0·21	30·8	*Stethojulis albovittata*	0·01	1·9
Pseudodax moluccanus	0·21	3·8	*Chaetodon lineolatus*	0·007	3·8
Dascyllus marginatus	0·19	23·1	*Cheilinus fasciatus*	0·007	3·8
Anampses twistii	0·14	51·9	*Dendrochirus bachypterus*	0·007	3·8
Epinephelus fasciatus	0·14	40·4	*Dunckerocampus multiannulatus*	0·007	3·8
Meiacanthus nigrolineatus	0·14	34·6	*Hologymnosus annulatus*	0·007	3·8
Chaetodon fasciatus	0·13	36·5	*Naso unicornis*	0·007	3·8
Canthigaster margaritata	0·13	32·7	*Paracirrhites forsteri*	0·007	3·8
Pomacanthus imperator	0·11	40·4	*Parupeneus cyclostomus*	0·007	3·8

TABLE 2—*continued*

Species	*RA*	*FA*	*Species*	*RA*	*FA*
Pseudochromis fridmani	0·11	26·9	*Parapercis hexophtalma*	0·007	3·8
Heniochus intermedius	0·11	21·2	*Parupeneus macronema*	0·007	3·8
Scarus ferrugineus	0·10	32·7	*Scorpaenopsis oxycephalus*	0·007	3·8
Chaetodon auriga	0·10	23·1	*Sufflamen albicaudatus*	0·007	3·8
Pseudochromis olivaceus	0·10	11·5	Labridae juvenile 2	0·007	1·9
Anampses meleagrides	0·09	23·1	Labridae sp. 1	0·007	1·9
Ecsenius gravieri	0·09	21·2	*Mulloides vanicolensis*	0·007	1·9
Dascyllus aruanus	0·09	19·2	*Pristotis cyanostigma*	0·007	1·9
Zebrosoma xanthurum	0·09	17·3	*Siganus argenteus*	0·007	1·9
Lethrinus sp. 1	0·09	1·9	*Siganus luridus*	0·007	1·9
Siderea grisea	0·08	26·9	*Petroscirtes mitratus*	0·004	1·9
Pterois radiata	0·08	26·9	*Stegastes nigricans*	0·004	1·9
Fistularia commersonii	0·08	25·0	*Abudefduf sordidus*	0·004	1·9
Thalassoma lunare	0·08	23·1	*Amanses scopas*	0·004	1·9
Bodianus axillaris	0·08	21·2	Blenniidae sp. 3	0·004	1·9
Chaetodon austriacus	0·08	19·2	*Cephalopholis hemistiktos*	0·004	1·9
Anampses lineatus	0·08	17·3	*Gomphosus caeruleus*	0·004	1·9
Coris aygula	0·07	28·8	*Grammistes sexlineatus*	0·004	1·9
Cantigaster coronata	0·07	26·9	*Hemigymnus fasicatus*	0·004	1·9
Paraglyphidodon melas	0·07	19·2	Labridae juvenile 3	0·004	1·9
Gobiidae sp. 1	0·07	5·8	*Lethrinus lentjan*	0·004	1·9
Plagiotremus rhinorhynchos	0·06	21·2	*Naso brevirostris*	0·004	1·9
Blenniidae sp. 1	0·06	15·4	*Pseudochromis flavivertex*	0·004	1·9
Corythoichthys nigripectus	0·06	13·5	*Variola louti*	0·004	1·9

Species are listed according to their RA rank.

