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Seasonal response of benthic foraminifera to anthropogenic pressure in two stations of the Gulf of Trieste (northern Adriatic Sea, Italy): the marine protected area of Miramare versus the Servola water sewage outfall

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Abstract

A seasonal survey of living benthic foraminifera was performed in 2013 in the Gulf of Trieste (N Adriatic Sea) to compare two marine coastal sites with different degrees of anthropogenic influence. An assessment of ecological quality statuses showed that the station located near the end of an urban pipeline (**Ser** station), has worse ecological conditions than the site located in a protected marine area (**Res** station) all year around. Stressed conditions at **Ser** station were mainly related to high contents of total organic carbon (TOC) and Zn in the bioavailable fraction, which were a limiting factor for the studied foraminiferal communities. *Ammonia tepida, Bolivina* spp., and *Bulimina* spp., which characterised this station, were the most tolerant taxa of the studied assemblage. Conversely, *Elphidium* spp., *Haynesina depressula, Nonionella iridea, Quiqueloculina* spp., *Reophax nana* and *Textularia* spp., could be considered less tolerant species as they benefitted from the less stressful conditions recorded at **Res** station in comparison to **Ser** station. Furthermore, foraminiferal assemblages were found to be quite resilient over an annual cycle, being able to recover from a seasonal unbalanced state to a mature one. The beginning of spring and latest summer would be the best period to assess the ecological quality status to avoid any under- or overestimation of the health of the environment.

Keywords: Meiofauna; seasonal biomonitoring; pipeline outfall; marine protected areas; heavy metals; sediments.

Introduction

Coastal marine environments are fragile ecotones at the border between marine and continental ecosystems. Over the last decades, increases in industrial, agricultural, aquacultural and tourism activities have led to pollution in these ecosystems (Bouchet & Sauriau, 2008; Frontalini *et al.*, 2009; Francescangeli *et al.*, 2016) since they serve as receptacle for the majority of coastal terrestrial runoff. The increasing loading of terrestrial nutrients into coastal marine ecosystems induced the expansion of dead zones where hypoxic to anoxic conditions occur (Diaz & Rosenberg, 2008). This pollution has deleterious effects on benthic communities, leading to the loss of sensitive species and the proliferation of opportunistic ones (Lardicci *et al.*, 2001), heavily modifying the functioning of the benthic-ecosystem (Solan *et al.*, 2004).

In order to protect these environments, restoration measures have been taken, e.g. OSPAR, Natura 2000, marine protected areas (MPAs), the European Water Framework Directive (WFD) and the European Marine Strategy Framework Directive (MSFD). Among these measures, the establishment of MPAs (i.e. marine reserves) has proven to be an effective method of conserving marine biodiversity (Guidetti *et al.*, 2008; Edgar *et al.*, 2014). Along the Northern Adriatic coast of Italy, the Gulf of Trieste (GoT, Fig. 1) hosts two contrasting environments: an area strongly affected by anthropogenic activities and a MPA. The GoT hosts two of the largest cargo shipping ports in the Adriatic Sea, Trieste and Koper. This coastal



Fig. 1: Study area and location of the Ser (Servola) and Res (Riserva Naturale Marina di Miramare) stations. The Servola pipeline is evidenced in the enlarged square.

area is also affected by many potential sources of organic and inorganic pollutants, discharged not only by rivers but also by sewers, industries, and activities related to the harbour including an oil-pipeline terminal (Olivotti *et al.*, 1986; Adami *et al.*, 1996, 1998; Cibic *et al.*, 2008). Furthermore, the Servola pipeline rejects the discharges from the main local urban and manufacturing activities in the GoT. To protect the ecosystems of the GoT, the MPA *Riserva Naturale Marina di Miramare* (EUAP 0167) was established in 1986 by decree of the Italian Ministry of the Environment, which was first managed by WWF Italy Onlus Association (D.M. November 12, 1986) and then by WWF Oasis srl.

Although there are numerous MPAs along the coast of Italy, their effectiveness in protecting marine biodiversity has rarely been assessed. Numerous biological groups have been proposed to assess the health of marine systems (e.g., Borja et al., 2000; Krause-Jensen et al., 2005; Coates et al., 2007). The importance of those organisms in characterising environmental status (ES) is highlighted by the MSFD, which aims to achieve Good ES (GES) of the EU's marine waters by 2020. Among these bioindicators, macroalgae, angiosperms, fish and benthic invertebrates are considered particularly relevant. Benthic macro-invertebrates are by far the most popular (e.g., Bouchet & Sauriau, 2008; Lavesque et al., 2009; Munari & Mistri, 2010). Lately, emphasis has been placed on benthic foraminifera (e.g. Bouchet et al., 2012; Barras et al., 2014; Alve et al., 2016; Dimiza et al., 2016; Jorissen et al., 2018).

Benthic foraminifera are single-celled protists with a short reproductive cycle, rapid growth, small size and their tests are well preserved in the sediments allowing for retrospective studies. They are also highly diversified and abundant in comparison with other hard-shelled taxa (e.g. molluscs or ostracods). Moreover, they are easy to collect and are able to provide reliable data for statistical analysis, even with small sample volumes (Schönfeld *et al.*, 2012). Furthermore, a wide range of papers highlights anthropogenic pressure in marine ecosystems (e.g. Murray & Alve, 2002; Martínez-Colón et al., 2009; Armynot du Châtelet & Debenay, 2010; Frontalini & Coccioni, 2011; Alve et al., 2016; Bouchet et al., 2018; Jorissen et al., 2018). It has been noted that in stressed and/or polluted environments, diversity and abundances could change, and therefore the structure of the community. It is possible to define a group of species with similar levels of tolerance to contaminant influence (e.g. Alve et al., 2016). In particular, some studies focused on the response of these organisms to the submarine outfall of domestic sewage that could represent significant source of contaminants (Stott et al., 1996; Hyams-Kaphzan et al., 2009; Teodoro et al., 2010; Eichler et al.; 2012, Tadir et al., 2017). All this evidence has led to the definition of monitoring methods based on benthic foraminifera (Bouchet et al., 2012; Barras et al., 2014; Schönfeld et al., 2012; Dimiza et al., 2016). Recently, diversity indices based on benthic foraminifera have been proven to be a suitable method to evaluate ecological quality status along the coast of Italy (Bouchet et al., 2018). Hence, benthic foraminifera appear to be a relevant group to compare environmental conditions in two contrasted areas of the Gulf of Trieste: the MPA of Miramare and the area impacted by the Servola sewage outfall.

their high potential to serve as relevant bioindicators of

To date, the GoT has not been carefully studied for living benthic foraminifera. Apart from Hohenegger *et al.* (1989, 1993) and Sabbatini *et al.* (2010), all other studies on foraminifera took into consideration dead assemblages or limited areas close to the Slovenian coast (Langlet *et al.*, 2014). In the present study, a seasonal survey was designed to analyse living benthic foraminifera communities sampled in two stations submitted to different degrees of anthropogenic disturbance located in the GoT (north Adriatic Sea): one station is located close to the domestic sewage outfall from the main submarine pipeline of the municipality and the second station is located in the MPA. The aims of this study are: (1) to describe benthic for a living communities and their response to environmental parameters and seasonal changes at the two sampling sites; (2) to assess the ecological quality status at sampling stations using the diversity index $Exp(H'_{bc})$ calculated on benthic for a minifera.

Study area

The Adriatic Sea is an elongated NW/SE oriented basin of the central Mediterranean where the depth varies from approximately 35 m in the northern part to a maximum depth of 1250 m in the southern part. In the nortern part, it receives the main contribution of freshwater and sediments from the Isonzo River.

The water circulation of the GoT is driven by the interplay of different forcing: the general circulation of the Adriatic Sea, wind stress (particularly the dominant Bora, N-NE direction) and buoyancy fluxes together with the tides. The surface layer is commonly characterised by a clockwise flow, while the intermediate and bottom layers usually move in a counterclockwise direction. The water column shows a marked seasonal variability. During winter, it is characterised by homogeneous conditions of temperature, salinity and density. Starting from the end of April the onset of the heating process, particularly of the surface layer, causes the beginning of the vertical stratification. Summer is characterised by strong thermal stratification with a temperature gradient of about 10-12°C/20 m in depth. During autumn, the eastern winds blow and cooling processes at the air-sea interface produce the beginning of the convective and mechanical mixing of the water column which continues during the winter months (Malačič & Petelin, 2001; Celio et al., 2006).

The sediment distribution varies from medium to fine sands along the beaches and the delta front to muds in the mid-Gulf and sandy sediments in the western open part of the GoT (Brambati *et al.*, 1983; Ogorelec *et al.*, 1991). Moreover, the site has been recognised as an area where particular conditions related to inputs of fluvial sediments or to a meteo-marine conditions led to important algal productions and blooms, resulting in eutrophication and subsequent hypoxic/anoxic conditions at the bottom at least until the mid-1980s (Giani *et al.*, 2012).

The sediment samples collected for this study come from two sites, one located in the proximity of the Servola pipeline termination and a second used as a reference point for a "pristine" situation in the *Riserva Naturale Marina di Miramare* (hereafter referred to as the Reserve).

