Saudi Journal of Biological Sciences (2016) 23, 327–334

King Saud University

Saudi Journal of Biological Sciences

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ORIGINAL ARTICLE

# Microbial–meiofaunal interrelationships in coastal sediments of the Red Sea

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Received 15 September 2015; revised 31 December 2015; accepted 2 January 2016
Available online 15 February 2016

**KEYWORDS**

Benthic microbial community;
Meiofauna;
Red Sea coastal sediment ecosystem;
Sediment biochemistry

**Abstract** Population density and biomass of bacteria and meiofauna were investigated seasonally in the sediments of the north-western bank of Red Sea. Samples of sediments were collected seasonally from three different stations to determine microphytobenthic biomass (chlorophyll *a*), protein, lipid, carbohydrate, and total organic matter concentrations. These investigations revealed that microbial components tended to increase their dominancy, whereas sensitive meiofauna were extremely reduced during the entire study period. Thus a very low density of the total meiofauna (with an annual average of 109 ± 26 ind./10 $cm^2$) was recorded whilst the benthic microbial population densities exhibited higher values (ranging from 0.31 ± 0.02 × $10^8$ to 43.67 ± 18.62 × $10^8$/g dry sediment). These changes in the relative importance analysis of benthic microbial components versus meiofaunal ones seem to be based on the impact of organic matter accumulation on the function and structure of these benthic communities. Proteins, lipids and carbohydrates showed very low concentration values, and the organic matter mostly consisted of carbohydrates, reflecting lower nutritional values for benthic fauna in general and meiofauna in particular. The distribution of microbial and meiofaunal communities seems to be dependent on the quality of the organic matter rather than on its quantity. Total organic matter concentrations varied between 5.8 and 7.6 mg/g, with organic carbon accounting for only 32% of the total organic matter. Chlorophyll *a* attained very low values, fluctuating between 0.11 and 0.56 μg/g, indicating the oligotrophy of the studied area. The very low concentration of chlorophyll *a* in the Red Sea sediment suggests that the sedimentary organic matter, heterotrophic bacteria and/or protozoa constitute an alternative resource

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Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.sjbs.2016.01.023
1319-562X 

that is consumed by meiofauna when algae are less abundant. Protozoa, therefore, represent the "missing link in bacteria–meiofauna interaction in the Red Sea marine sediment ecosystem.



## 1. Introduction

The health of the sedimentary ecosystem can be assessed using data concerning the structure and abundance of its biological communities (Maher et al., 1999). Since the early 1980s biologists have been increasingly interested in studying benthic meiofauna started. This work presents obstacles, however, due to their small size, and the difficulties of isolating the benthic communities from the sediments and identifying species belonging to different taxa (Austen et al., 1994; Harguinteguy et al., 2012).

Meiofaunal organisms play an important ecological role in the aquatic ecosystem and are well suited for environmental impact assessment studies. Their short life spans, continuous reproduction and direct development in situ mean that meiofauna have a high potential to respond rapidly to both natural and anthropogenic environmental changes (Giere, 1993; Mirto and Danovaro, 2004; Fraschetti et al., 2006; Gyedu-Ababio and Baird, 2006; Moreno et al., 2008; Harguinteguy et al., 2012). Moreover, beaches may function as naturalfilters responsible for the remineralisation of substances, which then return to the sea as nutrients (Coull and Chandler, 2001). The interstitial system of beaches, in particular the system protected by muddy sediments, is formed by long and intricate food chains of bacteria, protists (unicellular algae & protozoa), and meiofauna at the first levels. Marine biological systems are therefore dependent on the productivity of coastal areas (Higgins and Thiel, 1988; Leguerrier et al., 2003).

Measuring carbohydrate, lipid and protein contents in marine sediments is usually very important to evaluate the availability of food (Fabiano et al., 1995; Pusceddu et al., 1996). Meanwhile, benthic microbes, in the form of bacteria, play an effective role in converting this organic matter into living biomass in the sediment, which in its turn can be utilised by benthic protozoa (Fenchel, 1967; Sleigh et al., 1992; Danovaro et al., 1999; Foissner, 2012), and meiofauna (Danovaro, 1996). This allows the transfer of feeding materials and energy to the higher trophic levels (Hondeveld et al., 1994; Mirto et al., 2004). Currently, however, no study has provided quantitative information on the trophic interaction between the three important sedimentary groups (bacteria/protozoa/meiofauna) and sedimentary organic matter within the Red Sea benthic ecosystem (El-Serehy et al., 2015).

