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Wild fish aggregations around fish farms in the Gulf of Aqaba, Red Sea: implications for fisheries management and conservation

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ABSTRACT: Fish farm structures attract a variety of fish species by providing solid structure, and 'free meals' in the form of uneaten feed and feces that fall from the cages. In this study, we compared the composition and abundances of wild fish populations around 2 fish farms in the Red Sea and at nearby reference locations. Fish assemblages were evaluated by SCUBA divers carrying out rapid visual censuses in August, September and October 2007. A total of 87 238 fishes, representing 39 species and 25 families and a number of trophic levels, were observed. Overall, the abundance, biomass, and diversity of wild fish were much greater at the sea cages than at the open-water reference sites, at both fish farms. It is noteworthy that 35 out of the 39 species observed at the farms were juveniles and adults of coral-reef fish species. This finding is especially interesting, considering that the nearest coral reefs were >4 km away and reef fishes generally have small home ranges, typically <1 km. Among these, the Carangidae (5 species), Sparidae (3 species), and Pomacentridae (3 species) contributed the most to species richness. In light of strong fishing pressures in many areas, the large populations of wild fishes at the fish farms, the high availability of nourishment from artificial food pellets, and restrictions on fishing within farm lease areas, we suggest that coastal net-cage fish farms may serve as small marine protected areas.

KEY WORDS: Abundance · Visual census · Wild fishes · Red Sea · Aquaculture · Spatial-temporal variability · Impact

INTRODUCTION

Since the development of modern sea-cage aquaculture in the early 1980s, the number of net-cage fish farms has increased rapidly throughout the coastal areas of the world (Theodorou 1999, Ferlin & La Croix 2000, Sanchez-Mata & Mora 2000, Beveridge 2004, Halwart et al. 2007, Bostock et al. 2010). Total reported cage production of finfish amounted to 3.4 million tonnes yr^{-1} in 2010 (FAO 2012).

Natural and artificial fish aggregation devices (FADs) in the marine environment are widely recognized for their capacity to attract pelagic fishes (Hunter & Mitchell 1967, Deudero et al. 1999, Freon & Dagorn 2000). Sea-cage fish farms attract wild fish by providing structure in the pelagic environment, and uneaten feed and feces that fall through the cages may enhance the attractive effect (Phillips et al. 1985, Bjordal & Skar 1992, Dempster et al. 2002). Fish farms may therefore affect the presence, abundance, diet, and residence times of fishes in a given area (Carss 1990). Aquaculture facilities in the marine environment that serve as FADs show characteristics of healthy artificial reefs, and as such may help improve ecosystem and aquaculture management strategies (Costa-Pierce & Bridger 2002, Alston et al. 2006, Benetti et al. 2006).

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Aggregations of wild fishes are a global feature of sea-cage farms and were first documented by Carss (1990) around salmonid cages in Scotland. The phenomenon is ubiquitous, and large aggregations of pelagic and/or demersal fish have since been described around sea cages in a variety of locations, including Spain (Dempster et al. 2002), Greece (Smith et al. 2003, Thetmeyer et al. 2003), the Canary Islands (Boyra et al. 2004, Tuya et al. 2005), Norway (Bjordal & Skar 1992), the Adriatic Sea (Bubic et al. 2011), Turkey (Akyol & Ertosluk 2010), Indonesia (Sudirman et al. 2009), and Australia (Dempster et al. 2004, Felsing et al. 2005). Despite a growing literature on the occurrence of wild fishes around sea cages, only a few studies (including Angel & Spanier 2002, Angel et al. 2002, Golani 2003, Golani et al. 2008) have examined the wild fish populations near fish farms in the Red Sea. These studies suggest that the fish assemblages associated with the farms are a lot more similar to coral-reef fish communities than to local pelagic communities, despite considerable distance between farms and reefs. Coral-reef fishes generally have small home ranges (Ogden & Quinn 1984, Zeller at al. 2003), yet the distance between the fish farms and the closest coral reefs was >4 km, a range in excess of that recorded for most reef species.

In the present study, we evaluated species composition and total aggregated abundance and biomass of wild fish at 2 fish farms in the Red Sea and at reference locations in an effort to describe and understand the role of fish farms in structuring the wild fish assemblage in tropical environments.

MATERIALS AND METHODS

Study area and fish farms

This study was conducted at the fish farms 'Ardag' and 'Dagsuf', situated at the northern tip of the Gulf of Aqaba, near the Jordan-Israel border, from August to October 2007 (Fig. 1). The Gulf of Aqaba, Red Sea, supports a rich and highly diverse community of tropical and subtropical invertebrates and fishes, in spite of its generally oligotrophic waters and narrow range of water temperatures (annual range: 21 to 27°C; Reiss & Hottinger 1984). The diversity of fish and invertebrate species that characterizes the coral reefs and a host of other natural features make the gulf an increasingly popular tourist destination. Eilat's coral reefs are threatened by various anthropogenic activities, such as a port and phosphate terminal, oil pipeline, mariculture, municipal sewage, the municipal marina, and tourism (Zakai & Chadwick-Furman 2002, Atkinson et al. 2004).