TABLE 3

Alphabetic List of Fish Families, Including Number of Species, Recorded During the Study Period

Family	*No. of species*	*Family*	*No. of species*
Acanthuridae	5	Monacanthidae	2
Antennaridae	1	Muraenidae	1
Apogonidae	4	Nemipteridae	1
Balistidae	2	Ostraciidae	2
Blenniidae	9	Pomacanthidae	6
Caesioidae	2	Pomacentridae	22
Carangidae	1	Priacanthidae	1
Chaetodontidae	8	Pseudochromidae	4
Cirrhitidae	2	Scaridae	5
Diodontidae	1	Scorpaenidae	6
Fistulariidae	1	Serranidae	6
Gammistidae	1	Siganidae	3
Gobiidae	2	Sparidae	2
Holocentridae	2	Sphyraenidae	1
Labridae	30	Syngnathidae	2
Letherinidae	2	Synodontidae	1
Mugilidae	1	Tetraodontidae	4
Mullidae	4		

TABLE 4
Multiple Regression Between Fish Community Structure Features: Abundance, Species Richness (S) and Species Diversity (H'), and the Spatial–Temporal Features of the Pillars

Index	*(Abundance)$^{1/2}$*			(S)$^{1/2}$		H′		
Regression constant	*7·9*			*4·3*		*1·53*		
	Coef.	*ctg. con.*	F	*Coef.*	F	*Coef.*	*ctg. con.*	F
Independent variable								
Pillar height	0·91		47·4	0·220	25·7			
Wire height				0·080	11·7			
Wire coverage (%)	0·09		6·1	0·073	55·8	0·02		38·9
Categorical variables								
If July		−8·07	21·5					
If September		−6·75	15·8					
If November		−4·59	8·7					
If December		−5·73	7·9					
If April		8·88	14·2				−0·65	9·1
r^2		0·81		0·78			0·39	

The values of only the significant ($p < 0·01$) variables are given. Coef. = partial regression coefficient; ctg. con. = constants to be added according to the category (month of sampling). $n = 75$.

Fish assemblage, size and complexity

Fish abundance was affected positively by the pillar height and the percentage wire coverage on it, as expressed in the multiple regression (Table 4). The effect of the wire can be shown from the absolute abundances around the pillars: in November 1992, fish abundance at pillars 10a and 10b (20 m high, 55% wire coverage) was 774 and 1047 fish, respectively, while an average of only 122 fish per pillar was counted at the group of six pillars in the southern jetty (20 m high, 0% wire coverage). Similarly, pillar 7 (8 m high, surrounded partially by wire) had twice the number of fish as the adjacent pillar 8, which was 12 m tall with no wire, and, therefore, had almost half of the total calculated volume available for fish (Tables 1 and 4). Different CV values (Table 5) were found on structures with similar height, but with different total volume due to the wire; e.g. CV values on pillar 10 were 20–30% lower than on pillar 9 at the northern jetty, on 9b than 9a, and on 10b than 10a at the southern jetty.

Species richness was influenced by both the pillar and wire height and the percentage cover of wire. The importance of the wire for species richness can be seen in the data from the individual pillars; e.g. species richness was much higher on small pillars with a high percentage of wire cover (e.g. pillar 7, 37 species) than on a group of six pillars, 20 m high but with no wire (23 species, Table 5). Diversity was positively affected by the wire coverage (Table 4).

Fish assemblage and proximity to the bottom

The multiple regression analysis demonstrated that fish abundance decreased with increasing distance from the bottom (Table 6). However, during April 1993 abundance increased considerably (Table 6) mainly in the upper sections of the pillar where many recruits appeared. This probably explains the low regression coefficient. These trends are

TABLE 5
Averages and CV Values (in Parentheses) of Fish Abundance, Species Richness and Species Diversity at the Two Oil Jetties