In this research, population fluctuations of meiofauna and benthic heterotrophic bacteria were studied in relation to the seasonal fluctuation of sedimentary chlorophyll *a* and organic matter biochemical constituents at three different sites along the northern part of the Red Sea. The present work aims to investigate the microbial–meiofaunal population dynamics with relation to chlorophyll *a*, the organic matter content, biochemical composition and granulometric structure of the sediment.


**Figure 1** Location of the study sites (with red colour) along the north-western bank of the Red Sea.

## 2. Material and methods

Three stations were chosen along the north-western bank of the Red Sea for this study (Fig. 1). The three stations were selected based on their proximity to mangrove. Safaga (lat 26° 36′ 56″N, long 34° 00′ 43″E) and Al-Qulaan (lat 24° 21′ 28″N, long 35° 18′ 23″E) were closer to mangrove vegetation than Gabal El-Zeit (27° 48′ 10″N, long 33° 33′ 59″E). Station I (Gabal El-Zeit) is located in a triangular bay at the entrance of the Gulf of Suez, 70 km to the north of Hurghada city. This site is surrounded by an extensive oily land area used by the GABCO Company for oil production services. Sediments have a red colour and are dominated by coarse and median sand particles. In addition, vegetation consists of *Padaina* sp. (Phaeophyceae) and *Caulerpa racemosa* (Chlorophyceae). Station II (Safaga) is sheltered by mangrove trees (*Avicennia marina*). The sediment texture is composed mainly of fine sand

and muddy materials and is a grey colour with an odour of $H_2S$. Fiddler crabs (*Uca inversa*), blue green algal mats and a dense population of the muddy snail, *Pirenella cailliaudi*, are the most common fauna and flora inhabiting the sediment of this site. Station III (Al-Qulaan) is characterised by a huge mangrove forest of *A. marina*. The sediment texture is dominated by muddy sediments. Calcified fragments of the Chlorophycean *Halimeda opuntia* densely cover the sediment of this location.

Sediment samples were collected to assess environmental parameters, bacteria and meiofauna from the three stations of Gabal El-Zeit, Safaga and Al-Qulaan with the help of a hand core of 4.5 cm inner diameter and 10 cm length. Carbonates were removed from the sediment samples using the method described by Buchanan and Kain (1971). The total organic matter in each sediment sample was calculated using the method given by Parker (1983). Lipids, proteins and carbohydrates were determined using the methods described by Marsh and Weinstein (1966), Hartree (1972) and Gerchacov and Hatcher (1972), respectively. Concentrations recorded for the three components were converted to carbon equivalent using the conversion factor given by Fichez (1991). Blank and three replicates were made for each biochemical analysis. Chlorophyll *a* concentrations (in μg/g sediment) were measured according to Lorenzen and Jeffrey (1980).

Bacterial cells in the sediment samples were immediately fixed in 2% buffered formaldehyde and kept at 4 °C until further analyses (Epstein and Rossel, 1995). In the laboratory, bacterial cells were stained with Acridine Orange and counted under an epifluorescence microscope (Olympus BH-2) on ten randomly selected fields. The frequency of the bacterial cell's division was calculated according to Fry, 1988). Bacterial population density was standardised to biomass per 20 $cm^3$ of sediments according to Albertelli et al. (1999), and data on microbial biomass were expressed as mg C/g.

Meiofauna in the sediment samples were fixed in 4% buffered formaldehyde and sieved through 0.50 and 0.062 mm mesh size sieves. The fraction remaining on the 0.062 mm sieve was centrifuged three times. All meiobenthic animals were stained with Rose Bengal (0.5g/l), taxonomically classified and counted under a stereo microscope (Prior, S2000) according to the method of Heip et al. (1985). Meiofaunal biomass was calculated and expressed as mg C/10 $cm^2$ according to Ansari et al. (2001).

To test the relationships between the various biological and environmental parameters, a Spear-man-rank correlation analysis was performed. Shannon diversity (*H*; Shannon and Weaver, 1963) and evenness (*E*; Pielou, 1966) and species richness (*D*; Margalef, 1968) indices for meiofaunal parameters were also calculated.