The farms we observed reared mainly gilthead seabream *Sparus aurata*. The farms were established in 1989 (Ardag) and 1993 (Dagsuf), and both were dismantled in June 2008, in accordance with a government decision. The fish farms consisted of 2 to 3 parallel sets of fish cages, and in the last decade of their operation, overall annual production ranged from 2000 to 3000 t. Specific details for each fish farm are given in Table 1.

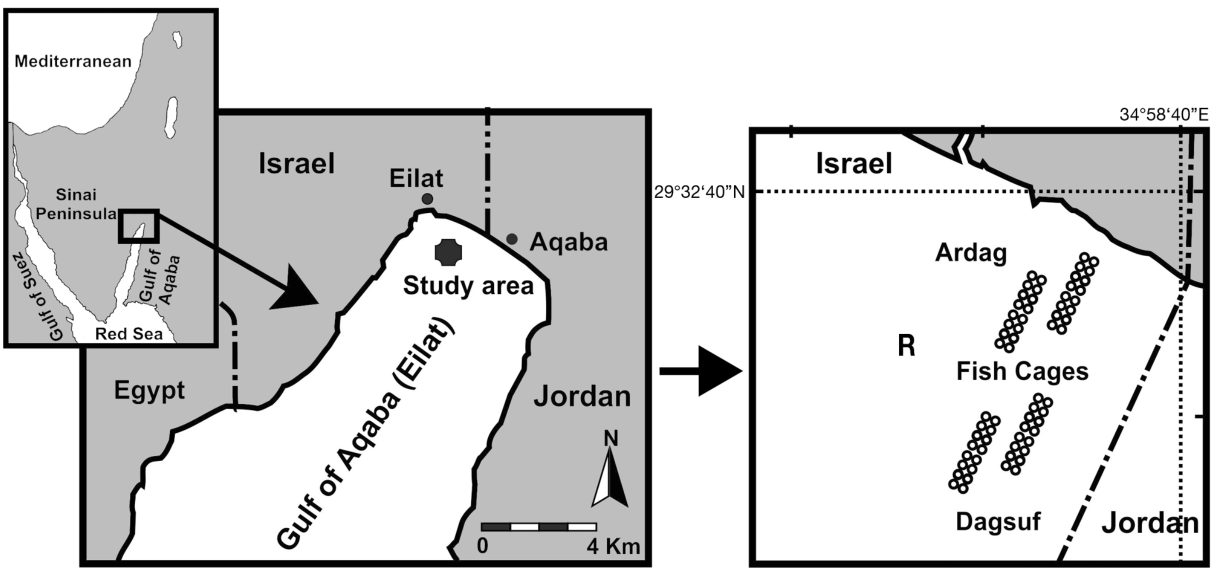

Fig. 1. Location of the study area at the northern end of the Gulf of Aqaba, Red Sea. The sandy seafloor in this area has few solid substrates (e.g. concrete moorings or debris associated with the fish farms, shown in Fig. 2) and there were no coral reefs near the fish farms. 'R' indicates the location of the reference station, ca. 500 m west of the fish farms

Table 1. Physical and environmental features of the net-cage fish farms. HDPE: high-density polyethylene

Fish farm	Location	Distance from shore (m)	Year established–Shut down	Seafloor depth range (m)	Maximum no. of cages	Cage material
Ardag	29° 32′ 28″ N, 34° 58′ 27″ E	300	1989–2008	19–30	54	HDPE
Dagsuf	29° 32′ 23″ N, 34° 58′ 22″ E	600	1993–2008	32–46	45	HDPE

Rapid visual counts

At each of the 2 fish farms, wild fish around the cages were counted on 3 randomly selected days over a period of 2 mo using a rapid non-destructive underwater visual census method that allowed for a high degree of replication (Dempster et al. 2002). Six 5 min census counts were conducted on each date within each farm complex. An equal number of counts (6) were performed at a reference location, situated ~500 m to the west of both farms, beyond the borders of the lease. All counts were made between 11:00 and 14:00 h. Each count covered a volume of approximately 11 250 m^3 (15 m wide × 15 m deep × 50 m long), and was conducted at depths of 5 to 12 m, allowing for the water column from the surface to the bottom of the adjacent cage to be scanned effectively (Fig. 2). Each count was made by 2 divers. The first diver concentrated on estimating the abundances of the dominant species present. Fish were counted in abundance groups of 1, 2–5, 6–10, 11–30, 31–50, 51–100, 101–200, 201–500, 501–1000, and >1000 to minimize error, based on the method of Harmelin-Vivien et al. (1985), and the average total length of each species was noted. The second diver followed slightly behind the first and specifically looked for both highly mobile species and smaller, less obvious fish that may have been missed by the first diver (Dempster et al. 2002, 2005).

Prior to the census, the various species of fish were identified visually by divers and documented by underwater photography. Conversions to biomass were made for each species based on estimated lengths and published length–weight relationships from FishBase (Froese & Pauly 2012). Seawater temperature (measured using a dive computer, Suunto-Stinger) and horizontal Secchi-disc readings (to estimate visibility) were recorded on days when census counts were conducted.