The Servola wastewater treatment plant is the largest sewage plant in the city, serving a maximum of 2.5 x 10⁵ equivalent inhabitants. The Servola pipeline began operations in 1992 and disposes of sewage that after chemical treatment, carries the residual waters through a submarine pipeline 7.0 km long of which the last 1.5 km are provided with specific diffusers in order to make the dispersion of wastewaters easier. The delivery capacity of the pipeline varies from 2 x 10³ (dry periods) to 6 x 10³ l/s (rainy periods). The pipeline reaches a depth of 24 m (Novelli, 1996). The Servola plant was studied by Mattassi *et al.* (2008) and Scroccaro *et al.* (2010) to assess possible risks connected with the microbiological parameter *Escherichia coli*. The authors highlighted that under particular meteo-marine forcing conditions and due to high input concentration values, the submarine discharges may influence the water quality creating several problems for shellfish farming activities located along the coast of Trieste. Starting in 2016, some modernisation works of this plant were undertaken to arm the system with a more effective purification system, such as biological treatment on land. The new plant is expected to be finished by 2018.

The Reserve is located in the GoT at the base of the promontory of Miramare and covers an area of 0.3 km² surrounded by a sea area of 0.9 km². The area is located along a rocky limestone stretch of marine coast that slopes in boulders, pebbles and muddy formations gradually from the coast to the sea with a maximum depth of 18 m. In June 2011, the Reserve was identified and proposed as a SCI - Site of Community Importance (directives 79/409/EEC and 92/43/EEC). The effectiveness of the application of these directives made it possible to achieve the ecological objectives set before the establishment of the reserve (Guidetti et al., 2008). Since 2009 the regional agency for environmental protection (ARPA-FGV) has been involved in monitoring the GoT following the directive of the Piano Regionale di Tutela delle Acque. Monthly monitoring of marine and transition (lagoons and river mouths) waters is performed as per ministerial decree D.lgs. 190/260/10 and 2010. Following the data guide provided by the colleagues from ARPA-FGV, it was decided to operate at Ser station, near the pipeline which discharges the urban waste of Servola and at Res station (Riserva Marina di Miramare) (Fig. 1).

Material and Methods

Two stations **Ser** (45°38.6480 N, 13°40.9620 E; water depth 24 m) and **Res** (45°42.050 N, 13°42.600 E; water depth 17 m) were sampled by the R/V Effevigi (ARPA FVG) for water column features, benthic foraminifera and sediment properties. Sampling was done seasonally for a year: 11/01/2013 - win13, 22/05/2013 - spr13, 26/08/2013 - sum13 and 18/11/2013 - aut13. The two stations are located off the Servola sewage sludge outfall (Ser) and close to the Reserve (Res) (Fig. 1) respectively.

Water column vertical profiles of pressure, temperature, conductivity, pH, dissolved oxygen and chlorophyll a from the surface to a depth of 22 and 17 m respectively for **Ser** and **Res** stations, were collected seasonally on board using an Idronaut mod. 316 multiparametric probe, which is calibrated following the manufacturer's protocols. The data obtained were processed by Idronaut software in order to verify the quality check. The sediments at each sampling station were sampled three times using a KC Haps bottom corer with a sample area of 0.013 m² and an effective depth penetration of 10 cm. The sediment from one box-core was sampled two times using Perspex pipes (inner \emptyset =5.4 cm, surface area 22.9 cm²) for foraminifera and for chemical analyses and sediment texture. Two other sediment samples were taken from the second and third box cores for microorganisms only, for a total of four short cores. The upper two cm from each core were sliced immediately on board into 1 cm thick layers (2 subsamples) with a thin metal plate. Immediately after sampling, the samples for benthic organisms were stored in plastic bottles filled with 23 cc of preservative solution (2 g of Rose Bengal per litre of ethanol at 95%). Sediments for chemical and grain-size analyses were frozen immediately on board. Three replicates were used for microorganism analysis (6 subsamples for each station).

Sixteen samples (2 stations, 0-1 and 1-2 cm, 1 replicate, 4 seasons) were analysed for grain-size analyses. The texture of each sample was determined using a Malvern Mastersizer Hydro2000S Diffraction Laser unit for the < 2 mm size fraction. Sand and mud classes were determined using the Udden-Wentworth (Wentworth, 1922) grain-size classification and the sediment was described following Shepard (1954). Grain-size parameters (Mean Size - Mz - and sorting) were determined using the Folk & Ward formulas (Folk & Ward, 1957). Total organic carbon (TOC) and total nitrogen (TN) content were detected as the mean value of 2 replicates of the same sample using an Elemental Analyser (ECS 4010 CHNSO) and acetanilide as standard for calibration. Prior to analysis, the samples were progressively acidified with HCl 0.1-1.0 N (Hedges & Stern, 1984).

An aliquot of the 16 sampled sediments were treated to determine the content of potentially toxic elements (hereafter PTEs) Cd, Cr, Cu, Ni, Pb and Zn, using the cold diluted HCl leaching technique proposed by Adami et al. (2000). This procedure is indicated to determine the "non-residual" metal fraction mainly accumulated in relation to anthropogenic sources (Chester & Voutsinou, 1981; Voutsinou-Taliadouri, 1995; Adami et al., 2000) and corresponds to its bioavailability in agreement with Morse & Luther (1999) and National Research Council (2003). This term defines the rate at which a chemical substance becomes accessible to an organism potentially causing toxic effects (National Research Council, 2003). In order to compare the results with heavy metal content representing a preindustrial condition, two levels of core GT3 (51 and 53 cm below the sea floor) collected in the Gulf of Trieste by R/V OGS Explora in 1997 (Covelli et al., 2006) were treated here in the same manner. All solutions were analysed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) using the Spectroflame Modula E instrument by SPECTRO® of the Department of Chemical and Pharmaceutical Sciences of the University of Trieste. The metal concentrations of Cd, Cr, Cu, Ni, Pb and Zn were evaluated using calibration curves obtained by the dilution of SPECTRAS-CAN® multi-element standard solutions (for ICP-AES analyses). The limits of detection (LOD) were in the range of 0.010-0.020 mg/L minuscule, that is: mg/l.

Samples for benthic foraminiferal analyses (2 stations, 0-2 cm, 3 replicates, 4 seasons) were stained in Rose Bengal in order to separate living from dead specimens. After 15 days in Rose Bengal solution, the ethanol in the samples was replaced by water and the samples were oven-dried at 50 °C and weighed. The sediment volume was detected subtracting the known preservative volume from the total sediment + preservative volume, as suggested by Schönfeld et al. (2012). Each sample was then wet-sieved over a 63 µm mesh. The total sandy sediments were used for picking all live (Rose Bengal stained) benthic foraminifera. Considering the well-known problems in the use of Rose Bengal (Corliss & Emerson, 1990; Bernhard, 2000), only the foraminifera specimens showing a clear pink colour (or red, depending on the species) in all but the last chambers were considered to be living fauna in agreement with Goineau et al. (2012) and Barras et al. (2014). If necessary, opaque porcellaneous and agglutinated specimens were broken to check for the presence of protoplasm. The generic taxonomy of foraminifera was assessed in line with Loeblich & Tappan (1987), and species classification followed the Mediterranean systematic studies of Jorissen (1987, 1988), Albani & Serandrei Barbero (1990), Cimerman & Langer (1991), Levy et al. (1992), Sgarrella & Moncharmont Zei (1993), Fiorini & Vaiani (2001), Milker & Schmiedl (2012). For original descriptions of species, the Ellis & Messina (2017) online catalogue on foraminifera was used (http://www. micropress.org/). The taxa pertaining to genus Bolivina (i.e. Bolivina dilatata, B. seminuda, B. spathulata and B. variabilis) are linked by numerous intermediate forms (see Barmawidjaja et al. 1992) where a consistent division in the different species could be problematic. These species were treated here as group *Bolivina* spp., as also suggested by Duijnstee et al. (2003) and Sabbatini et al. (2010) in their study of the northern Adriatic Sea. Selected specimens were displayed using a scanning electron microscope (Leica Stereoscan 430i) at the University of Trieste (Fig. S1).

To process the results concerning the foraminifers, we decided to pool the counts from the three replicates (rather than the average) of each sample since the aim of the study was not to assess the local micro-distribution of benthic foraminifera, following the suggestion of Schönfeld & Numberger (2007) and Bouchet *et al.* (2012). For each station, the following faunal parameters were calculated: 1) foraminiferal density (as the number of specimens normalised to 50 cc), 2) species richness, and 3) the respective proportion of the three principal foraminiferal groups (hyaline, porcellaneous and agglutinated foraminifera). To describe the foraminiferal density and to compare it with bottom water column parameters, we used their "complete living assemblage", considering the levels 0-1 and 1-2 cm of each sample as an only assemblage.