Pillar number	*Pillar height (m)*	*Fish abundance*	*Species richness (S)*	*Species diversity (H')*
Northern jetty				
2	3	19·5 (130)	83·3 (5)	0·732 (46)
3	4	27·0 (114)	6·5 (9)	1·616 (12)
4	4	73·5 (74)	13·0 (18)	1·827 (13)
5	6	168·8 (51)	21·2 (30)	2·203 (24)
6	7	267·0 (60)	18·8 (17)	1·740 (32)
7	8	437·3 (88)	37·2 (16)	2·329 (22)
8	12	217·7 (81)	11·3 (4)	1·300 (37)
9	16	367·3 (58)	30·5 (35)	2·193 (11)
10	16	652·0 (35)	45·7 (16)	2·461 (8)
11	16	311·3 (39)	37·3 (11)	2·807 (4)
Southern jetty				
6a	7	224·3 (6)	29·3 (3)	2·357 (4)
6b	7	211·7 (8)	27·3 (10)	2·623 (7)
6c	7	185·7 (43)	24·7 (23)	2·397 (15)
6d	7	218·7 (20)	28·7 (12)	2·599 (9)
6e	7	167·3 (26)	23·0 (27)	2·178 (25)
6f	7	158·0 (13)	24·0 (24)	2·459 (15)
9a	16	527·8 (79)	36·2 (14)	2·499 (12)
9b	16	576·9 (59)	40·8 (25)	2·393 (21)
10a	20	991·8 (73)	44·2 (12)	2·238 (26)
10b	20	1006·0 (48)	40·8 (10)	2·119 (26)
Group[a]	20	729·0	23·0	1·687

[a] The group of pillars was censused only once and, therefore, no CV values are given (see Table 1).

demonstrated for pillar 10a (Fig. 2). The high temporal variability in the upper sections is evidenced by the higher CV values (Table 7).

The multiple regression showed a greater species richness with depth, while the time of year explained a small part of the variation (Table 6). Richness reached 30 species on average near the bottom of the highest pillars surrounded by wire, while exposed sections held much lower numbers (Table 6, Fig. 2). Species diversity also correlated positively with depth, which explained most of the variation (Table 6). Diversity was always much higher where wire was present (Table 7), with values ranging between 2 and 2·5, and a maximum of 3 near the bottom (Fig. 2).

Fish assemblage and temporal variability

The high CV values (Table 5) indicate that fish abundance varied greatly among censuses, and was highest at the shortest pillars at the northern jetty (pillars 2 and 3). Sampling date was important in determining fish abundance (Table 4) and a substantial rise in fish abundance was noted during April 1993, mainly in the upper section of the wire (Fig. 2). Sampling date did not significantly affect species richness (Table 4). However, it negatively affected diversity (April 1993, Table 4) due to high recruitment of only a few species, mainly *Neopomacentrus miryae* and the apogonid species (Rilov, 1993) which was evident

TABLE 6
Multiple Regression Between Fish Community Structure Features: Abundance, Species Richness (*S*) and Species Diversity (*H′*), and Spatial–Temporal Variables Along the Pillars

Index	*Abundance*			$(S)^{1/2}$			H′		
Regression constant	*277*			*−0·01*			*−0·05*		
	Coef.	*ctg. con.*	F	*Coef.*	*ctg. con.*	F	*Coef.*	*ctg. con.*	F
Independent variables									
Distance from bottom (m)	−14		9·4						
Depth (m)				0·32		73·9	0·13		94·3
Categorical variables									
If wire is present					0·75	6·6			
If September					0·68	11·0		0·36	5·7
If November					0·60	5·7			
If April		212	15·1		1·2	3·27			
r^2		0·26			0·82			0·59	

The values of only the significant ($p<0·01$) variables are given. Coef. = partial regression coefficient; ctg. con. = constants to be added according to the category (presence of wire and month of sampling). $n=82$.

also around the short pillars which had little or no wire, resulting in the low regression coefficient. This negative effect can be seen by the drop in diversity at the upper sections of the wire during this period (Fig. 2).

DISCUSSION

Species composition

A rich and diverse fish community has become established around the pillars of the oil jetties in Eilat during the approximate 25 years of their existence. We counted 146 species distributed among 35 families; in addition, some small cryptic species hiding within the wire were present but not recorded. Out of 75 species from the families Chaetodontidae, Pomacentridae, Labridae, Acanthuridae, Serranidae and Scaridae which appear in the northern Gulf of Eilat (Shepperd *et al.*, 1992), 71 were recorded at the jetties. This richness is even more pronounced when compared to the nearby damaged natural coral reef (Rilov, 1993). The focus of the present study was on the relationships between the structural characteristics of the site and the fish community features in order to use them for a conceptual model for future design of artificial reef for other damaged coral reef areas. Nevertheless, this is also the first comprehensive quantitative report on the fish community in the Gulf of Eilat.

