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Research paper

Benthic foraminiferal response to the removal of aquaculture fish cages in the Gulf of Aqaba-Eilat, Red Sea

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ABSTRACT

For about 20 years, finfish were reared in floating cages at the northern end of the Gulf of Aqaba-Eilat, Red Sea. The benthic ecosystem at the fish cages area was severely impacted by organic enrichment, resulting in an environment with no living foraminifera. A government decision led to the fish cages' removal in June 2008, creating a unique opportunity to monitor and assess post-removal changes in the benthos. Three years of benthic foraminiferal assemblage monitoring, beginning in July 2008 and ending in July 2011, are summarized here. Monitoring was carried out monthly by collecting sediment samples from stations of varying distances from the fish farm location, and, after its appearance in the summer of 2009, sampling the native seagrass *Halophila stipulacea*. Living foraminifera first appeared in the sediment in January 2009, progressively increasing in abundance thereafter. A clear difference in the rate of the rehabilitation process was observed on a spatial scale, related to distance from the point source of the organic enrichment. Recovery began with the first appearances of a few living individuals of *Ammonia* spp., *Amphistegina lessonii* and *Nonion* spp. By July 2009, a significant increase in overall abundance was recorded in the stations furthest from the fish cages, with *Operculina ammonoides* strongly dominating the assemblages. Populations of *O. ammonoides* revealed polymorphism in the coiling mode of their shells. Inflated involute and semi-involute forms dominate the living assemblages, whereas flattened evolute tests are more common in the dead assemblages, representing the period that preceded the fish farms. Unlike previous interpretations in the literature, in which such morphological variation was attributed to hydrodynamic energy or depth habitats, here it is hypothesized that the inflated involute and semi-involute forms are a morphological trait characteristic of the pioneer assemblages colonizing the area after its recovery from fish cages eutrophication. The re-establishment of the native *H. stipulacea* seagrass community was an important factor enabling epiphytic foraminifera to colonize the previously impacted sediments. All living foraminiferal species found on the seagrasses were also found in the former assemblages, suggesting that seagrass meadows existed before eutrophication and were the main habitats of the dead assemblages.

1. Introduction

1.1. Fish cage aquaculture and the environment

Net cage fish farms are ubiquitous in many coastal and offshore waters throughout the world and these farms may impact the local environment due to the release of effluents. Farm effluents consist of organic and inorganic compounds that may enrich the water column and the sediment, and create hypoxic–anoxic conditions in the underlying sediment. The impact on the environment is a function of the balance between the flux of farm effluents and the rates of effluent uptake, decomposition, transformation and dilution.

Geochemical studies at a variety of fish farm sites recorded high levels of organic matter and nutrients in sediments under the cages, and a decrease of these with increasing distance from the cages (Gowen and Bradbury, 1987; Hall et al., 1990; Angel et al., 1995). The organic enrichment gradient that occurs in such environments has a direct effect on benthic biota as described by Pearson and Rosenberg (1978) and in many other studies (reviewed by Kalantzi and Karakassis, 2006). Schafer and Cole (1974) documented "azoic zones" (devoid of eukaryotes) in sediments that were most severely impacted by such organic loadings. Schafer et al. (1995) and Scott et al. (1995) found an inverse relationship between fish production and foraminiferal abundance in sediments below commercial fish farms.

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In many cases, the presence of active fish cages caused the development of a benthic "dead zone" immediately beneath them, whereas directly outside this azoic area there was a hypertrophic zone with increased abundance and biomass of opportunistic species, possibly caused by increased organic matter availability and reduced predation and competition. Pearson and Rosenberg (1978) named this phenomenon "biostimulation" and observed that the benthic community in such hypertrophic zones was dominated by a small number of "tolerant" and opportunistic species as compared to unimpacted sediments that are inhabited by a more diverse community. La Rosa et al. (2001) investigated bacterial and meiofaunal abundance and biomass and their response to the disturbance induced by fish-farm biodeposition in Gaeta Gulf, Italy and found that bacterial abundance increased significantly beneath fish cages, while numbers of meiofauna were lower than at the reference stations.

In cases of eutrophication, the ecosystem has to cope with lowered dissolved oxygen (DO) levels as microbes decompose the organic matter. When DO falls below ≤2 ml O_2/l (hypoxia), benthic fauna show aberrant behavior (e.g. abandoning burrows). Mass mortality may occur when DO levels drop below 0.5 ml O_2/l (Diaz and Rosenberg, 1995, 2008). Development of anoxia in the sediment may also favor some species of polychaetes, (e.g. capitellids) which are less sensitive to reduced conditions (Tomassetti and Porrello, 2005), or may lead to development of sulfide oxidizing bacterial mats (Pearson and Rosenberg, 1978; Angel et al., 1995; Pearson and Black, 2001).