From the complete living foraminiferal assemblage, three measures of species diversity were calculated for each station using the PAST (PAlaeontological STatistics) data analysis package (Hammer *et al.*, 2001): 1) species richness (S) as the total number of taxa for each station; 2) Shannon diversity (H') and 3) Dominance (D) indexes. To define the true diversity, bias-corrected Shannon (H'_{bc}) (Chao & Shen, 2003) was converted with the exponential function $Exp(H'_{bc})$ proposed by Hill (1973), which represents the number of species that would, if each were equally common, produce the same H'_{ba} as the sample (see Bouchet et al., 2012, p. 68 for discussion). Distribution patterns of living foraminiferal abundances are represented by using rank-frequency diagrams (RFD) (Frontier, 1976; Legendre & Legendre, 1984). Ecological interpretation of RFDs was reviewed by Frontier (1985) in a comparison of mathematical models (Mouillot & Lepretre, 2000). It relies on the recognition of 3 ecological succession stages associated with 3 different RFD curve shapes: linear-concave = pioneer assemblage with low species richness (stage 1); convex = intermediate assemblage with increasing species diversity (stage 2) and straight-line = mature assemblage (stage 3) (see Fig. 3 in Frontier, 1976). In some cases, a straight-line may reflect mixtures of different assemblages of intermediate diversity. The method was successfully applied to assess short-term variations in foraminiferal assemblages due to environmental conditions changes (Bouchet et al., 2007). Finally, Exp(H'_{be}) was used to evaluate the ecological quality status (EcoQ) of the studied areas, following the criteria set by Bouchet et al. (2012) where ecological quality is expressed as: $Exp(H'_{bc}) \le 5$: bad, $5 \le Exp(H'_{bc})$ <10: poor, 10 <Exp(H'_{bc}) <15: moderate, 15 <Exp(H''_{bc}) <20: good and Exp(H'_{bc})> 20: high.

All statistical analyses were performed considering the species with relative abundance higher than 4% (8 species and 5 genera). Species with a relative abundance < 4.0% were omitted, or gathered into major generic groups (i.e. Elphidium spp., Quinqueloculina spp., Textulariina spp.) in order to reduce background noise due to the infrequent taxa. Taking into consideration the pooled counts from three replicates for each species in all the samples, contingency tables tested by the chi-square test $(\chi 2)$ were used to compare the absolute abundance of the most significant foraminifera between the two studied stations and among the seasonal samplings. Two correlations using Spearman's rank correlation were made: a) in the first case the absolute abundance of the major species was used using the 0-2 cm level and the bottom water column parameters and, b) in the second case a matrix with the absolute abundance of the foraminifera was used in the 0-1 cm level with their relative content of heavy metals, TOC, N_{tot} and grain-size. The significance threshold was set at p < 0.05 and the analysis was performed using STATISTICA 7.1 software.

Results

Water column

In both stations during the sampling period, the water **temperature** profiles showed a similar pattern during winter, spring and autumn, while they differ slightly during summer, where the **Res** station showed a thermocline close to the bottom. Considering both stations, the maximum thermal stratification was observed during spring. **Salinity** values were obtained from temperature and conductivity. The values were comparable and almost constant around a mean value of 37.3 ± 0.3 along the water column in both stations during summer and autumn. During the winter a particularly anomalous fresh water mass outflowing from the pipe caused a salinity decrease (mean value 29.1 ± 0.1) all over the water column at Ser station. During spring, a salinity decrease approximately 33 in the first 5 m of the water column was observed. The pH values were quite homogenous along the water column and very similar between the two stations during winter and autumn. They were generally higher than 8 at the surface with a tendency to decrease slightly at the bottom, mainly during spring and summer at **Res** station. Water dissolved oxygen during winter, summer and autumn in both stations records values from 90 to 100% of saturation. Values < 90% were registered from 15 m toward the bottom layers of Ser station during summer. On the contrary, in spring the water column is oversaturated (> 110% sat.) at all depths except for the bottom layer of both stations which recorded a value of 92.5 and 93.5% sat., for Ser and Res, respectively. Chlorophyll a showed the lowest values in autumn in both stations, with mean values of $0.26 \pm 0.05 \,\mu$ g/l throughout the water column, a slight increase during winter and summer (around $0.8\mu g/l$) and higher values were seen at both stations during spring. Chlorophyll a reached values higher than $2.0 \,\mu g/l$ at the depth interval of 6 to 14 m at both stations, indicating significant phytoplankton activity (mainly due to the diatom Chaetoceros spp., ARPA FVG, unpublished data). At **Res** station, the chlorophyll *a* content is higher than that of Ser station, reaching the maximum value of $3.2 \mu g/l$ at a depth of 7 m (Fig. 2).

Sediment composition

Grain-size distribution

The grain-size analyses indicated that the sediments from **Ser** station varied from clayey silt, sandy silt to silty sand. The sand content varied from 13.3 to 44.8% with a mean value of $21.1 \pm 11.1\%$, the silt from 44.4 to 71.9 with a mean value of $64.8 \pm 9.7\%$ and clay ($< 4 \mu$ m) from 10.8 to 15.9 with a mean value of $14.1 \pm 1.7\%$ (Table 1). Sediments were poor to very poorly sorted with a mean size (Mz) varying from 4.8 to 6.0 phi. Altogether, the grain-size were quite similar in two sublevels (0-1 and 1-2 cm) of the same sample and during the seasons except for autumn, where a higher sand content was found in sublevel 1-2 cm.

The sediments from **Res** station were quite homogenous in time and depth. They were prevalently silt, and differ from **Ser** station having lower sand content. The percentage of sand varied from 3.5 to 9.8% with a mean value of $5.3 \pm 2.2\%$, silt from 74.4 to 78.5 with a mean value of $76.5 \pm 1.3\%$ and clay (< 4 µm) from 12.5 to 22.1 with a mean value of $18.1 \pm 3.0\%$ (Table 1). The sediments were poorly sorted with a mean size (Mz) varying from 5.9 to 6.6 phi.



Fig. 2: Vertical profiles of temperature, salinity, pH, oxygen saturation and chlorophyll *a* at **Ser** and **Res** stations during the seasonal sampling.

Organic matter content

At **Ser** station the total organic carbon (TOC) content varied from 1.88 to 3.81% with a mean value of 2.46 \pm 0.74 (Table 1). The highest content was recorded during autumn for both the studied levels (0-1 and 1-2 cm). No substantial differences were recorded between the superficial (0-1 cm) and subsurface (1-2 cm) levels of the same sample. The C/N ratio was always > 10.

At **Res** station, TOC was lower than organic carbon content from **Ser**, varying from 1.31 to 1.56% with a mean value of 1.42 ± 0.08 (Table 1). The lowest TOC contents were recorded during summer and the highest during winter at the subsurface level. No substantial differences were recorded between the superficial (0-1 cm) and subsurface (1-2 cm) levels of the same sample. The C/N ratio was always > 10.

Potentially Toxic Element concentration

PTE content detected using HCl extraction are reported in Table 1 and expressed as micrograms per gram. Generally, their concentration was higher at **Res** station than at **Ser**, especially for Cr, Ni and Pb at the superficial levels (0-1 cm). On the contrary, **Ser** station presented values higher than **Res** for Zn, in all the levels and seasons (Fig. 3).

Cd concentration was always below the limit of de-

Medit. Mar. Sci., 20/1, 2019, 120-141

tection (LOD) value, except for the autumn sample from Ser station (1-2 cm), where it reached a value of 0.64 μ g/g. Cr concentration ranged from 0.52 to 1.03 and from 0.25 to 7.35 μ g/g for Ser and Res, respectively. Higher values were recorded in the superficial levels of Res. Cu content varied from 1.07 to 12.11 and from 0.29 to 15.34 µg/g, for Ser and Res, respectively. The highest concentrations (15.34 μ g/g) were recorded in winter at **Res** (0-1 cm). Ni values ranged from 2.68 to 4.14 and from 1.50 to 8.85 μ g/g for Ser and Res, respectively. The highest concentrations (8.85 μ g/g) were recorded in summer at Res (0-1 cm). Pb concentration ranged from 0.50 to 11.37 and from 0.50 to 37.89 μ g/g for Ser and Res respectively. The highest concentrations $(37.89 \,\mu g/g)$ were always recorded at Resin winter (0-1 cm). Zn concentration varied from 70.20 to 195.38 and from 8.43 to 67.41 μ g/g for Ser and **Res** respectively. This element reached the highest concentrations at Ser station, especially during autumn and at the superficial levels of this station.

Living benthic foraminifera

Total standing stocks and diversity

In total, 3868 and 8565 living foraminifera, undetermined specimens included, were counted respectively at **Table 1.** Textural data of the studied sediments (% of sand, silt, clay, mean size - Mz, Shepard classification, total organic carbon (TOC), total nitrogen (Ntot), molar ratio TOC/Ntot (C/N) and potentially toxic element (PTE) concentration (expressed micrograms per gram - $\mu g/g$) in the **Ser** and **Res** stations. The limits of detection (LOD), the PTE concentration for the reference levels of the core GT3 (Covelli *et al.*, 2006), the literature data of PTE concentration in unpolluted areas (Voutsinou-Taliadouri, 1995) and the PTE concentration in the moderately and polluted sectors of the harbour of Trieste (Adami *et al.*, 2000).

25	b) and the PTE concentration in the moderately and polluted sectors of the harbour of Trieste (Adami <i>et al.</i> , 2000),
	were reported.