Bohnsack *et al.* (1991) speculated that increased exposure to water currents on high profile reefs would favor planktivore fishes over other species. In the present study, the 10 most abundant fish species were indeed planktivores, accounting for 78·4% of the total number of fish censused during the study (Table 2). This percentage is slightly higher than that found in the nearby natural reef (*ca* 70%, Rilov, 1993), indicating that the numeric dominance of planktivores is a natural occurrence in Eilat, albeit accentuated on the jetty structures. The dominance of one planktivore species, the damselfish *Neopomacentrus*

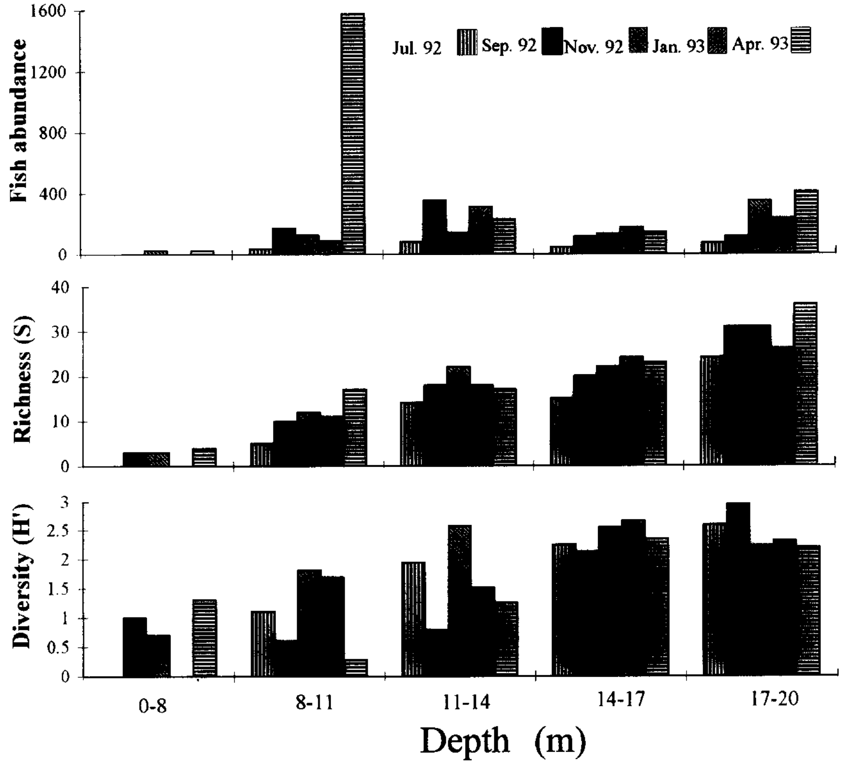

Fig. 2. Relationship between distance from the bottom (depth), sampling dates abundance, species richness (S) and species diversity (H') at one of the two highest pillars censused in the southern jetty (pillar 10a).

miryae, which appeared in great numbers around the upper sections of the wire/pillar habitat (Rilov, 1993), is probably related to the vertical orientation of the structure. Such a structure allows high exposure to plankton, and the formation of a 'wall of mouths' (Hamner *et al.*, 1988) preying on plankton at this region. *Neopomacentrus miryae*, together with another planktivore fish, *Pseudanthias squamipinnis*, which was also abundant at the upper sections of the wire, settled as larvae mainly at the upper units of vertical experimental installations located *ca* 2 km to the south of the jetties (Rilov, 1993). Therefore, their presence high above the bottom may be attributed either to settlement preferences, or to the distribution of their larvae in the water column as they approach the shore.