Multivariate analysis

Fish abundance data for each fish farm were analyzed using non-metric multidimensional scaling (nMDS) (Clarke 1993) to assess differences in community structure among the farms and reference locations for each sampling time. Abundance indices

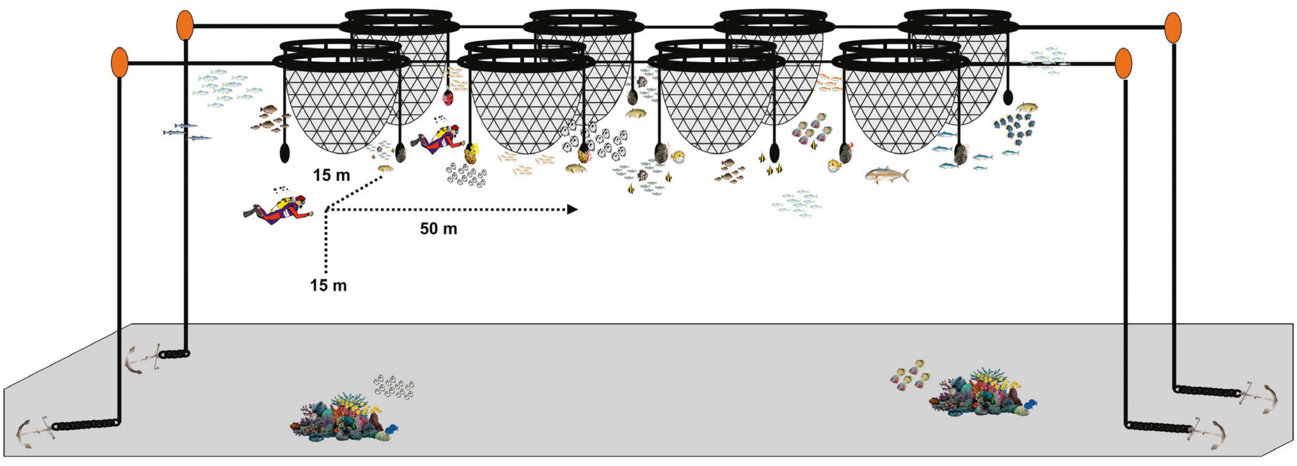

Fig. 2. Sketch showing 2 divers carrying out the underwater rapid visual census around fish cages at depths of 5 to 12 m, with the water column scanned from surface to bottom of adjacent cage (extension of census volume indicated). The sandy seafloor in this area has few solid substrates (e.g. concrete moorings or debris associated with the fish farms, shown in the sketch) and there were no coral reefs near the fish farms

(Clarke & Warwick 1994) and the results were presented as 2-dimensional plots. The analysis of similarity (ANOSIM) permutation test was used to assess the significance of differences between locations and among times within locations (Clarke 1993). The similarity percentage (SIMPER) procedure for the abundance data pooled over time was used to identify the contribution of individual species to differences between locations for each farm. All multivariate analyses were carried out using the PRIMER© statistical package (Clarke & Warwick 1994).

Univariate analysis

To examine the differences between the farm and reference sites, in terms of total abundances and biomass of aggregated wild fish, we used ANOVA and tested the factors Impact/Reference, Location, and Times initially. However, due to a majority of 0 values at reference sites, this analysis was considered unnecessary, and we simplified the design to the factors Location and Times nested in Location.

Prior to ANOVA, heterogeneity of variance was tested with Levene's test. Data were square-root ($x + 1$)-transformed if variances were significantly different at $p \leq 0.05$, and $\ln(x + 1)$-transformed if variances were still heterogeneous. When variance remained heterogeneous, untransformed data were analyzed, as ANOVA is robust to heterogeneity of variances, particularly for large balanced experiments (Underwood 1997). All univariate statistical analyses of data were performed using the SPSS 15.0 statistical package.

RESULTS

Abundance

We counted a total of 87 238 fishes, representing 39 species and 25 families, at both sea-cage farms and nearby reference sites. Twenty-nine species were observed only at the fish cages, 4 species occurred at both farm and reference sites, and 5 species were seen only at the reference sites (Table 2). Of the 39 fish species recorded, 35 were reef-associated spe-

Table 2. Abundance (mean ± SE) and body length (or range of lengths) of wild fish species for the 3 sampling dates at the fish farms and reference site. Values are from 18 rapid visual counts. Blank: not present