Sample	sand	silt	clay	Mz	Shej (19	pard 54) 1	TOC	N tot	C/N
	%	%	%	μm			%	%	
station Ser									
win13 (0-1)	17,4	66,7	15,9	16,	7 sand	y silt 2	2,19	0,18	14,2
win13 (1-2)	17,6	67,6	14,7	17,9	e sand	y silt 2	2,19	0,18	14,6
spr13 (0-1)	13,3	71,5	15,2	15,0	6 claye	y silt	1,89	0,18	12,3
spr13 (1-2)	14,8	71,9	13,3	17,9) sand	y silt 2	2,20	0,19	13,8
sum13 (0-1)	14,0	71,4	14,6	16,	7 claye	y silt 2	2,08	0,16	15,2
sum13 (1-2)	15,7	68,9	15,4	17,9	9 sand	y silt 1	1,88	0,15	15,1
aut13 (0-1)	30,7	56,3	13,0	25,4	4 sand	y silt 3	3,48	0,28	14,5
aut13 (1-2)	44,8	44,4	10,8	35,9	9 silty	sand 3	3,81	0,31	14,6
station Res									
win13 (0-1)	9,8	77,7	12,5	16,	7 si	lt	1,42	0,15	11,4
win13 (1-2)	7,5	76,3	16,2	13,	5 si	lt	1,56	0,15	12,6
spr13 (0-1)	4,9	77,4	17,7	11,5	3 si	lt	1,48	0,14	12,3
spr13 (1-2)	3,5	74,4	22,1	10,.	3 claye	y silt	1,41	0,13	13,2
sum13 (0-1)	4,4	78,5	17,1	11,	3 si	lt	1,31	0,12	13,3
sum13 (1-2)	3,6	76,8	19,6	10,	3 si	lt	1,37	0,11	14,5
aut13 (0-1)	4,5	75,5	19,9	11,0) si	lt	1,43	0,14	12,4
aut13 (1-2)	4,2	75,7	20,0	11,0) si	lt	1,35	0,10	16,6
Cd		Cr	(<u></u>	Ni		Ph		Zn
ug/g		ца/а	Ц	g/g	ця/я		цд/д		19/g
		r8'8	r	88	ra a		r8'8		****
< LOD		1,03	9	,36	3,82		11,37	1	10,09
< LOD		0,56	2	,54	3,46		4,39	1	08,60
< LOD		0,61	3	,03	3,58		4,62	7	7,59
< LOD		0,54	1	,25	3,41		1,54	7	0,20
< LOD		0,62	4	,18	3,93		6,50	9	3,28
< LOD		0,74	6	,14	4,14		9,10	8	4,65
< LOD		0,97	12	2,11	3,77		10,03	1	95,38
0,64		0,52	1	,07	2,68		0,50	1	17,59
< LOD		7,35	15	5,34	8,83		37,89	6	7,41
< LOD		0,59	0	,73	1,50		0,50		8,43
< LOD		3,11	7	,01	4,42		25,90	4	0,40
< LOD		0,31	2	,08	3,64		17,41	3	8,69
< LOD		2,76	4	,81	8,85		18,15	3	1,48
< LOD		0,51	2	,02	3,73		13,06	3	0,76
< LOD		4,40	9	,50	5,70		33,16	4	5,85
< LOD		0,25	0	,29	2,98		6,83	3	0,85
	L0	D	0,12	0.25	0.25	0.25	0.500	0.25	
	GT3-51		< 0.005	0.49	0.52	1.14	< 0.020	< 0.010	
	GT3-53		< 0.005	0,56	0,54	1,12	< 0.020	< 0.010	
	Voutsinou-T 1995	Faliadouri,	n.d.	14-180	3-35	12-207	5-32	17-72	
	Adami <i>et al.</i> .	. 2000	n.d.	4.1-14.5	27.4-62.3	10.7-26.6	106-234	147-321	



Fig. 3: Potentially toxic elements (PTE) concentration in the **Ser** (a) and **Res** (b) stations calculated for the 0-1 cm level. PTEs are expressed in micrograms per gram (μ g/g).

Ser and Res stations during the sampling period. For both stations, the foraminiferal density (hereafter FD) showed the lowest values during winter (99 specimen/50cc at Ser and 132 specimen/50cc at Res), increased considerably during spring reaching the highest values (805 specimen/50cc at Ser and 2027 specimens/50cc at Res) and decreased during summer and autumn (Fig. 4a). FD values were, however, higher at Res station than at Ser. More specifically, the FD of Res was up to 2.5 times higher than Ser during spring and a minimum of 1.3 times higher during winter. The percentage of biocoenosis was mainly concentrated in the 0-1 cm level for all stations and seasons, reaching a mean value of $69.1 \pm 11.2\%$ in this level. A particularly high percentage of biocoenosis was recorded in the 0-1 cm level during spring and summer (Res) and autumn (Ser).

Species richness varied in the studied stations and during the sampled period (Fig. 4a). Winter, summer and autumn at **Ser** and winter at **Res** were characterised by lower richness, while spring presented the highest num-



Fig. 4: Foraminiferal data for **Ser** and **Res** stations using the complete living assemblage of the 0-2 cm level: a) Foraminiferal density (FD) as the number of specimens normalised to 50 cc of sediments and species richness; b) Dominance index; c) bias corrected Shannon (H'_{bc}) and the exponential function $Exp(H'_{bc})$ indexes.

ber of species at both stations. Without considering the genera *Bolivina*, *Fissurina*, *Lagena*, *Textularia* and Miolids, which were grouped as spp., **Ser** showed a mean richness of 38 ± 8 species, except for spring, where the richness reached 50 species. **Res** was generally richer

than Ser, having a mean richness of 46 ± 9 species, except for winter with its lower value of 35 taxa. Spring is richer in species than other seasons with a total of 58 species.

Dominance, H' and $\text{Exp}(\text{H}'_{bc})$ values are shown in Figs. 4b, c. Dominance values were comparable in the two stations in winter and spring and, conversely, they were lower at **Res** station than **Ser** in summer and autumn. Higher values were recorded in spring (D = 0.16) for both stations (Fig. 4b) while the lowest value pertained to **Res** during autumn (0.05). H' varied from 2.66 (**Ser**, spring) to 3.29 (**Res**, autumn); it was lower at **Ser** during spring and autumn (Fig. 4c). $\text{Exp}(\text{H}'_{bc})$ values varied from 12.47 (**Ser**, autumn) to 25.92 (**Res**, autumn) with a mean value of 15.74 ± 4.39 and 19.85 ± 5.32 for **Ser** and **Res**, respectively. The lowest values were recorded at **Ser** during autumn and at **Res** during spring (Fig. 4c).

Species composition of benthic foraminiferal communities

A total of 65 species pertaining to 39 genera were recorded at **Ser** station and 68 species pertaining to 37 genera were recorded at **Res** station (Table S1). Of these, about 70% were in common to both stations.

The most common foraminifera were Ammonia tepida, Bolivina spp., Bulimina spp., Eilohedra vitrea, Elphidium spp., Haynesina depressula, Hopkinsina pacifica and Nonionella iridea among the Rotaliina, Cribrostomoides kosterensis, Eggerelloides scaber, Reophax nana and Textularia spp. among the Textulariina. Species pertaining to Miliolina were less abundant and mainly represented by Miliolinella subrotunda, Quinqueloculina spp. and Spiroloculina spp. Genera pertaining to Rotaliina were more abundant at Ser station, except for winter where the species of Textulariina dominate. Agglutinated species prevailed at **Res** station during spring and summer; Miliolina were more abundant at **Res**, they were very subordinate at Ser, except for winter 2013 (Table S1). The fourteen major taxa (> 4% in at least one sample considering both stations) are shown in Table 2.

Considering their density (Fig. 5), *A. tepida, Bolivina* spp., *Bulimina* spp. and *E. vitrea* were more abundant at **Ser**, while *E. scaber, Elphidium* spp., *H. depressula, M. subrotunda, N. iridea, Quinqueloculina* spp., *R. nana* and *Textularia* spp. characterised **Res** station. *Miliammina fusca*, agglutinated, was present only once (summer, **Res**) with very high abundance (Table S1). As for the relative abundance, *Bolivina* spp., *E. scaber, Textularia* spp., and



Fig. 5: Distribution of the foraminiferal density of those species and genera comprising at least 4% of the assemblage in at least one sample from the studied stations. Red histogram: **Ser** station; blue histogram: **Res** station. Note that y-axis scale is variable depending on species foraminiferal density.