## 3. Results

Station I showed the highest contents of chlorophyll *a* with an annual average of 0.56 ± 0.3 μg/g, but contained the lowest values of total organic matter and organic carbon with annual values of 5.8 ± 0.4 mg/g and 1.85 ± 0.88 mg C/g, respectively. On the other hand, station III showed the lowest values of chlorophyll *a* and the highest annual values of total organic matter and organic carbon, with values of 0.11 ± 0.01 μg/g; 7.5 ± 1.1 mg/g and 2.4 ± 0.45 mg C/g, respectively (Fig. 2).

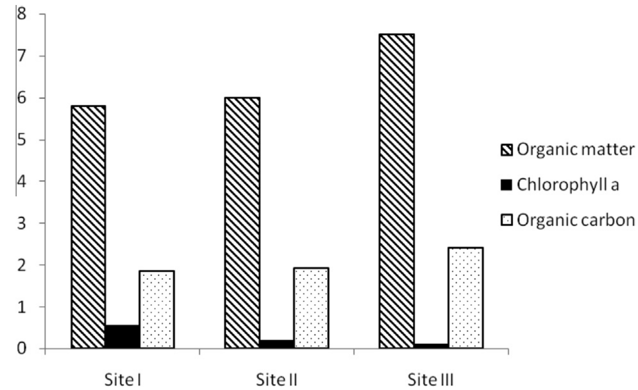


**Figure 2** Concentrations of total organic matter (mg/g), chlorophyll *a* (μg/g) and organic carbon (mg C/g) in the sediment of the three sites.

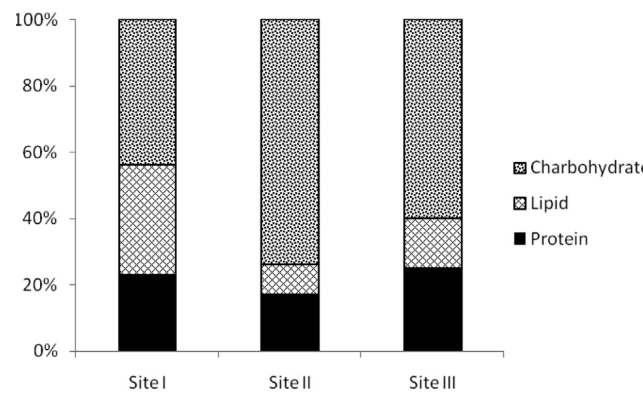


**Figure 3** Carbohydrate, lipid and protein contents in the sediments of the three sites of the Red Sea.

Fig. 3 shows the contribution of carbohydrate, protein and lipid to organic matter. Carbohydrates were the dominant component, representing 44% at station I and 74% of total organic matter at station II. Proteins were the second most dominant component, representing 17% and 26.6% of total organic matter at station II and station III, respectively, followed by lipids with 33.3% and 9.5% for stations I and II, respectively.

Total bacterial numbers fluctuated between 0.31 ± 0.02 and 43.18 ± 16.77 × $10^8$ cells/g, during summer at station I, and during autumn at station III, respectively (Fig. 4). On an annual average, the highest values were recorded at stations II and III with values of 30.18 ± 8.74 and 32.69 ± 5.50 × $10^8$ cells/g, respectively, whilst the lowest value of 0.06 ± 0.02 mg C/g was recorded at station I. Station I also sustained the lowest annual bacterial density with a total average of 1.33 ± 0.39 × $10^8$ cells/g, whilst station III showed the highest annual average of bacterial biomass, with a value of 1.79 ± 0.32 mg C/g, (Fig. 5). The frequency of dividing bacterial cells showed similar values at the three stations, with an annual average ranging from 4.75 ± 2.36 to 7.5 ± 0.65%.