Fish	Ardag		Dagsuf		Reference site	
	Abundance (ind. 11 250 m^{-3})	Length (cm)	Abundance (ind. 11 250 m^{-3})	Length (cm)	Abundance (ind. 11 250 m^{-3})	Length (cm)
Actinopterygii						
Atheriniformes						
Atherinidae						
Atherinomorus lacunosus	13.89 ± 13.89	3	61.11 ± 61.11	3		
Beloniformes						
Belonidae						
Tylosurus choram			13.33 ± 7.80	10–15		
Hemiramphidae						
Hyporhamphus gamberur	30.89 ± 19.47	15–25	34.44 ± 27.25	15–18		
Perciformes						
Acanthuridae						
Ctenochaetus striatus	0.72 ± 0.61	6–14				
Apogonidae						
Apogon fleurieu	1.67 ± 1.67	5				
Blenniidae						
Petroscirtes mitratus	0.06 ± 0.06	8	1.11 ± 0.58	6–10		
Caesionidae						
Caesio suevica	58.39 ± 19.08	15–23	110.17 ± 45.42	15–23	0.67 ± 0.67	20
Carangidae						
Atule mate	700.28 ± 188.34	8–12	1560.83 ± 191.52	10–15		
Carangoides ferdau			0.11 ± 0.11	25		
Carangoides fulvoguttatus			0.83 ± 0.83	80		
Carangoides plagiotaenia	0.28 ± 0.28	18				
Decapterus macarellus	104.11 ± 56.53	8–32	3.56 ± 1.88	12–35	22.22 ± 22.22	12
Chaetodontidae						
Chaetodon fasciatus	0.83 ± 0.83	5				
Heniochus diphreutes					0.33 ± 0.33	15

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Table 2 (continued)

Fish	Ardag Abundance (ind. 11 250 m^{-3})	Ardag Length (cm)	Dagsuf Abundance (ind. 11 250 m^{-3})	Dagsuf Length (cm)	Reference site Abundance (ind. 11 250 m^{-3})	Reference site Length (cm)
Cirrhitidae						
Cirrhitichthys oxycephalus			0.06 ± 0.06	5		
Labridae						
Thalassoma lunare			0.06 ± 0.06	30		
Thalassoma rueppellii	1.22 ± 0.68	6–16	0.83 ± 0.45	6–16		
Mullidae						
Mulloides flavolineatus					1.28 ± 1.11	12–15
Nemipteridae						
Scolopsis ghanam					0.06 ± 0.06	15
Pomacentridae						
Abudefduf vaigiensis	35.33 ± 15.00	5–10	10.56 ± 3.52	5–10		
Neopomacentrus miryae	965.00 ± 189.48	6–8	585.00 ± 130.11	6–8	11.11 ± 11.11	4
Pomacentrus trichourus					0.28 ± 0.28	8
Scombridae						
Auxis rochei rochei	0.11 ± 0.11	40				
Scomber japonicus			97.22 ± 51.84	23–26		
Serranidae						
Anthias taeniatus	5.06 ± 4.43	6–8				
Pseudanthias squamipinnis	15.56 ± 7.25	5–8	3.17 ± 1.91	5–8	1.06 ± 1.06	8
Siganidae						
Siganus rivulatus	137.94 ± 33.86	4–30	216.83 ± 90.05	4–20		
Siganus luridus			0.17 ± 0.12	6–8		
Sparidae						
Acanthopagrus bifasciatus	0.28 ± 0.28	7				
Diplodus noct	28.33 ± 27.75	8–12	1.11 ± 1.11	9		
Sparus aurata	0.06 ± 0.06	16	0.06 ± 0.06	15		
Sphyraenidae						
Sphyraena flavicauda	5.28 ± 3.62	15–17				
Tetraodontiformes						
Balistidae						
Rhinecanthus assasi			0.06 ± 0.06	6		
Monacanthidae						
Aluterus scriptus	0.11 ± 0.11	20				
Ostraciidae						
Ostracion cubicus	0.39 ± 0.18	28–32	0.67 ± 0.21	30–40		
Tetraodontidae						
Arothron hispidus	0.94 ± 0.24	15–40	1.17 ± 0.34	30–40		
Arothron stellatus	0.11 ± 0.11	30				
Scorpaeniformes						
Scorpaenidae						
Pterois miles					0.17 ± 0.17	15
Syngnathiformes						
Fistulariidae						
Fistularia commersonii	0.06 ± 0.06	55			0.06 ± 0.06	40

cies which were reported at the Eilat coral reef reserves (Table 3).

Overall, the abundances and biomass of wild fish were greater at the sea cages than at the open-water reference sites at both farms. Among these, the Carangidae (5 species), Sparidae (3 species), and Pomacentridae (3 species) were the 3 groups that contributed most to species richness. The diversity of wild fishes at both farms was greater than the diversity at the respective reference sites (Fig. 3, Table 4).

Univariate analyses

Abundances, biomasses, and number of species of wild fish were all significantly greater near fish cages than at reference sites, at both farms ($p < 0.05$).