Table 2. The fourteen most common foraminiferal species and genera (in decreasing order of their relative abundance) found
at the two sampling stations summed over 0-2 cm and averaged between seasons. These species were present at least one time
(station or season) with a relative abundance $> 4\%$.

station	Ser (winter - au	tumn 2013)		Res (winter - au	tumn 2013)
	min-max %	mean %		min-max %	mean %
species			species		
Ammonia tepida	0.6-4.5	2.2	Ammonia tepida	0.0-0.1	0.07
Bolivina spp.	9.7-36.7	25.3	Bolivina spp.	3.3-12.0	5.81
Bulimina spp.	9.0-13.9	11.3	Bulimina spp.	1.6-6.1	3.76
Cribrostomoides kosterensis	0.0-5.2	1.6	Cribrostomoides kosterensis	0.1-2.3	1.06
Eggerelloides scaber	6.3-26.6	16.2	Eggerelloides scaber	3.9-19.4	10.65
Eilohedra vitrea	1.0-4.0	2.3	Eilohedra vitrea	0.2-1.5	0.72
Elphidium spp.	1.1-3.1	2.3	Elphidium spp.	3.8-29.9	11.62
Haynesina depressula	0.0-0.2	0.1	Haynesina depressula	1.8-7.4	3.99
Hopkinsina pacifica	2.1-9.8	5.5	Hopkinsina pacifica	0.5-7.6	3.76
Miliammina fusca	0.0	0.0	Miliammina fusca	0.0-37.3	9.39
Nonionella iridea	0.0-5.3	2.4	Nonionella iridea	0.2-11.5	5.73
Quinqueloculina spp.	0.1-4.5	1.6	Quinqueloculina spp.	2.0-5.5	3.59
Reophax nana	0.0-11.9	4.9	Reophax nana	0.5-21.5	8.59
Textularia spp.	5.7-25.3	13.0	Textularia spp.	6.8-31.4	16.11

Bulimina spp. exceeded 10% at **Ser** station and *Textularia* spp., *Elphidium* spp., and *E. scaber* exceeded 10% at **Res** station (Table 2).

The Chi-square test (χ^2) indicates an overall significant difference between Ser and Res stations ($\chi^2 = 2012.4$; df = 12; p< 0.0001) in terms of species composition; the main contributions to the χ^2 were given by 5 taxa over 13 species (Table S2). Comparing the two stations and considering all the season, the first and most important contribution in term of difference was due to Bolivina spp. (41.3% with respect to the total contribution), followed by Elphidium spp. (13.3%), Bulimina spp. (12.0%), H. depressula (10.1%) and N. iridea (10.0%). Even with moderate contributions, R. nana and A. tepida were also significant (5.3 and 3.6%, respectively). Bolivina spp., Bulimina spp. and A. tepida were more abundant at Ser station while Elphidium spp., H. depressula, N. iridea and R. nana dominated at Res station (Fig. 5). Considering the seasons separately, the difference between Ser and **Res** which occurred during winter ($\gamma^2 = 140.3$; df = 12; p < 0.0001) saw the main contributions of *Elphid*ium spp. at **Res** station and *E. scaber*, which was more abundant at Ser station. During spring ($\chi^2 = 320.8$; df = 12; p < 0.0001) the difference between Ser and Res had the main contributions of H. depressula, Textularia spp., both more abundant at Res station (Fig. 5) and Bolivina spp., at Ser station. In summer ($\chi^2 = 645.3$; df = 12; p < 0.0001) the difference was mainly due to Bolivina spp. and, subordinately, by Bulimina spp., both more abundant at **Ser** station and finally in autumn ($\chi^2 = 1293.4$; df = 12; p < 0.0001) to *Bolivina* spp. and *Elphidium* spp., more abundant at Ser and Res stations, respectively.

Foraminifera vs. textural and geochemical indicators Spearman's rank order correlations between absolute abundance of living foraminifera of the superficial level (0-1 cm) and the relative geochemical characteristics of the sediments are shown in Table 3, where significant correlations are reported in **bold** (p < 0.01) and *italic* (p < 0.05). Haynesina depressula and Quinqueloculina spp. correlated negatively with sand content. Elphidium spp., H. depressula correlated positively with silt content. Only Quinqueloculina spp. correlates with clay content. The other species did not correlate significantly with any textural fraction.

Concerning the other geochemical characteristics, *A. tepida* positively correlated with TOC and N_{tot} contents, while only *H. depressula* negatively correlated with TOC content. *Ammonia tepida* and *Bulimina* spp. were negatively correlated with Cr, Ni and Pb. *Hopkinsina pacifica* was negatively correlated with Cu. *Elphidium* spp., *H. depressula*, *Quinqueloculina* spp. and *Textularia* spp. were negatively correlated with Zn.

State of foraminiferal communities and EcoQ assessment

At **Ser** station, RFDs appeared as a straight-line in winter, linear-concave in spring and convex during summer and autumn (Fig. 6a). From winter to autumn, foraminiferal assemblages showed an ecological succession from a mature assemblage in winter to an unbalance done in spring, reaching an intermediate assemblage in summer and autumn. At **Res** station, RFDs changed from a straight-line in winter to a linear-concave shape in spring, a convex one in summer, ending up with a straight-line shape during the autumn (Fig. 6b). This highlighted an

Table 3. Spear (PTEs),	man's rai total orge	nk corre. mic cart	ation usi on (TOC	ng the al (), total r	osolute a nitrogen (bundanc Ntot) an	e of the r id grain-s	najor spe size. The	scies at tl significa	ne 0-1 cr unce thre	n level o: shold p <	t Ser and 0.01 an	d p < 0.0	tions and 5 were r	the relate ported i	iive cont n bold ai	ent of po 1d <i>italic</i> ,	tentıally respecti	toxic ele vely.	ments
Sunnin (0 1 mm)	C	Ţ	С	'n	2	Ii	Р	þ	Z	а	TO	С	N t	ot	san	þ	silt		clay	
	r	b	\mathbf{r}_{s}	d	\mathbf{r}_{s}	b	\mathbf{r}_{s}	b	r	b	\mathbf{r}_{s}	b	\mathbf{r}^{s}	b	\mathbf{r}^{s}	b	\mathbf{r}_{s}	b	\mathbf{r}_{s}	Р
Ammonia tepida	-0.916	0.001	-0.470	0.240	-0.892	0.003	-0.916	0.001	0.651	0.081	0.747	0.033	0.800	0.017	0.699	0.054	-0.699	0.054	-0.289	0.487
Bolivina spp.	-0.667	0.071	-0.476	0.233	-0.690	0.058	-0.667	0.071	0.214	0.610	0.452	0.260	0.407	0.317	0.262	0.531	-0.405	0.320	0.048	0.911
Bulimina spp.	-0.762	0.028	-0.524	0.183	-0.714	0.047	-0.762	0.028	0.310	0.456	0.500	0.207	0.455	0.257	0.333	0.420	-0.476	0.233	-0.048	0.911
C. kosterensis	0.180	0.670	-0.060	0.888	0.108	0.799	0.180	0.670	-0.156	0.713	-0.275	0.509	-0.241	0.565	-0.299	0.471	0.132	0.756	0.419	0.301
Eggerelloides scaber	-0.071	0.867	-0.143	0.736	0.190	0.651	-0.071	0.867	-0.333	0.420	-0.095	0.823	-0.323	0.435	-0.310	0.456	0.119	0.779	0.405	0.320
Eilohedra vitrea	-0.443	0.272	-0.539	0.168	-0.275	0.509	-0.443	0.272	-0.072	0.866	0.168	0.691	0.114	0.787	0.084	0.844	-0.012	0.978	-0.108	0.799
Elphidium spp.	0.571	0.139	0.143	0.736	0.476	0.233	0.571	0.139	-0.738	0.037	-0.690	0.058	-0.515	0.192	-0.643	0.086	0.786	0.021	0.190	0.651
Haynesina de- pressula	0.659	0.076	0.049	0.909	0.610	0.108	0.659	0.076	-0.903	0.002	-0.756	0.030	-0.810	0.015	-0.878	0.004	0.781	0.022	0.659	0.076
Hopkinsina pa- cifica	-0.333	0.420	-0.762	0.028	-0.095	0.823	-0.333	0.420	-0.500	0.207	-0.167	0.693	-0.299	0.471	-0.405	0.320	0.262	0.531	0.524	0.183
Nonionella iridea	-0.192	0.649	-0.683	0.062	0.120	0.778	0.120	0.778	-0.635	0.091	-0.323	0.435	-0.464	0.247	-0.539	0.168	0.419	0.301	0.527	0.180
Quinqueloculina spp.	0.371	0.365	-0.252	0.548	0.407	0.317	0.371	0.365	-0.838	0.009	-0.599	0.117	-0.699	0.054	-0.790	0.020	0.647	0.083	0.826	0.011
Reophax nana	-0.167	0.693	-0.667	0.071	0.238	0.570	-0.167	0.693	-0.690	0.058	-0.452	0.260	-0.539	0.168	-0.619	0.102	0.524	0.183	0.452	0.260
Textularia spp.	0.024	0.955	-0.619	0.102	0.190	0.651	0.024	0.955	-0.762	0.028	-0.524	0.183	-0.563	0.146	-0.690	0.058	0.595	0.120	0.595	0.120
aboundance	0.000	1.000	-0.429	0.289	0.167	0.693	0.000	1.000	-0.690	0.058	-0.405	0.320	-0.491	0.217	-0.619	0.102	0.476	0.233	0.571	0.139
richness	-0.168	0.691	-0.515	0.192	-0.108	0.799	-0.168	0.691	-0.515	0.192	-0.180	0.670	-0.283	0.497	-0.443	0.272	0.252	0.548	0.647	0.083
bold ($p < 0.01$) <i>italic</i> ($p < 0.05$)																				



Fig. 6: Rank-frequency diagram for the Ser(a) and Res(b) stations using the cumulative abundance (as relative frequency) for y-axe and the decreasing rank order for x-axe of each species for each sample. Both axes are on logarithmic scale.

annual ecological succession from a mature assemblage in winter, to an unbalanced one in spring, an intermediate assemblage in summer, ending up with a mature assemblage in autumn. Ecological quality statuses assessed at both stations varied seasonally. Based on $Exp(H'_{bc})$ calculated on benthic foraminifera, the EcoQ is high in winter and autumn, moderate in spring and good in summer at **Res** station. Conversely, the EcoQ is always moderate at **Ser** station except during the winter season, where it is high (Fig. 4c).