In general, the array of fish species on the oil jetty pillars represented all common Red Sea families (Randell, 1983). Nonetheless, some guilds of species were less well represented in the censuses than others. For example, the herbivorous fishes of the families Scaridae, Acanthuridae and Siganidae, were not abundant at the jetties (Tables 2 and 3), perhaps as a result of the poor macroalgal cover at the site through most of the year (Rilov, 1993). Such fishes and their juveniles were shown to be more abundant at the shallow fore-reef than at deeper sites (Shepperd *et al.*, 1992; Rilov, 1993), due to higher availability of algal food (see also Buchon-Navaro and Harmilin-Vivien, 1981). The piscivores, especially groupers, were usually crepuscular and difficult to detect within

TABLE 7

Average and CV Values (in Parentheses) of Fish Abundance, Fish Density, Species Richness (S) and Species Diversity (H') at the Different Depth Transects

Depth of transects (m)	*Pillar exposed or surrounded by wire*	*Fish density (m^3)*	*Fish abundance*	*Species richness (S)*	*Species diversity (H′)*
Southern jetty					
Pillar 10					
0–8	P	0·5 (147)	7·2 (142)	1·4 (112)	0·406 (126)
8–11	P+W	21·1 (184)	355·9 (128)	10·5 (34)	0·925 (70)
11–14	W	5·4 (58)	254·4 (63)	15·3 (22)	1·507 (38)
14–17	W	3·6 (45)	159·3 (56)	19·5 (25)	2·159 (13)
17–20	W	4·0 (85)	221·8 (57)	29·9 (18)	2·415 (14)
Pillar 9					
0–7	P	2·2 (116)	53·4 (98)	3·9 (85)	0·925 (27)
7–10	P+W	6·5 (127)	135·0 (138)	11·6 (44)	1·569 (28)
10–13	W	3·0 (79)	164·5 (85)	18·1 (23)	2·039 (26)
13–16	W	3·9 (60)	166·0 (52)	29·3 (25)	2·628 (7)
Northern jetty					
Pillar 10					
0–5	P	6·9 (150)	87·2 (132)	6·2 (66)	1·006 (67)
5–7	W	7·5 (81)	74·4 (70)	8·5 (21)	1·478 (11)
7–10	P+W	13·4 (82)	227·0 (69)	17·2 (103)	1·314 (65)
10–16	W	1·5 (27)	242·0 (57)	30·7 (44)	2·431 (16)
Pillar 7					
0–4	P	12·0 (129)	132·7 (129)	4·7 (81)	0·661 (38)
4–8	P	5·8 (38)	64·3 (38)	5·7 (8)	1·076 (31)
8–12	P	1·8 (38)	20·7 (38)	6·3 (27)	1·476 (18)

Data from pillars in groups 9 and 10 of the southern jetty are pooled together. W = presence of wire; P = exposed pillar; P + W = presence of wire around part of the transect.

the wire. These species, together with the butterfly and emperor fishes, were restricted to the pillar sections surrounded by wire. This finding is probably related to their territorial behavior and need for shelter. One piscivore, *Pterois miles*, was seen in many of the censuses. Its relatively high frequency and abundance, as compared to the scarcity of the groupers, may be related to selective fishing activity (such as spear fishing by intruders) seen occasionally at the site. The scarcity of fish species inhabiting branching corals is due to the low percentage coverage of these corals on the jetties (Goren, 1992).

In conclusion, the vertical orientation of the pillars seems to be especially conducive to the aggregation of juvenile planktivorous fish that were observed in large numbers, though not distinguished in this study, possibly facilitating their exposure to food (plankton), while the wire provides shelter from predators.