There were differences in abundance, biomass, and number of species between the fish farms and the reference sites (Table 5). Post hoc Student-Newman-Keuls (SNK) tests indicated that abundances were greater at Dagsuf (mean ± SE =

Table 3. List of fish species observed (listed in the same order as Table 2). Trophic tendency (TR; C = carnivore, H = herbivore, O = omnivore), trophic level (TL, mean ± SD), environment (P = pelagic, RA = reef-associated), phylogenetic diversity index (PD_{50}), and feeding mode (V = variable, SPF = selective plankton feeding, BS = browsing on substrate, GAP = grazing on aquatic plants), were taken from Froese & Pauly (2012). Note: all fish species are of commercial value, except *Apogon fleurieu*, *Neopomacentrus miryae*, and *Arothron stellatus*

Fish species	Common name	TR	TL	Environment	PD_{50}	Feeding mode
Atherinomorus lacunosus	Hardyhead silverside	C	3.28 ± 0.47	RA	0.5005	SPF
Tylosurus choram	Red Sea houndfish	C	4.39 ± 0.79	P	0.5156	P
Hyporhamphus gamberur	Red Sea halfbeak	C	3.02 ± 0.30	RA	0.5000	P
Ctenochaetus striatus	Striated surgeonfish	H	2.00 ± 0.00	RA	0.5020	BS
Apogon fleurieu	Bullseye cardinalfish	C	3.63 ± 0.49	RA	0.5000	P
Petroscirtes mitratus	Floral blenny	H	2.00 ± 0.00	RA	0.5005	GAP
Caesio suevica	Suez fusilier	C	3.40 ± 0.45	RA	0.5039	SPF
Atule mate	Yellowtail scad	C	4.45 ± 0.79	RA	1.0000	P
Carangoides ferdau	Blue trevally	C	4.50 ± 0.80	RA	0.5000	P
Carangoides fulvoguttatus	Yellowspotted trevally	C	4.39 ± 0.78	RA	0.5000	P
Carangoides plagiotaenia	Barcheek trevally	C	4.03 ± 0.67	RA	0.5000	P
Decapterus macarellus	Mackerel scad	C	3.40 ± 0.45	P	0.5002	P
Chaetodon fasciatus	Diagonal butterflyfish	O	3.34 ± 0.61	RA	0.5000	V
Heniochus diphreutes	False moorish idol	C	3.40 ± 0.45	RA	0.5039	SPF
Cirrhitichthys oxycephalus	Coral hawkfish	C	4.01 ± 0.66	RA	0.5039	P
Thalassoma lunare	Moon wrasse	C	3.48 ± 0.56	RA	0.5000	V
Thalassoma rueppellii	Klunzinger's wrasse	C	3.50 ± 0.37	RA	0.5000	P
Mulloides flavolineatus	Yellowstripe goatfish	C	3.27 ± 0.39	RA	0.5156	P
Scolopsis ghanam	Arabian monocle bream	C	3.62 ± 0.51	RA	0.5000	P
Abudefduf vaigiensis	Indo-Pacific sergeant	O	2.59 ± 0.35	RA	0.5000	GAP
Neopomacentrus miryae	Miry's demoiselle	C	3.40 ± 0.45	RA	0.5000	SPF
Pomacentrus trichourus	Paletail damsel	C	2.68 ± 0.30	RA	0.5000	SPF
Auxis rochei rochei	Bullet tuna	C	4.13 ± 0.61	P	0.7500	P
Scomber japonicus	Chub mackerel	C	3.09 ± 0.43	P	0.5625	P
Anthias taeniatus	Red Sea anthaes	C	3.40 ± 0.45	RA	0.5000	P
Pseudanthias squamipinnis	Sea goldie	C	3.40 ± 0.45	RA	0.5000	SPF
Siganus rivulatus	Marbled spinefoot	H	2.00 ± 0.00	RA	0.5000	BS
Siganus luridus	Dusky spinefoot	H	2.00 ± 0.02	RA	0.5000	BS
Acanthopagrus bifasciatus	Twobar seabream	C	3.39 ± 0.43	RA	0.5005	P
Diplodus noct	Red Sea seabream	O	2.74 ± 0.25	RA	0.5001	V
Sparus aurata	Gilthead seabream	C	3.26 ± 0.48	RA	1.0000	P
Sphyraena flavicauda	Yellowtail barracuda	C	3.76 ± 0.60	RA	0.5000	P
Rhinecanthus assasi	Picasso triggerfish	C	3.50 ± 0.37	RA	0.5078	P
Aluterus scriptus	Scrawled filefish	O	2.76 ± 0.45	RA	0.5312	V
Ostracion cubicus	Yellow boxfish	O	3.37 ± 0.48	RA	0.5020	V
Arothron hispidus	White-spotted puffer	O	3.11 ± 0.27	RA	0.5000	V
Arothron stellatus	Starry toadfish	O	3.34 ± 0.46	RA	0.5000	P
Pterois miles	Devil firefish	C	3.73 ± 0.63	RA	0.5020	P
Fistularia commersonii	Bluespotted cornetfish	C	4.26 ± 0.74	RA	0.6250	P

2702.4 ± 295.8) than at Ardag and reference sites. Calculated biomass was also significantly higher at Dagsuf (82 143.9 ± 16 088.3 kg), but the number of wild fish species was almost identical at the 2 farm sites, with 7.6 ± 0.6 and 7.1 ± 0.7 at Dagsuf and Ardag, respectively.