Discussion

Environmental conditions

Hydrological features represented typical seasonal variabilities of the GoT (Malačič & Petelin, 2001). Homogenous oceanographic conditions occurred in winter and autumn, while during spring and summer the water column was stratified. Anomalous salinity values observed at **Ser** station during winter indicates that freshwater outflow from the pipeline can occasionally modify the salinity pattern. During spring, the high values of dissolved oxygen indicated the significant activity of primary producers (mainly phytoplankton) occurring in the middle of the water column, as seen by the chlorophyll *a* value higher than 2.0 μ g/l from 5 to 17 m of depth at **Ser** station and from 4 to 14 m of depth at **Res** station (Fig. 2).

Environmental parameters at the studied stations showed diverse conditions, both for the stations and for the sampling periods. Grain-size demonstrates that sediments from **Ser** station (from 15 to 45%) were always richer in sand than **Res** station. The relatively high occurrence of sand at **Ser** station differs with the sediment distribution proposed by Brambati *et al.* (1983), Ogorelec *et al.* (1991) and Acquavita *et al.* (2010) for the GoT. These authors indicated high sand content along beaches, in proximity to the Marano and Grado lagoon outlet and in the western open sector of the Gulf and clayey silt for the studied area. This increase in sand at **Ser** station is probably due to the concomitant effect of the greater influence of the solid load of the Isonzo in this area compared to the more strictly coastal one, as well as to the contribution of "organic" residue carried out by the pipeline. The grain-size composition of **Res** station sediments was, on the contrary, in agreement with previous studies and remained comparable over all sampling periods.

TOC content (and N_{tot}) was always higher at Ser than at **Res**, especially during autumn, where TOC content > 3.0% was recovered at Ser (both levels). These data are in agreement with Cibic et al. (2008) which demonstrated a mean TOC content of $2.41 \pm 0.4\%$ for June 2004. TOC correlated significantly with sand content ($r_{e} = 0.919$, p < 0.001). This behaviour is not common since TOC is generally associated with finer sediments in relation to adsorption effects (Guerzoni et al., 1984; Faganeli et al., 1991). On the contrary, the positive correlation of TOC with sand which occurred at Ser station probably indicates that in this case, the sandy sediments convey the organic residue probably derived from the human activity of the sewage carried out by the pipeline. Mean values of 1.42% at **Res** station were comparable with data from Acquavita et al. (2010), but slightly higher than data reported for the Slovenian sector (Faganeli et al., 1991; Covelli & Fontolan, 1997; Acquavita et al., 2010). In all cases, C/N molar ratio was always > 10, indicating that the organic matter is a mixed composition of marine and terrestrial organic compounds (e.g. Meyers, 1994; Twichell et al., 2002; Ramaswamy et al., 2008).

The HCl etching procedure used to determine the heavy metal concentrations allowed us to determine the "non-residual", more labile fraction likely due to recent input, as highlighted by Adami et al. (2000). The slightly higher concentration of all the PTEs, except Zn, at Res station than at Ser (Fig. 3), raises some questions about their origin. The proximity of a touristic harbour and the relative use of different types of paints, including antifouling ones, in an area located at about a quarter of mile to the Reserve might explain this increased concentration, especially as far as Pb is concerned. The presence of elements such as Cd, Cr, Cu, Ni, Sn and Zn has already been observed in sediments contaminated by antifouling paints used for nautical activities (Turner, 2010). A comparison with data obtained by Adami et al. (2000) using the same procedure, indicates that the concentrations of Cr, Cu, Ni and Pb obtained in this study were always lower than those found in the moderately polluted and polluted sites of the Trieste harbour.

Zn, on the other hand, was always found with higher values at **Ser** station. Its concentration in this station is comparable with the Zn content found at the moderately polluted sites of the harbour, especially for the autumn sampling and it always exceeded the limit of unpolluted environment defined by Voutsinou-Taliadouri *et al.* (1995). High Zn concentrations are usually related to industrial tailing and wastes (e.g. Donazzolo *et al.*, 1984). Furthermore, when precipitation is scarce and the water column is homogeneous metals such as Cu and Zn discharged by the pipeline can reach the surface waters (Cozzi *et al.*, 2004). Particularly, in our study Zn was

probably transported by the organic residue from the Servola pipeline, as evidenced by its positive correlation ($r_s = 0.916$, p < 0.001) with the TOC occurring in the sandy size of the sediments.

Living foraminiferalassemblage

Diversity and foraminiferal density

In this study, species richness was about 30 to 60 species (Fig. 4a) which is relatively higher than the approximately 30 species, without the allogromiids ones, recorded by Sabbatini et al. (2010) in their study in the GoT. However, they only carried out one sampling (May 2006) and used a lower volume of sediment than in this work, so their species richness may have been underestimated. A mean of 50 species recorded in this study is comparable with other studies carried out in the northern Adriatic Sea (Jannink, 2001; Duijnstee et al., 2004) and is in agreement with the general mesotrophic-oligotrophic conditions, with episodic eutrophic events that characterise the GoT (Horvat et al., 1999; Turk et al., 2007; Giani et al., 2012). The foraminiferal species found in this study, including the most common ones (A. tepida, Bolivina spp., Bulimina spp., E. vitrea, Elphidium spp., H. depressula, H. pacifica, N. iridea, C. kosterensis, E. scaber, R. nana and Textularia spp.) are characteristic of infra-circalittoral Mediterranean and northern Adriatic Sea environments (Jorissen, 1987, 1988; Hohenegger et al., 1989; Cimerman & Langer, 1991; Barmawidjaja et al., 1992; Sabbatini et al., 2010; Melis & Covelli, 2013). Although approximately 70% of the species are in common between the two studied stations, differences were observed. Cornuspira involvens, Elphidium macellum, Fursenkoina complanata, F. schreibersiana, Quinqueloculina milletti, Q. oblonga and Trochammina ochracea were found only at Ser station. They are, however, rare species. Ammonia beccarii, Cibicides lobatulus, Cycloforina rugosa, Lagenammina atlantica, Miliammina fusca, Nouria polymophinoides, Quinqueloculina pygmaea, Reophax subfusiformis, Spiroloculina dilatata and Triloculina tricarinata were recorded only at Res station (Table S1).

In this study, species richness varied during the seasons in a predictable manner (higher richness during spring and summer and vice versa in winter and autumn). However, species richness was always lower at Ser station than at **Res**, while diversity was comparable between the two stations in winter and spring and mainly differed in autumn (Fig. 4c). It suggests that the area around the Servola sewage pipeline (Ser station) is more problematic than the Reserve (Res station) for the foraminiferal communities. Along the Italian coast lagoons, lakes, and human activities (industries, aquaculture) also induce low diversity in terms of benthic foraminifera (Bouchet et al., 2018). Similarly, in the Saguenay (Canada), benthic foraminiferal diversity was very low due to discharges from a paper mill (Schafer et al. 1991). In the Firth of Clyde (Scotland), foraminiferal densities and diversity similarly decreased in the vicinity of a sewage sludge (Mojtahid et al., 2008).

In this study, both number of species and abundance decreased when Zn concentration increased (Table 3). Zn reached higher concentration values in Ser during autumn (about 200 μ g/g), in the situation of a homogenous water column, and this concentration was comparable with the Zn concentration found in the industrial harbour of the city which is considered highly polluted by Adami et al. (2000). Even if Zn is essential for metabolism of the microorganisms (e.g. Venugopal & Luckey, 1975), these high values seem to be a limiting factor for the foraminiferal communities, so confirming the deleterious effects of the trace metals on benthic foraminiferal densities and diversity (e.g. Armynot du Châtelet et al., 2004; Le Cadre & Debenay, 2006; Coccioni et al., 2009; Denoyelle et al., 2012; Nardelli et al., 2013; Francescangeli et al., 2016). As for the other PTEs, no significant correlation was observed.