During the present study, meiofaunal population density was very low, ranging from 18 ± 8 to 193 ± 17 ind./10 $cm^2$ during autumn at station I and during summer at station II,

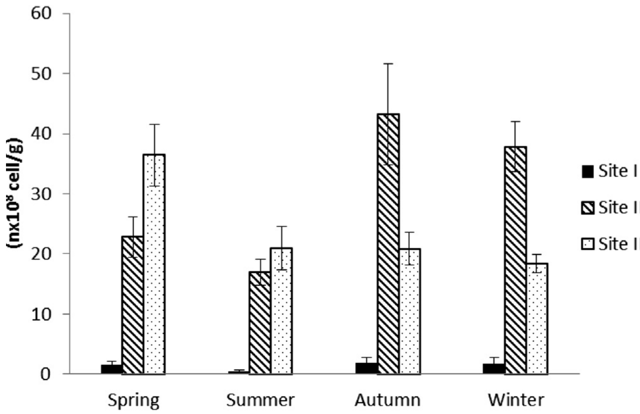


**Figure 4** Seasonal fluctuations in total bacterial numbers (no. $\times$ $10^8$ cell/g sediment) at the three sites of the Red Sea.

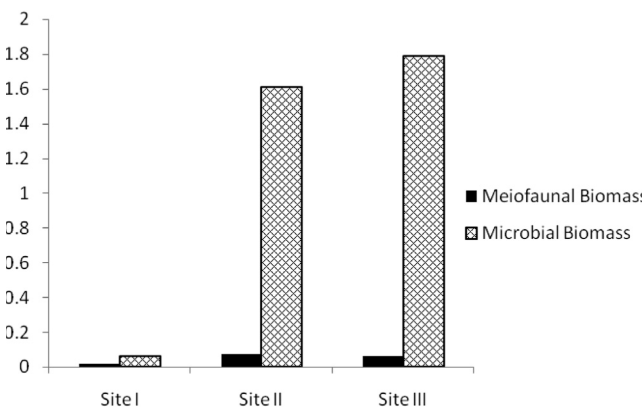


**Figure 5** Meiofaunal and microbial biomass ratio values in the sediment of the three sites of the Red Sea.

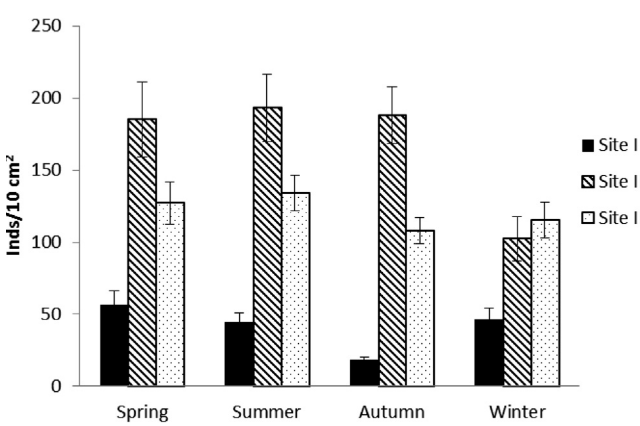


**Figure 6** Seasonal fluctuation in the meiofaunal population density (ind./10 $cm^2$) at the three sites of the Red Sea.

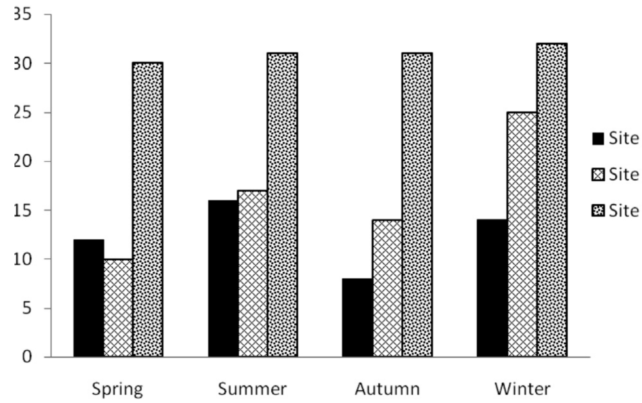


**Figure 7** Total number of meiofaunal species sustained in the sediment of the three sites during the different seasons.

respectively (Fig. 6). Station III showed the highest meiofaunal species number followed by station II, whilst station I sustained the smallest number of meiofaunal species (Fig. 7). Nematodes were the most dominant group, contributing 67% of the total meiofaunal density, followed by harpacticoid copepods, contributing 12%. Polychaetes 10%, ostracods 4%, whilst oligochaetes and gnathostomulids contributed 3% each. Other taxa (Amphipoda, Cumacea, Isopoda and Nemertina) occurred in limited numbers and collectively averaged 1% of the total meiofauna (Fig. 8). The four major meiofaunal groups represented in the present study were dominated by nematodes with an annual average of 81.4% at station I; 49.1% at station II and 46.7% at station III (Fig. 9).