Fish assemblage, size and complexity

The physical dimensions of the pillars were important determinants of fish abundance. However, complexity, as expressed by the wire coverage in our study, seems to have a greater effect on the number of fish at specific locations. Clarke (1988) claimed that the size of a coral patch, as a reef ecosystem, cannot be efficiently used to predict fish abundance. In our study, nonetheless, we found a high correlation between fish abundance and pillar size (Table 4). However, along with the effect of the pillar's height the percentage of wire coverage on the pillar explained some of the variation in fish abundance. This is probably because the complexity of the wire supplies the appropriate shelter for most coral reef species apart from the pillar itself. Variability in abundance, as expressed in the CV values, usually decreased with increasing volume of pillars surrounded by wire. This can be explained by a rise in community stability with increased availability of shelter (see also Ogden and Ebersole, 1981; Sale *et al.*, 1994). Schroeder (1987) demonstrated that daily recruitment rates of several fishes increased markedly with size and degree of isolation of fish attractors. Post-recruitment survival was shown to correlate with habitat complexity in a temperate reef fish population (Connell and Jones, 1991). Potts and Hulbert (1994) compared different FAD designs and natural rock outcrops in Onslow Bay, North Carolina, and showed that fish abundance significantly increased with structural volume and complexity. Similarly, we suggest that a complex structure with a variety of internal spaces, such as supplied by the wire, provides better refuge for recruits and allows higher survival rates than the pillar itself or other artificial reefs made of quarry rocks or solid concrete blocks (e.g. Bohnsack *et al.*, 1994).

Complexity (percentage wire coverage) also contributes much to species richness and diversity. In the multiple regression analysis, richness was explained primarily by the pillar size; however, diversity (H') was mostly explained by complexity. The H' values ranged between 2 and 3 at pillars surrounded by wire, and were similar to those found for fish communities in the reefs of Eilat (Rilov, 1993), Nueba, Red Sea (Ben-Tuvia *et al.*, 1981), the Sudanese Red Sea (Edwards and Roswell, 1981), and Hawaii (Brock, 1979).

The relationship between biological diversity of the substratum and the number of fish species in the Red Sea was demonstrated by Roberts and Ormond (1987) as has a relationship between epifauna and fish community on artificial reefs (e.g. Bailey-Brock, 1989; Hueckel *et al.*, 1989). Around the oil jetties, high wire complexity was associated with rich sessile communities (see Goren, 1992). Therefore, the primary complexity of the wire, together with the secondary complexity created by the organisms on it, resulted in high niche heterogeneity and a variety of food resources for the fish, thus allowing a high diversity and species richness (see also Clarke, 1988; Gorham and Alevizon, 1989).

Fish assemblage and proximity to the bottom

Proximity to the bottom influenced all community indices. Values of fish abundance, richness and diversity tended to increase towards the bottom, even for pillars with no wire. The high number of recruits around the upper sections of the pillars during April 1993 resulted in low predictability of abundance in relation to depth, as opposed to richness and diversity. Depth positively affected fish abundance and richness in natural reefs, as a result of a higher structural complexity at greater depths (Roberts and Ormond, 1987; Cole and Tarr, 1990). However, at our study site the complexity of the wire seemed uniform throughout its length, and thus behavioral preferences related to proximity to the bottom may be the main reason for this relationship. Most demersal fish on studied artificial reefs remained within 3 m of the bottom (reviews by Grove *et al.*, 1989; Bohnsack *et al.*, 1991). Our observations at the site indicated that movement of most species among pillars occurred near the bottom, suggesting that this may be a defensive behavior against open water predation.