Foraminiferal densities (FD) of Res station was always higher than Ser indicating the more favourable environmental conditions of the Reserve. However, FD peaked at both stations during spring when trophic conditions were favourable (Fig. 4a). It is well known that phytoplankton blooms occur during the spring period in the GoT (Cabrini et al., 2012). This suggests that benthic foraminifera would benefit from the phytodetritus accumulation derived from settled phytoplankton (mainly diatoms), as universally recognised (e.g. Gooday, 1988; Boon et al., 1998; Pusceddu et al., 2003; Sabbatini et al., 2012). The same pattern of the foraminiferal bloom following the natural cycle of chlorophyll a was also reported by Hyams-Kaphzan et al. (2009) along the coast of Israel. In addition, the bottom water oxygen concentration was likely an important factor in controlling the density variability of some species at Ser station during the rest of the year, in agreement with Barmawidjaja et al. (1992), Jorissen et al. (1992) and Jannink (2001). In fact, during summer and autumn, high FD values of Bolivina spp. and Bulimina spp., occurred in oxygen stressed bottom water environments of the Ser station (% sat. < 90; Fig. 2), confirming their ability to flourish at reduced levels of oxygen concentration (Bernhard, 1986; Barmawidjaja et al., 1992; Jorissen et al., 1992; Donnici & Serandrei-Barbero, 2002; Langlet et al., 2014).

Species responses to environmental conditions

Grain-size is a well-known driver of benthic foraminiferal distribution (e.g. Armynot du Châtelet *et al.*, 2009, Frontalini *et al.*, 2013). Considering the correlation with the sediment composition of our study, most of the species prefer to live in silty sediments, except for *Quinqueloculina* spp., which were more abundant in clayey sediments and *A. tepida*, which was more abundant in sandy sediments. This last taxon correlates well with TOC, as previously discussed. Conversely, *Elphidium* spp. and *Haynesina depressula* did not occur at **Ser** station which was the more enriched in TOC, preferring the Miramare MPA.

The correlation between species abundance at the superficial levels (0-1 cm) with PTEs (Table 3), shows significant negative correlations of *A. tepida*, *Bulimina* spp.

and H. pacifica, with Cr, Ni and Pb concentrations in the bioavailable fraction. This would suggest that these taxa are rather sensitive to these elements and would benefit from the less stressful conditions occurring at Ser station especially for lower Cr and Pb content. As already explained in the previous paragraph, the **Res** station showed a greater accumulation of these elements, while remaining within the limits of areas in unpolluted conditions, according to Voutsinou-Taliadouri et al. (1995) and Adami et al. (2000). Only the concentration of Pb in winter and autumn at Res station, exceeds these limits (Table 1). On the contrary, H. depressula, Quinqueloculina spp., Textularia spp. and Elphidium spp., in decreasing order, are very sensitive to high Zn content and would benefit from the less stressful conditions of Miramare MPA station (Res). Conversely, A. tepida, Bolivina spp., Bulimina spp. and Eilohedra vitrea were more abundant at Ser station (Fig. 5), where less oxygenated bottom water conditions, coarser sediment texture, higher Zn and TOC contents were highlighted. Species such as A. tepida and Bolivinidae are generally known to be good indicators of trace metal pollution (see discussion in Frontalini & Coccioni, 2011). In this study they represent the best tolerance toward the organic matter accumulation and higher Zn content.

In the following, we will discuss the response of the most significant species to the environmental conditions, considering both stations along the studied seasons.

Amongst the calcareous species, Bolivina spp. (mainly B. dilatata, B. striatula and B. variabilis) was the more abundant genus in the sediments and it represents the main contribution in terms of statistical differences between the stations, except for winter (Table S2); their densities reached about 300 specimens/50 cm³ during spring at Ser station, where it was often the dominant genus. *Bolivina* spp. were more abundant in the superficial sediments. These species are considered deep infaunal taxa usually associated with high organic matter flux, low oxygen concentrations and related to finer texture (Bernhard, 1986; Barmawidjaja et al., 1992; Jorissen et al., 1992; Donnici & Serandrei-Barbero, 2002; Langlet et al., 2014). B. dilatata is considered able to respond to fresh phytodetritus input (Barmawidjaja et al., 1992; Jorissen et al., 1992; Duchemin et al., 2008; Goineau et al., 2012). The occurrence of *Bolivina* spp., mainly in the superficial studied sediments, could indicate a tendency of these species to colonise shallower sediments especially during autumn when the TOC concentration was higher at deeper levels (Table 1). This finding is in agreement with those of Jorissen et al. (1992) and Kaiho (1994). Furthermore, Bolivina dilatata and B. variabilis have been considered "Indifferent species" to the first stages of organic enrichment in the sediments by Jorissen et al. (2018) and this could explain the absence of a significant correlation between Bolivina spp. and TOC content (Table 3).

Bulimina spp. (mainly *B. aculeata*, *B. elongata* and *B. marginata*), were, on the contrary, homogenously distributed in the 0-2 cm level, except for autumn at **Ser** station, where their density was higher at 0-1 cm, as already observed for *Bolivina* spp. The genus *Bulimina*

prefers environments characterised by the first stages of organic matter enrichment, and can tolerate low oxygen concentrations (e.g. Barmawidjaja et al., 1992; Jorissen et al., 2018). Furthermore, Bulimina marginata (mainly the morphotypes B. aculeata, B. denudata) can survive periods of severe anoxic conditions with hydrogen sulphide content (e.g. Pucci et al., 2009; Geslin et al., 2014; Langlet et al., 2014). Nevertheless, in other cases their capacity to migrate into the disoxic superficial sediments to escape conditions of severe oxygen depletion was observed (de Stigter et al., 1998; Barmawidjaja et al. 1992; Duijnstee et al., 2003). Since an abundance of Bolivina and Bulimina are associated with oxygen-deficient environments, these conditions in our study can be always inferred in the sediments of Ser station, where the black colour of the sediments confirm this situation. However, considering the two genus as a whole, no significant statistical correlation with TOC content was observed (Table 3).

Elphidium spp. (mainly E. advenum, E. granosum, E. lidoenese and E. decipiens) and H. depressula are common in Mediterranean infralittoral settings also in the presence of vegetation cover (Jorissen et al., 1988; Albani & Serandrei-Barbero, 1990; Sgarrella & Moncharmont Zei, 1993; Donnici & Serandrei-Barbero, 2002; Murray, 2006; Melis & Protopsalti, 2008). These species were undoubtedly more abundant at Res station and in the superficial sediments (0-1 cm). They are all positively correlated with silt content and H. depressula is negatively correlated with sand content (Table 3). There is an evident negative correlation between TOC content and *H. depressula* (Table 3), confirming its tendency to disappear in situation of increased organic supplies as evidenced by Jorissen et al. (2018). They areal so negatively correlated with Zn. H. depressula was nearly absent at Ser station and reached a higher abundance during spring in relation to fresh phytodetritus accumulation. This species is frequent in infralittoral fine sands and in shallow deposits near river mouths and in lagoons (Jorissen, 1988; Sgarrella & Moncharmont-Zei, 1993; Bellotti et al., 1994; Melis & Covelli, 2013).

Hopkinsina pacifica is negatively correlated to Cu and it too can be considered a sensitive species with regards to this metal. Hopkinsina pacifica is considered a species tolerant to organic matter accumulation (Frontalini & Coccioni, 2011; Jorissen et al., 2018) and like N. iridea, it is able to feed on fresh phytodetritus (Goineau et al., 2012). Nonionella iridea was very frequent during spring and summer, above all at **Res** station and in the superficial sediments (Fig. 5), however, it did not correlate to any of the studied parameters. Nonionella iridea have been recorded in limited numbers by Donnici & Serandrei-Barbero (2002). On the contrary Nonionella turgida, often reported in the GoT (Sabbatini et al., 2010; Langlet et al., 2014), was not present in high densities at either of the studied stations.

Ammonia tepida is recognised worldwide as a brackish-water species able to live in conditions of variable salinity and temperature. It assumes the highest concentra-

tions in confined settings such as lagoons, estuaries, tidal flats, etc. (Jorissen, 1987; Albani & Serandrei Barbero, 1990; Sgarrella & Moncharmont Zei, 1993; Debenay et al., 2000; Melis & Violanti, 2006; Melis & Covelli, 2013). Its presence at Ser station is mainly concentrated in the upper level studied (0-1 cm) and, even if in moderate frequency, probably indicates more pronounced salinity variations due to the frequent fresh water discharge from the pipeline. Furthermore, the high correlation of this taxon with TOC and N_{tot} content (Table 3) indicates that A. tepida could be favoured by an increase in total organic matter used as food resources, as suggested by Armynot du Châtelet et al. (2009) and confirms its role of "Second-order opportunist species" underlined by Jorissen et al. (2018). It is also negatively correlated with silt content referring to the sandy sediments (Table 3). In particular, it is commonly known that A. tepida can live in stressed environments and could be very tolerant to high concentrations of trace elements, including Hg (Yanko et al., 1994; Ferraro et al., 2006; Bergamin et al., 2009; Carboni et al., 2009; Coccioni et al., 2009; Caruso *et al.*, 2011). This study suggests its tolerance versus Zn only.

Eilohedra vitrea was distributed in both levels of the studied sediment. This species is not very frequent in the Adriatic Sea. It is also reported by Duijnstee *et al.* (2004) at the mouth of the Po River delta mainly in relation to low O_2 and temperature values of the bottom waters and by Capotondi *et al.* (2015) in the muddy sediments rich in fresh organic matter of the central Adriatic coasts. In our study it does not correlate to any environmental characters (Table 3). Hence, it is difficult to reach a conclusion regarding the ecological requirements of this species in the GoT.