Statistical analysis (Table 2) showed that station III was the station which sustained the highest diversity indices with values of 0.92; 2.86 and 4.0 for evenness (*E*); Shannon-weaver index (*H*) and species richness (*D*), respectively. Also, a significant positive correlation was recorded between the median sediment particles and copepods ($r = 0.68$, $p < 0.05$); whilst a negative correlation was recorded between median sediment particles and nematodes ($r = -0.78$, $p < 0.01$).

## 4. Discussion

Concentrations of chlorophyll *a* recorded on the north-western bank of the Red Sea (Fig. 2) were very low compared to other marine coastal areas, but comparable to those recorded in various aquatic oligotrophic habitats (Plante et al., 1986; Fabiano et al., 1995; Albertelli et al., 1999; Mirto et al., 2004). The very low values of chlorophyll *a* recorded during the present study (< 1.0 μg/g, Fig. 2) therefore confirm the oligotrophy of the Red Sea area, in other words suggesting a low input of fresh primary organic matter from microalgal organisms. During the present work, proteins, lipids and carbohydrates showed very low concentrations, and the organic matter was mostly composed of carbohydrates (Fig. 3), reflecting lower nutritional values for benthic fauna in general and meiofauna in particular. Concentrations of chlorophyll *a* in the sediment are generally correlated with the biochemical classes of organic compounds in the form of proteins, lipids and carbohydrates (Fabiano and Danovaro, 1994; Albertelli et al., 1999).

According to Danovaro (1996) a high ratio of protein to carbohydrate indicates the presence of living organic matter and/or freshly generated detritus. In the present study, this ratio was very low (equal 0.31), similar to the values found in deep-sea sediment of the highly oligotrophic Ceratin Sea (Danovaro et al., 1993), and shelf areas (e.g. the Ligurian Sea, NW Mediterranean) (Albertelli et al., 1999). This also, therefore, tends to confirm the oligotrophic status of the studied area.

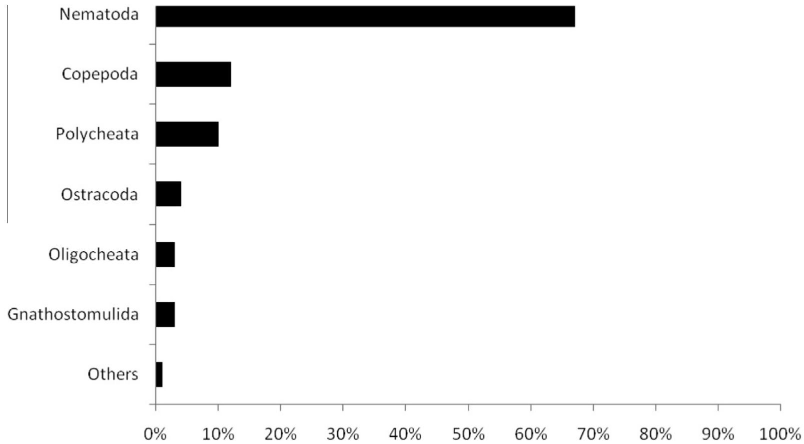


**Figure 8** Meiofaunal community structure in the sediment of the Red Sea.

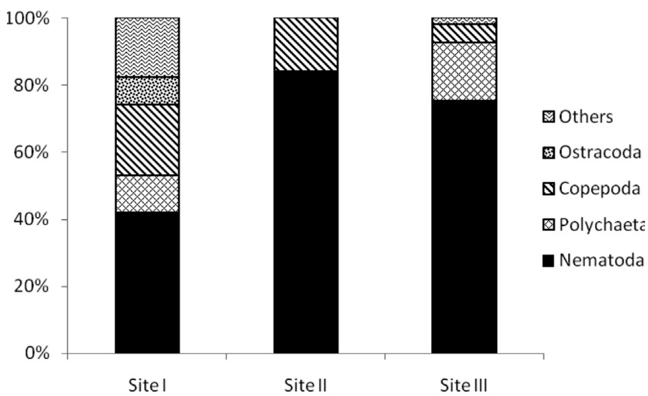


**Figure 9** The percentage contribution of nematodes, polychaetes, copepods, ostracods and other taxa to the meiofaunal community at each of the Red Sea three sites.