Fish assemblage and temporal variability

Low stability of the fish assemblages at the jetties is evidenced by the high variability in abundance as expressed by the high CV values (Table 4). This is probably a result of the seasonal recruitment of the numerically dominant species (Williams, 1983; Sale and Steel, 1986, 1989; Sale *et al.*, 1994), spatial variability in recruitment (Shulman, 1985), or high mobility (Robertson and Sheldon, 1979) of some fishes. In the present study, changes in fish abundance were mainly determined by the recruitment of only a few species, such as *Neopomacentrus miryae* (Rilov, 1993), which led to a high rise in abundance around all pillars, with or without wire. We suggest that recruits of most abundant planktivores settle initially on any conspicuous artificial structures at Eilat. Later, they either decrease in numbers due to post-recruitment mortality (Carr and Hixon, 1995) and/or migrate from exposed sites to others with more shelter. Later qualitative observations at the site during summer 1993 showed that aggregations of *N. miryae* seemed to remain mostly around pillars surrounded by wire. The planktivore *Cheilodipterus quinquelineatus*, similarly demonstrated high variability in abundance, appearing in high numbers during April 1993 (Rilov, 1993), while on lagoon coral patch reefs in Australia it showed relatively low CV values (Sale *et al.*, 1994). Though Doherty *et al.* (1997) showed high recruitment levels in reef areas with low coral cover, which followed a catastrophic storm, survival rates are probably more important than initial stages of recruitment for the establishment of a coral reef community. On both natural and artificial reefs in Barbados, temporal variability in recruitment was overridden by post-settlement events, resulting in a relatively uniform population density with time (Tupper and Hunte, 1994). The latter study suggested that the reefs were close to their carrying capacity and were 'space-limited' rather than 'recruitment-limited'. At our study site, further investigation is still needed in order to determine whether these jetties are now at their full carrying capacity. However, it is reasonable to assume that the combination of high rates of recruitment together with the relatively low number of predators resulted in less pronounced and immediate post recruitment events, such as predation.

CONCLUSIONS AND RECOMMENDATIONS

The question of whether artificial reefs redistribute fishes from surrounding areas, or whether they, in fact, increase production of fish, is as yet unresolved (Bohnsack *et al.*, 1994). Reports from Australia and Costa Rica have indicated their potential for habitat enhancement and increased local fish productivity (Campos and Gamboa, 1989; Brandon *et al.*, 1994). Bohnsack (1989) proposed guidelines for fish production in artificial reefs, including isolation of the artificial reefs, and the supply of extra shelter and food. He also suggested that production will occur primarily for demersal, territorial and obligatory reef species (e.g. damselfishes), while attraction should apply to species with fewer substratum demands (e.g. jacks and barracudas). Our study demonstrated a rich and diverse resident and visitor fish species composition. The jetties are located on a sandy bottom, and are relatively far (1–2 km) from the local natural reefs. Fishelson *et al.* (1974) described some of the numerically dominant species of Eilat (e.g. *Neopomacentrus miryae* = *Abudefduf azysron* and *Pseudanthias squamipinnis*) as stationary schooling fish that form mixed groups which remain together at the same place for years. Therefore, we presume that most reef-associated species did not migrate from the natural reefs to the jetties. Furthermore, we suggest that since the pillars are conspicuous in the water column, they attract recruits in the same way as FADs (see also Beets, 1989). The space within the wire provides shelter for the fish recruits, thus diminishing risk of predation (Hixon and Beets, 1993), and thereby allowing high survival rates (Carr and Hixon, 1995). The associated epifauna provides a wide range of niches, allowing the existence of a diverse fish assemblage. Since the jetties clearly answer all of Bohnsack's requirements (Bohnsack, 1989), we may assume that they, at least in part, increased the total fish biomass in the area. It is suggested that the jetties function as a 'nature reserve', and thus add to the overall fish pool in the depleted area, as modeled by Man *et al.* (1995).

We suggest that the jetties can provide a model for an appropriate design of modular artificial reefs aimed at mitigating the stress upon coral reef fish communities. According to the findings in our study, modular artificial reefs should possess the following features. (1) They should be high and vertical in orientation with a large base. This will attract more fish larvae for settlement than low-relief horizontal structures (Rilov, 1993). The upper sections will function as solid FADs, which will enhance recruitment of fishes to the entire structure. (2) They should consist of numerous internal spaces of various sizes, thus supplying refuge for new recruits as well as a variety of niches which will allow high fish diversity. In areas which are not recruitment limited, large vertical and complex structures will yield the maximum diversity per unit area and the assemblage will be relatively stable.

Finally, we presume that if an attractive artificial reef is available to the public, and recreational activities on it are managed properly, man-made pressure on the nearby natural reefs will be reduced, facilitating their rehabilitation and restoration.

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