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Impact of fish farming on foraminiferal community, Drvenik Veliki Island, Adriatic Sea, Croatia

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ABSTRACT

This study examined the impact of fish farming on foraminiferal communities in the Adriatic coastal zone. Samples were taken directly beneath the farm, near the edge of the farm, and at a reference station away from the farm. The foraminiferal community near the farm is characterized by *Epistominella exigua*, *Globocassidulina subglobosa*, *Haynesina germanica* and the genera *Elphidium*, *Bulimina* and *Brizalina*. These foraminiferal species are less abundant seaward. *Asterigerinata mamilla*, *Neoconorbina terquemi* and genus *Cibicides* are almost absent below the cages. Total phosphorus (TP) and total nitrogen (TN) in the sediments decrease with distance from the cages. The abundances of *E. exigua*, *G. subglobosa*, *H. germanica* and the genera *Elphidium*, *Bulimina* and *Brizalina* are correlated with TP and TN, indicating their dependence on nutrient input. The absence of *A. mamilla*, *N. terquemi* and the genus *Cibicides* below the cages is a due to a degraded *Posidonia* community. According to our study, foraminiferal community composition can be used as indicator of organic enrichment caused by fish farm activities.

1. Introduction

Foraminifera are small, unicellular marine organisms that have been increasingly used as bioindicators in pollution studies over the last 30–40 years. Foraminifera are useful for this type of study because of their wide distribution in marine environments, great taxonomic diversity, relatively simple identification, and high sensitivity to environmental variations. Foraminifera generally form calcareous tests that are preserved in sediment. Besides being calcareous, foraminiferal tests can be composed of particles cemented onto a layer of tectin. These particles (e.g. sand grains, the tests of other microorganisms, or distinctive sedimentary particles such as oolites) can be loosely bound in place or permanently cemented within a mineral matrix (Haq and Boersma, 1998). They are small (0.02 mm to 2 mm) and highly abundant in small samples (up to a few thousands tests per cm^3), which provides a strong statistical foundation for studies that utilize these organisms. Foraminifera have short reproductive cycles (Murray, 1991a), which make them suitable for registering environmental changes over short periods of time. These changes can be visible in the test itself (in its morphology and/or chemical composition) or in community changes such as the disappearance or presence of species, changes in species abundance and species richness (Debenay et al., 2000).

The number of papers dealing with anthropogenically induced pollution's effects on foraminiferal assemblages has increased enormously from the late 1950s (Zalesny, 1959; Resig, 1960; Watkins, 1961). Despite the large number of studies in this area, there are few studies on foraminiferal community changes caused by fish farming (Schafer et al., 1995; Scott et al., 1995; Angel et al., 2000; La Rosa et al., 2001; Bouchet et al., 2007; Sutherland et al., 2007).

Fish farms are locations with enhanced organic matter input. Their effects have been observed using parameters such as phosphorus and nitrogen concentrations in sediment (Hargrave et al., 1997; Kalantzi and Karakassis, 2006; Aguado-Giménez et al., 2007; Apostolaki et al., 2007; Holmer et al., 2007). Nitrogen concentration can be partially reduced due to denitrification and anaerobic ammonium oxidation (Risgaard-Petersen et al., 2003), while phosphorus concentration remains stable due to adsorption, dissolution or precipitation processes (Benitez-Nelson, 2000; Paytan et al., 2003). There have been only a few studies of phosphorus and nitrogen concentrations in sediments at fish farms in the Adriatic Sea (Matijević et al., 2004, 2006, 2008).

The aim of this study was to describe the impacts of fish farming on foraminiferal communities (composition, dominance and abundance) and sediments in the Central Dalmatian offshore area. In order to do this, we documented faunal changes in sediments in relation to their distances from the fish cages, and analyzed them

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using the chemical characteristics of the sediments. Additionally, we described changes in faunal succession in sediment cores. In this paper, we report on the suitability of using benthic foraminifera as bioindicators of changes in the environment caused by fish farming activities.