The distribution of benthic communities in the bottom sediment of oligotrophic environments varies in response to many variables (Albertelli et al., 1999; El-Serehy et al., 2015). Among these variables is the food quality, which plays an important role for bacteria (Deming and Yager, 1992; Bahgat et al., 2013), meiofauna (Danovaro et al., 1995; Danovaro, 1996; El-Serehy et al., 2015) and macrofauna (Rosenberg, 1995). Moreover, the sediment texture influences the structuring of meiobenthic communities. The three sampling localities chosen for the present study along the north-western bank of the Red Sea showed different sediment textures with median sediment particle diameters at station I, and a prevalence of muddy sediments in the other two stations (Table 1). The significant positive correlations recorded between the median sediment particles and copepods ($r$ = 0.68, $p < 0.05$); and the negative relationships recorded between median sediment particles and nematodes ($r$ = -0.78, $p < 0.01$) during the present study

**Table 1** Locations and descriptive features of anthropogenic activities of the three sampling stations.

| Sampling sites | Coordinates of sampling sites | General features of anthropogenic activities |
|---|---|---|
| Gabal El-Zeit (Station I) | 27° 48′ 10″N-33° 33′ 59″E | – Extensive oily land areas for GABCO Company<br>– Sediments have red colour<br>– Sediment texture are dominated by median sand<br>Vegetation:<br>*Padaina* sp. (Phaeophyceae)<br>*Caulerpa racemosa* (Chlorophyceae)<br>– Macrofaunal abundance:<br>Low abundance |
| Safaga (Station II) | 26° 36′ 56″N-34° 00′ 43″E | – Phosphate Abu Tartour Company<br>– Sediments have grey colour<br>– Sediments have an $H_2S$ odour<br>– Sediment texture are dominated by silt and clay<br>Vegetation:<br>Mangrove forest<br>Blue green algal mats<br>– Macrofaunal abundance:<br>High abundance |
| Al-Qulaan (Station III) | 24° 21′ 28″N-35° 18′ 23″E | – Wadi El Gemale Protectorate<br>– Sediments have grey colour<br>– Sediments are dominated by silt and clay<br>Vegetation:<br>Mangrove forest<br>Algal calcified fragments<br>– Macrofaunal abundance:<br>High abundance |

**Table 2** Meiofaunal species number, diversity indices, biomass and abundance in the sediments at the three different sites. Also the correlation values of copepods/median sand, and nematodes/median sand are given below.

| Diversity index | Site | | |
|---|---|---|---|
| | I | II | III |
| Number of species | 13 | 17 | 31 |
| Population density (ind./10 $cm^2$) | 41 | 167 | 141 |
| Biomass (mg C/10 $cm^2$) | 0.018 | 0.075 | 0.063 |
| Eveness ($E$) | 0.91 | 0.84 | 0.92 |
| Shannon-weaver index ($H$) | 2.53 | 2.63 | 2.86 |
| Species richness ($D$) | 3.6 | 3.6 | 4.0 |
| Source of variation | $R$ value | | $P$ value |
| Median sand*copepods | 0.68 | | $<0.05$ |
| Median sand*nematodes | −0.78 | | $<0.01$ |

might suggest that sediment texture has a strong effect on the structuring of meiofaunal communities along the northwestern bank of the Red Sea. Copepods showed their highest population density, 21% of the total meiofaunal densities, at station I (Fig. 9). Nematodes showed the opposite pattern, however; displaying their lowest population density at this station: only 42% of the total meiofaunal density. Station I was characterised by the dominance of median sand particles (Table 1). In stations II and III, however, there was a predominance of muddy sediments and it is in these stations that nematodes recorded their highest population densities (84% and 75% of the total meiofauna, respectively). The distributional patterns of meiofaunal communities which this study describes in the marine sediment of the Red Sea are similar to those described in most other marine environments, with an increasing nematode dominance but decreasing copepod dominance in muddy sediments (Heip et al., 1985; Higgins and Thiel, 1988; Brown and McLachlan, 1990; Villora-Moreno et al., 1991).