Multivariate community analyses

A dendrogram compiled from a Bray-Curtis similarity analysis of fish abundances shows that one distinct group, fish farm (similarity 64.66%), is significantly different from the abundances at the reference sites (Fig. 4). Two-dimensional nMDS of fish abundances revealed a clear separation between the reference and Ardag sites (stress = 0.01), but a less clear separation between Dagsuf and the reference site (stress = 0.01). These differences were statistically demonstrated by the ANOSIM test. Pairwise ANOSIM comparisons between reference and sea-cage locations (Table 6) gave highly significant global R values for Ardag (comparison between reference and farm: p = 0.001) and Dagsuf

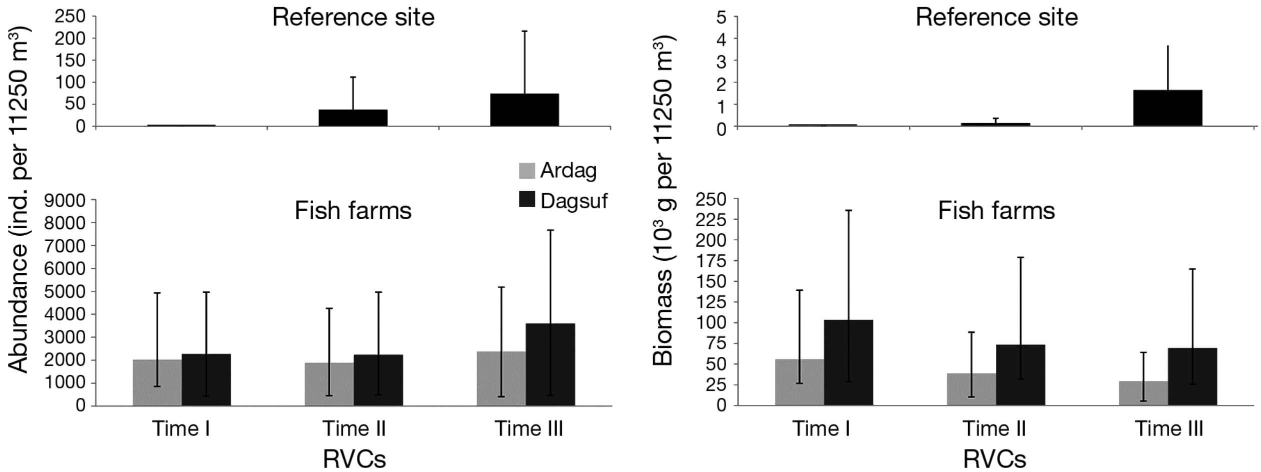

Fig. 3. Total abundance (mean ± SE) (left panel) and biomass (mean ± SE) (right panel) of coral reef-associated fish species at the reference site and fish farms on the 3 sampling dates (I = August, II = September, III = October in 2007). RVC = rapid visual count

Table 4. ANOVA comparison among abundance, biomass, and number of species at the fish farms and reference sites on 3 dates nested within locations. Significant at **p ≤ 0.01; ***p ≤ 0.001; ns = no significant difference. NT = no transformation performed

	df	Abundance		Biomass		No. of species	
		MS	*F*	MS	*F*	MS	*F*
Location	2	12100.84	205.62***	29927.51	48.67***	270.02	24.02**
Time	2	334.31	5.68^{ns}	1950.40	3.17^{ns}	50.46	4.49^{ns}
Location × Time	4	58.85	0.44^{ns}	614.90	0.27^{ns}	11.24	3.61**
Residual	45	134.32	2242.54	3.12			
Levene's test		0.06		0.00		0.016	
Transformation		Square root		NT		NT	

Table 5. Total abundance, biomass, Shannon-Weaver diversity, and number of species per 11 250 m^3 at fish farm and reference locations categorized by times of rapid visual counts (Times I to III, see Fig. 3). Values are mean ± SE

Site		Count	Abundance	Biomass (kg)	Diversity	No. of species
Ardag	Farm	I	2034.67 ± 856.30	56220.34 ± 26898.66	1.17 ± 0.13	6.00 ± 0.63
	Reference	I	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	Farm	II	1899.00 ± 460.62	39089.91 ± 10350.46	1.29 ± 0.21	7.50 ± 1.12
	Reference	II	37.67 ± 36.27	136.75 ± 80.77	0.21 ± 0.14	0.83 ± 0.40
	Farm	III	2387.00 ± 413.21	29437.02 ± 5379.82	1.90 ± 0.25	9.17 ± 0.98
	Reference	III	74.00 ± 67.72	1643.37 ± 1474.21	0.19 ± 0.15	1.00 ± 0.52
Dagsuf	Farm	I	2267.00 ± 434.53	103477.11 ± 28649.04	0.82 ± 0.22	4.33 ± 0.56
	Reference	I	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	Farm	II	2237.33 ± 496.42	73447.09 ± 31823.59	1.15 ± 0.18	6.33 ± 0.61
	Reference	II	37.66 ± 36.27	136.75 ± 80.77	0.21 ± 0.14	0.83 ± 0.40
	Farm	III	3603.00 ± 462.13	69507.67 ± 25855.43	1.74 ± 0.16	10.50 ± 0.67
	Reference	III	74.00 ± 67.72	1643.37 ± 1474.21	0.19 ± 0.15	1.00 ± 0.52

(comparison between reference and farm: p = 0.001), and also between Ardag and Dagsuf (p = 0.001).