Regarding porcellaneous species, Quinqueloculina was one of the less tolerant genus in comparison to Zn concentration (Table 3). Furthermore, more oxygenated bottom water conditioned their presence (r = 0.857, p = 0.006). Among this group, Q. parvula, Q. pygmaea, Q. seminulum and Q. stalkeri were the dominant species. This genus, and miliolids in general, are considered sensitive to heavy metal pollution (Samir & El-Din 2001; Valenti et al. 2008; Ferraro et al. 2006), although in some cases, Q. parvula was recognised as a pollution-tolerant taxon by Romano et al. (2009) and Q. seminulum has been considered a stress tolerant species in relation to organic matter accumulation (Mangoni et al., 2016) and capable of surviving in conditions of prolonged anoxic conditions in combination with sulfides (Langlet et al., 2014). This study suggests that Quinqueloculina spp. are sensitive species to Zn concentration, only.

As for the agglutinated foraminifera, *Reophax nana*, *Textularia* spp. and *Eggerelloides scaber* do not have the same level of tolerance towards PTE concentration (Table 3). *Reophax nana* (also reported as *R. nanus* and *Aacostata mariae*) is frequent in the northern Adriatic Sea (Barmawidjaja *et al.* 1992; Donnici & Serandrei-Barbero, 2002; Sabbatini *et al.*, 2010; Langlet *et al.*, 2014). It showed a negative correlation with sand, TOC, and N content (Table 3). It was found mostly

in the shallowest first centimetres of the sediments, in agreement with Langlet et al. (2014). Genus Textularia was present with several species, mainly represented by T. conica, T. pala and T. calva (Table S1). Its density distribution did not vary significantly between the two stations, even if they were more abundant at **Res** where in terms of frequency they are the most representative genus (Fig. 5). *Textularia* spp. were distributed in both superficial and sub superficial levels, preferring oxygenated bottom waters ($r_{e} = 0.762$, p = 0.028) and it was negatively correlated with sand content and Zn concentration (Table 3). Eggerelloides scaber was preferably abundant at Res especially during spring and summer (Fig. 5) and was more abundant in the surface layer, even if the genus Eggerelloides is usually considered a deep infaunal (Duijnstee et al., 2004; Langlet et al., 2014). This taxon is a continental shelf species living in microhabitats with different oxygenation conditions (e.g. Jorissen et al., 1992; Donnici & Serandrei-Barbero, 2002; Duijnstee et al., 2004; Langlet et al., 2014); it is also able to colonise the seaward part of estuaries and lagoons (Albani & Serandrei Barbero, 1990; Murray, 2006; Melis & Covelli, 2013). Although this species could be regarded as a tolerant species, at least in environments with relatively low levels of pollution by Frontalini & Coccioni (2008, 2011), in this study, *Eggerelloides scaber* is not correlated with any of the PTEs (Table 3).

Miliammina fusca was observed in very high densities during spring at Res station. It is an epifaunal taxon living mostly in marshes, shallow lagoons (Murray, 2006) or in relict marine areas (Lloyd & Evans, 2002). Its high occurrence practically only during spring (with over 700 specimens/50 cc) and only in this station is not easily explained. This species has never been recorded in the GoT, whereas it has rarely been found in the Marano and Grado lagoon (as a dead specimen) (Melis & Covelli, 2013). The similar environmental conditions of the bottom waters recorded at two stations during spring, except for small differences in bottom water temperature and pH. Particularly, the pH value, which reaches the lowest value at **Res** station during spring (Fig. 2), could justify its presence, as also suggested by Burone et al. (2006). In addition, a greater presence of chlorophyll a during the spring at this station than at Ser station at a depth closer to the seabed (Fig. 2), may have favoured the Miliammina bloom. Lagenammina atlantica was observed in high density during summer at **Res** station. This taxon is frequently found in the northeastern Adriatic Sea (Sabbatini et al., 2010) and is considered a passive detritivore organism consuming diatoms and bacteria (Burmistrova et al., 2007). This high density during summer could suggest that this species only found these optimal conditions during this season.

<u>Benthic foraminifera used to assess the ecological</u> <u>status of the studied environment</u>

Following the suggestions of Bouchet *et al.* (2012, 2018), we used the $Exp(H'_{bc})$ index based on benthic foraminifera to evaluate the ecological status of the studied environments (EcoQs). In this study we decided to define the highest expected $\text{Exp}(\text{H'}_{bc})$ to 25 effective species using the complete living assemblage (0-2 cm interval, living foraminifera from cumulative triplicate samples). In fact, these are the same criteria as those designed for Norwegian fjords (Bouchet *et al.*, 2012). Note that in Italian transitional waters (lagoons, coastal lakes), where highly variable environmental conditions occur, Exp(H'bc) calculated on benthic living foraminifera was successfully used to the EcoQs assessment (Bouchet *et al.*, 2018).

In this study, the EcoQs based on benthic foraminifera indexes demonstrated conditions varying from moderate to good, in agreement with the environmental situations occurring at each station. This suggests that criteria developed at higher latitudes (Norwegian fjords) can be used in other environments such as the Gulf of Trieste. This must be further investigated in other open marine coastal habitats. Furthermore, it confirms that although developed along a decreasing bottom-water oxygen gradient, the foraminiferal method used to assess EcoQs works well against organic matter and trace metal pollution.

In general, diversity indices tend to have "natural" seasonal variations, often in relation to the recruitment which occur in spring and summer (Reiss & Kröncke, 2005; Murray, 2006). Such "natural" variations were also observed in this study. It is crucial to make sure that these variations do not hamper the assessment of EcoQs. Hence, our results suggest that the early spring season and latest summer would be the best periods of the year for EcoQ assessment using the foraminiferal method, since assemblages seem to reach equilibrium after an intense period of recruitment.

According to the rank-frequency diagrams (RFDs), benthic foraminiferal assemblages reached different degrees of maturity throughout the year at both stations. Foraminiferal assemblages were found to be quite resilient over the annual cycle under consideration, as they recovered from an unbalanced to a mature state, depending on the season. Seasonal variations in RFDs at both stations are due to changes in diversity and in dominant species. Stressful conditions at Ser station, mainly due to TOC accumulation and high Zn concentration, produced a more unbalanced foraminiferal assemblage in comparison with Res station. Only winter produces a mature assemblage at Ser, despite the low salinity values observed (<30), which do not seem to have had an effect on the foraminifers. Conversely, the mature assemblage observed at **Res** station suggests that the Miramare MPA is efficient in preserving good environmental conditions in the GoT, despite the fact that in this station there was a larger accumulation of Pb and Cr than Ser station. Benthic foraminiferal assemblages responded well to the contrasted conditions occurring at both stations. These results obtained via RFDs support the worse EcoQs obtained at Ser station. These findings are in agreement with previous works showing that RFDs are helpful in assessing the health of benthic communities (Sanvicente-Anorve et al., 2002; Bouchet et al., 2007). Furthermore, this confirms that benthic foraminifera are good indicators of organic matter pollution induced by sewage outfalls (Schafer et al., 1991; Mojtahid et al., 2008) and trace metal pollution (Armynot du Châtelet & Debenay 2010; Frontalini & Coccioni 2011).

Conclusions

This study is the first to investigate the effects of MPA on the conservation of benthic foraminifera. The two studied stations (Ser and Res) showed both similarities and differences among the foraminiferal assemblages in terms of species richness, diversity, and composition during the seasons. Foraminifera bloomed at both stations during spring, corresponding to the peak of chlorophyll a recorded in the water column. The taxonomic differences and above all, the diverse density distribution of the major species in two stations were partially driven by the geochemistry of the sediment as well as by the difference in the oxygen concentration of the bottom waters.

Stressed conditions occurred near the sewage outfall (Ser station) characterised by coarse sediment texture, high contents of TOC and Zn in the bioavailable fraction, which were a limiting factor for the studied foraminiferal communities. A. tepida, Bolivina spp. and Bulimina spp., which characterised this station, could be considered the most tolerant taxa of the studied assemblage, thus representing good indicators of heavy metal pollution, in agreement with previous studies from the literature. Conversely, Elphidium spp., H. depressula, N. iridea, Quiqueloculina spp., R. nana and Textularia spp., could be considered less tolerant species, as they benefitted from the less stressful conditions (lower TOC and Zn contents) recorded at Res station. Such benefits occurred despite slightly higher concentrations of some PTEs, especially Pb, was recorded in this station with respect to Ser station. However, these PTE values were always within the limits of the unpolluted environments.

As a result, the reported EcoQs near the Ser sewage outfall were usually worse than those recorded in the marine protected area of Miramare (Res station). This suggests that the marine reserve would be effective at preserving benthic foraminiferal communities. Furthermore, foraminiferal assemblages were found to be quite resilient over an annual cycle, being able to recover from a seasonal unbalanced state to a mature one. We therefore suggest that EcoQ assessment using the foraminiferal method should be applied at the beginning of the spring season, before recruitment starts, or right after the summer when assemblages reach equilibrium after an intense period of recruitment. This study confirms that benthic foraminifera are good bioindicators and encourages further need for testing and assessment in other environments.

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