Bacterial population density and biomass recorded in the sediment collected from the Red Sea coasts during the present study were higher than those found in other oligotrophic environments (Albertelli et al., 1999; La Rosa et al., 2001). In oligotrophic areas, the distributional pattern of benthic bacteria varies in response to food quality rather than food quantity (Deming and Yager, 1992). Thus, the quality of feeding particles available for bacteria in the Red Sea sediments seems to be the main factor for the higher bacterial population density recorded in this study. On average, the benthic bacterial biomass accounted for just 15% of the sedimentary carbon, which suggests that the microbial loop strongly dominates the sedimentary compartments in the Red Sea.

On the other hand, meiofaunal population densities were very low, ranging between 41 and 167 ind./10 $cm^2$, and fluctuating seasonally with a peak of 192.52 ind./10 $cm^2$ during summer at station II (Fig. 6). These low values of meiofaunal population densities suggest that the organic matter accumulated in the Red Sea sediments is not able to support a higher meiofaunal density, which may be due to, the lower nutritional values of organic matter. Food quality usually controls population density and spatial distribution of meiofauna in the sediment (Lee et al., 1977; Pusceddu et al., 2009, 2014).

Despite the extremely low density of the total meiofauna, the benthic microbial population densities exhibited higher values, ranging from $0.26 \pm 0.02 \times 10^8$ to $102.67 \pm 18.62 \times 10^8$/g dry sediment (Fig. 4). Moreover, a higher ratio of benthic microbial biomass to total meiofaunal biomass was recorded in the Red Sea during the present study (Fig. 5). This high ratio clearly indicates that the benthic community in the Red Sea sediments is strongly dominated by microbial components in the form of bacteria, whilst also showing that a large proportion of the benthic microbes (bacteria) are not converted into meiofaunal biomass. This high ratio of bacterial/meiofaunal biomass can provide important information on the energy transfer pathways in the benthic food web of the Red Sea, whereby bacteria in the sediment of the Red Sea clearly play a primary role as a trophic reservoir for higher trophic levels by converting refractory compounds into available food in the form of bacterial biomass. A large quantity of organic carbon (derived from bacterial biomass) is not channelled towards higher trophic levels (meiofauna) in the Red Sea marine ecosystem, however. Thus, there is a missing link in the bacterial–meiofaunal interaction in this ecosystem. Data from the literature indicates that whilst the meiofauna can consume bacteria, protozoa are a more likely and more attractive meiofaunal food source. On this basis, protozoa, as the primary bacterivores in most aquatic systems, can be postulated to be the missing link in bacterial–meiofaunal interaction in the Red Sea marine ecosystem. Bacterivory by meiofauna is undetectable in most aquatic sediments (Montagna et al., 1982; Bott, 1999; Bott and Borchardt, 1999; Mirto et al., 2004; Pascal et al., 2009), but meiofaunal consumption of protozoa is detectable in different marine sediments (Bott and Borchardt, 1999; Epstein and Gallagher, 1992; Walters and Moriarty, 1993), whilst, protozoa are the primary bacterivores in most aquatic ecosystems (Fenchel, 1968, 1978; Schönborn, 1982, 1984; Sleigh et al., 1992; Bott and Borchardt, 1999; Foissner, 2012).

In conclusion, the very low values of chlorophyll *a* recorded during the present study confirm the oligotrophy of the investigated area and can suggest that sedimentary organic matter, heterotrophic bacteria and/or protozoa constitute an alternative resource that is consumed by meiofauna. Despite the extremely low density of the total meiofauna, the benthic microbial population densities exhibited higher values in the Red Sea sediments. Changes in the relative importance analysis of benthic microbial components versus meiofaunal ones seem to be based on the impact of organic matter accumulation on the function and structure of these benthic communities. The distributional pattern of microbial communities seems to be organic matter quality dependent, and protozoa are postulated to be the missing link in bacterial–meiofaunal interaction in the Red Sea.

## Acknowledgments

The authors extend their sincere appreciation to the Deanship of scientific Research at King Saud University-Saudi Arabia for funding this work through Research Group number (RG-1436-242).

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