Further comparisons between sites performed by means of SIMPER analysis accentuated the relative contribution of fish species abundances to dissimilarities in the fish assemblages (Table 7). Noteworthy species that had a major impact on this were the highly abundant *Atule mate* and *Neopomacentrus miryae*.

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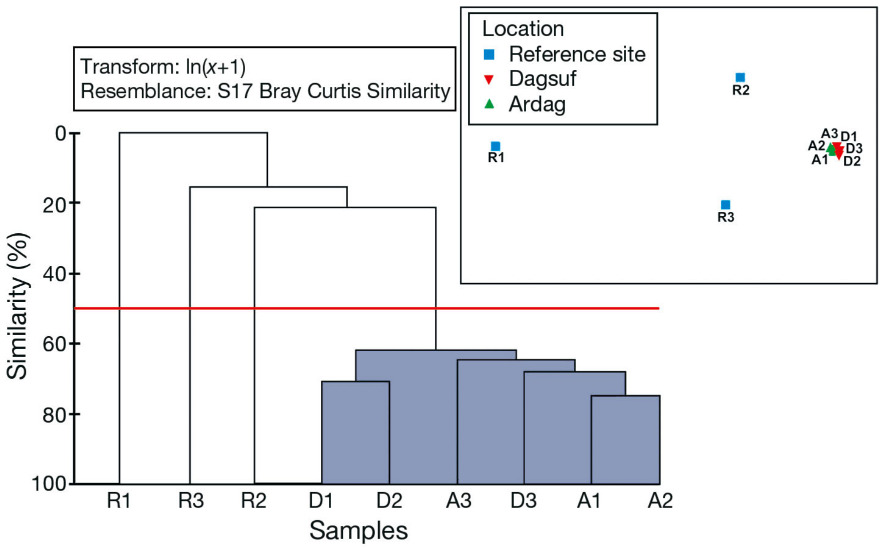

Fig. 4. Similarity dendrogram based on cluster analysis and non-metric multidimensional scaling (nMDS) plot ordination of fish species abundances associated with the fish farms (A = Ardag; D = Dagsuf) and reference (R) site on the 3 sampling dates in 2007 (1 = August, 2 = September, 3 = October, these numbers corresponding to Times I to III noted elsewhere)

Table 6. Pairwise analysis of similarity (ANOSIM) comparisons among reference, Ardag, and Dagsuf sites

Groups	R-value	R significance level (%)	Possible permutations	Actual permutations	No. observed
Ardag–Dagsuf	0.296	20	10	10	2
Ardag–Reference	0.222	20	10	10	2
Dagsuf–Reference	0.222	10	10	10	1

Table 7. Similarity percentage (SIMPER) procedure to test the degree of dissimilarity (D) between farms and reference sites and between the 2 farm sites on the basis of the abundances of the dominant fish species

Comparisons between sites	Species	Contribution to dissimilarity (%)
Ardag–Reference (D = 86.49)	*Atule mate*	13.66
	Neopomacentrus miryae	11.45
	Siganus rivulatus	11.10
	Caesio suevica	8.19
	Abudefduf vaigiensis	8.02
Dagsuf–Reference (D = 88.30)	*Atule mate*	15.68
	N. miryae	10.79
	C. suevica	9.53
	Siganus rivulatus	8.12
	Scomber japonicus	7.23
Ardag–Dagsuf (D = 36.84)	*Scomber japonicus*	9.73
	Tylosurus choram	7.69
	Hyporhamphus gamberur	7.16
	Sphyraena flavicauda	6.64
	Atherinomorus lacunosus	6.13
	Siganus rivulatus	6.03

DISCUSSION

Although aquaculture is not very new in the Red Sea, this is one of the first studies to describe the fishes that aggregate around net-cage fish farms in this region. The abundances, biomasses, and numbers of wild fish species were much greater adjacent to the 2 commercial fish farms studied than at nearby reference areas. Similar observations have been published in previous studies on wild fish around fish farms from different parts of the world, as reviewed above (see 'Introduction'). Moreover, a comparison of observed fish sizes to FishBase data (Froese & Pauly 2012) suggests that more than half of the individuals recorded in the immediate vicinity of the fish cages were adults.

One of the surprising findings of the present study was the composition of the wild fish community. The most frequently observed species at the farms were *Neopomacentrus miryae*, *Atule mate*, *Siganus rivulatus*, *Decapterus macarellus*, *Caesio suevica*, *Abudefduf vaigiensis*, and *Hyporhamphus gamberur* — all usually coral-reef-associated species (Shpigel 1994). Although the net-cage fish farms were not situated near the coral reefs of Eilat or of Aqaba, 35 out of the 39 species observed at the farms were juveniles and adults of coral-reef fish species (Table 3). In a variety of studies on the movements of coral-reef fishes, including several studies conducted just south of the city of Eilat (Mazeroll & Montgomery 1998, Jones et al. 2005, Claydon et al. 2012), most species did not exceed a range of 1 km from the reefs, whereas the fish farms in the present study were situated >4 km from the nearest reef systems. It is also noteworthy that the composition of the fish community associated with the fish farms was not similar to the nearby sandy-shore community described by Golani et al. (2008).