1.2. Benthic foraminifera as bioindicators of anthropogenic eutrophication

Benthic foraminifera are a particularly useful group for environmental monitoring because they are highly sensitive to environmental changes, their tests are well preserved in many types of sediment, and they are distributed worldwide (Schafer, 2000; Murray, 2006; Schönfeld et al., 2012). Moreover, the abundance of benthic foraminifera in marine sediments is usually high, making it possible to work with relatively small samples to achieve statistically significant results. These qualities present particular advantages in biomonitoring in comparison to the more commonly used macrofaunal organisms (e.g., Mojtahid et al., 2006; Bouchet et al., 2007, 2012; Schönfeld et al., 2012). Some of the main factors that affect the distribution and microhabitats of foraminiferal assemblages are hydrodynamic energy, light, fluvial influence, food availability and oxygen concentrations in the sediment (Jorissen et al., 1995; Renema and Troelstra, 2001; Murray, 2006). Some of these factors may be affected by changes in the flux of organic material. Therefore, environmental perturbations leading to organically enriched sediments are most likely to be reflected in the foraminiferal assemblages. For example, Hyams-Kaphzan et al. (2009) reported very low species diversity at the Shafdan sewage sludge injection site in the Eastern Mediterranean. The assemblages at this site consisted primarily of opportunistic species that occur at shallow sediment depth. Aquaculture sites are similar in some ways to sewage outfalls, as they are also a significant source of organic matter, where both presence and absence of foraminiferal species and changes in species abundance can be used as indicators of environmental changes caused by aquaculture (Clark, 1971; Schafer et al., 1995; Angel et al., 2000; Vidović et al., 2009).

1.3. The Gulf of Aqaba-Eilat

The Gulf of Aqaba-Eilat is a morphotectonic branch of the Red Sea, which is a part of the Syrian African rift system (Fig. 1). It is situated in the desert between the Sinai and the Arabian peninsulas, an area characterized by high evaporation rates due to high temperatures and dry air. There are seasonal fluctuations in the water temperature (20.5–28.6 °C) and salinity (40.3–41.6 psu), oxygen saturation is close to 100% for the entire water column (Shaked and Genin, 2012), and the overall composition of the seawater in the Gulf is oligotrophic (Reiss and Hottinger, 1984). Since the Gulf is a nearly enclosed segment of the Red Sea, from which it is separated by the shallow straits of Tiran, and is surrounded by deserts, the terrestrial sediment influx into the Gulf is very limited. The oceanographic and ecological system of the Red Sea in general and the Gulf of Aqaba-Eilat in particular, is largely separated from the Indian Ocean, and as a result it is very sensitive to disturbance (Reiss et al., 1980; Almogi-Labin, 1982; Edelman-Furstenberg et al., 2001; Arz et al., 2003).

In the last few decades, the northern end of the Gulf has been under increasing anthropogenic pressure, as a result of intensive development of the shoreline, tourism, agriculture, urban expansion and the fish farms that started operating in 1988 (Fig. 1). Rising concerns about the potential damage inflicted by the fish farms on the health of the Gulf's ecosystem was the center of a heated debate that ended with the Israeli government ordering their removal in June 2008.

The cessation of open water fish cage aquaculture operations in the Gulf of Aqaba-Eilat created a unique opportunity to monitor the process and assess the time that is required for the benthic environment to rehabilitate. The goal of this research was to monitor the changes in the benthic foraminiferal assemblages in the area where the fish cages were located, and to use these data as a measure for the recovery of the benthos. For aquaculture to be carried out in a responsible and sustainable manner, i.e. both economically and environmentally, it is crucial to understand the long and short-term consequences of this activity. This study presents empirically-based practical information for coastal management and sustainable fish farming.

2. Material and methods

2.1. Sediment sampling

Short core sediment samples were collected monthly between July 2008 and December 2009, and also in July 2010 and July 2011. The samples were collected from four marked stations along a transect, located at 27 m water depth. The sampling stations were located 0, 20, 40 and 80 m to the west from the previous location of the fish cages (34°58.40′E; 29°32.45′N) (Fig. 2), and were labeled "Station Ø", "W20", "W40" and "W80". Three cores were taken at each station (a total of 12 cores per sampling). The cores were collected with plastic tubes (30 cm long, 5 cm diameter), which were pushed vertically into the sediment by a SCUBA diver, capped, pulled, plugged at the base to secure the sediments, and carried vertically in an especially designed core holder until sub-sampled in the laboratory. Additional cores that were sampled in January 2008 were used for Loss on Ignition analysis (LOI) as a reference for the pre fish cages removal conditions.

In August 2009, the seagrass *Halophila stipulacea* was observed in the study area for the first time after almost two decades of absence (Fig. 3). Leaves of *H. stipulacea* were sampled during subsequent collections to determine the composition of the epiphytic foraminiferal assemblages living upon them. The samples were collected in 50 ml tubes at station W40, where the seagrass was most abundant, between August 2009 and December 2009, and also in July 2010 and July 2011.

2.2. Laboratory work

The cores and seagrass were transported directly to the lab by boat, and the sub-sampling and treatment in the laboratory took place approximately 1 h after the field sampling. The top 10 cm of the cores were sliced into 1 cm intervals for foraminifera and organic matter analyses. Foraminiferal assemblage data are presented in this study only from the top 0–1 cm interval of the cores. Below this level, living foraminifera were not found throughout the study period.

An aliquot of one half of the 0–1 cm slice from two cores was taken for foraminiferal study; one quarter of each slice for organic matter composition by LOI (loss on ignition), and the remaining one quarter was dried and archived for future purposes. The sediment sample