Whereas larval and juvenile fishes often migrate great distances from the reefs they originated in (e.g. Palumbi 2003, McMahon et al. 2012), it is believed that the home range of the adults of these species is limited (Zeller et al. 2003). Although many reef species generally do not exceed a range of hundreds of meters from their home reefs, tagged individuals have been observed moving across much greater distances, occasionally in excess of several kilometers. It is assumed that such movements may be motivated by disturbance (e.g. habitat or predators), reproductive activities, and the pursuit of food, and limited by a variety of barriers (Appeldoorn et al. 2009). It is not clear what caused the reef fishes to migrate from their natural habitat to the Eilat fish farms, but the overwhelming numbers suggest that it was sufficient to overcome the barriers that normally prevent such movements.

In an earlier study, Angel et al. (2002) described a fish assemblage dominated by *Neopomacentrus miryae* and *Pseudanthias squamipinnis* associated with benthic artificial reefs that were deployed near the Ardag farm. Likewise, Sudirman et al. (2009) found several members from the nearby coral reefs when they examined the wild fish community associated with grouper cages in Indonesia. Although >72% of the species we recorded were carnivores (Table 3), as defined by Bell & Harmelin-Vivien (1983), several other trophic modes were observed in the unique fish-farm ecosystem. *Atule mate*, *Caesio suevica*, and *Decapterus macarellus* were all observed consuming other fishes around the fish cages, and many other carnivores, e.g. *Fistularia commersonii*, benefited from the presence of large schools of small fishes. Among the prey species, large schools of juvenile *N. miryae* and *Siganus rivulatus* were prevalent, and often found in close proximity to the net pens and components of the mooring systems, e.g. ropes, pipes, weights, etc. *Abudefduf vaigiensis*, *Scomber japonicus*, and *Siganus rivulatus* were all observed consuming uneaten feed pellets that fell through the cages, acting as omnivores. Dempster et al. (2002) and Sudirman et al. (2009) found similar behavior in their studies where different wild fish species fed on waste pellets and on fish feces.

Size class information indicated that 65% of the fish observed in the immediate vicinity of the fish farm swere adults. Of the 39 species, 35 were reef-associated species, which were reported at the Eilat's coral reef reserves, and 34 were considered 'commercial' species. The majority of the observed species were trophically classified as carnivores (Table 3).

The persistent artificial food input and chemical attraction from farmed fishes probably influences which species of wild fishes associate with farms (Dempster et al. 2002). For example, carangids show particularly strong associations with FADs (Kingsford 1993) and with net-cage fish farms in the Mediterranean (Castro et al. 1999, Deudero et al. 1999). Two other groups that stand out in particular are the planktivorous pomacentrids and the siganids (Table 2). In addition to the aggregation of wild fish species, one of the ecological concerns regarding net-cage fish farms has to do with escapes. In their intensive surveys at numerous commercial fish farms, neither Boyra et al. (2004) nor Dempster et al. (2002) reported more than a few *Sparus aurata* and *Dicentrarchus labrax* escapees. Small escapes (10s to 100s of fish) are generally due to the loss of fishes during harvesting, whereas mass escapes (10 000s to 100 000s of fish) are generally caused by storms, accidents, and poaching. In the present study, we observed only a few seabream/seabass escapees near the cage farms, and it is still unclear whether these introduced species have become established in the Red Sea.

Dempster et al. (2004, 2005) and Valle et al. (2007) emphasized that there are potentially negative ecological interactions between fish farms and wild fish populations, as a result of e.g. escapes and spreading of disease. Whereas these negative interactions may occur, there are some benefits that may be reaped as a result of wild fish aggregations. If the fish farms are turned into fish sanctuaries, with spatial protection for endangered wild fish stocks, due to the fact that they aggregate there, this may be regarded as an advantage. This idea may be extended to enable enhanced production of local fisheries through spillover of adults and increased spawning-stock biomass, which may consequently amplify larval recruitment, as described by Chiappone & Sullivan (2000) and McClanahan & Mangi (2000). A constant supply of uneaten fish feed to the wild fish population may enhance both growth and reproduction in this population while reducing the flux of organic matter to the sea floor and subsequent impacts on the benthos (Katz et al. 2002, Dempster et al. 2005, Bayle-Sempere et al. 2013). The diverse and colorful community of wild fishes and invertebrates present around fish farms, such as those observed in the Red Sea, may also provide an opportunity to develop highly attractive eco-tourism and agro-tourism, as described in Angel et al. (2002).

Due to the strong aggregative effect of fish farms, possible residence of fishes for periods of weeks to months, and the restrictions on fishing that apply within farm leasehold areas, we suggest that coastal net-cage fish farms may act as small marine protected areas. The reference sites used in the present study were situated only 500 m from each of the farms, yet they clearly showed that very few fish were present in waters adjacent to fish farms. This result is analogous to the association of reef fishes with artificial reefs, where a steep decline in abundance is typically observed at distances of just a few meters from the artificial structure (Bohnsack & Sutherland 1985, Sanchez-Jerez & Ramos-Espla 2000).

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