2. Study area

The fish farm used for this study is located in the Mala Luka Bay (16°07′30″E, 43°26′15″N) on Drvenik Veliki Island, an island in the coastal area of the Adriatic Sea (Fig. 1). The Drvenik Veliki maritime zone consists of open sea and inland waters with an open sea trophic level (oligotrophic area). Although situated relatively close to the coast (1.5 nautical miles), the Drvenik Veliki maritime zone is characterized by relatively high water depths (up to 100 m).

Mala Luka Bay is situated on the NW side of Drvenik Veliki Island and is entirely protected from the strongest winds, which blow from the SE, and the second strongest winds, which blow from the NE. The area of the bay is 180,000 m^2, with a maximum depth of 40 m at the entry to the bay. The sea currents are weak, flowing at 4.18 cm/s at a 6 m water depth (Ecoina, 1999). The diurnal tide amplitude is around 85 cm, and maximum tide fluctuations do not exceed 150 cm (Ecoina, 1999).

The fish farm was set up in 1998. It provides supplemental nutrition for bluefin tuna (*Thunnus thynnus*) caught from wild Adriatic populations. The maximum capacity of the farm is 200 tons/year. The tuna are fed 2000 tons of oily fish every year. The farm is made up of three floating cages measuring 50 m in diameter with an effective depth of 17 m, enclosing 5890 m^2 of sea surface and 100,000 m^3 in volume. Fish excretion totals approximately 600,000 kg/year (Ecoina, 1999).

Three stations were established according to the monitoring program developed by the Croatian Ministry of Environmental Protection, Physical planning and Construction and in line with an impact study of Drvenik Island fish farms carried out by the Institute of Oceanography and Fisheries and the Hydrographic Institute of the Republic of Croatia. The first station (DT1) was located directly beneath the cages, while the second (DT2) was situated at the edge of the farm towards the opening of the bay. The reference station (DTR) was located outside the bay in an area minimally affected by the fish farm (16°06′46″E, 43°26′40″N, Fig. 1). The water depth beneath the cages was 44.9 m, increasing to 55.7 m around the reference station. A mediolittoral survey of the area under the cages found a degraded community of endemic Mediterranean seagrass *Posidonia* (Petricioli et al., 2006).

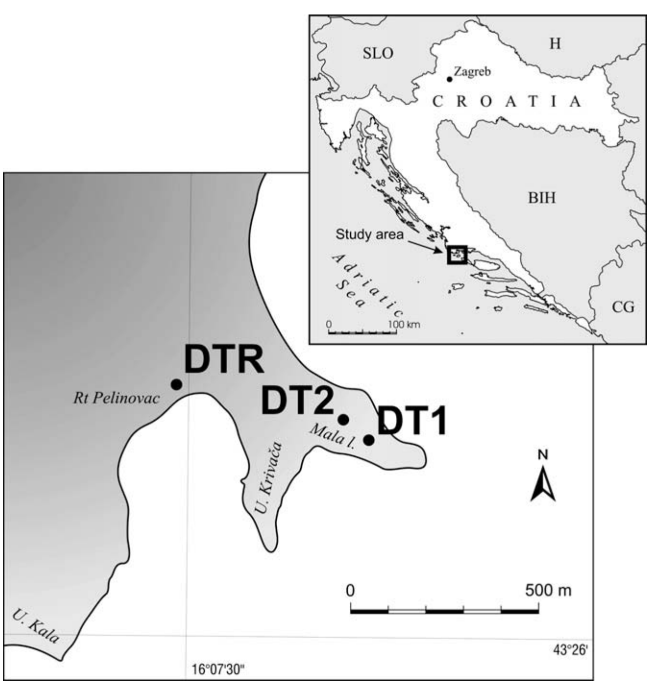

Fig. 1. Study area and locations of investigated stations (DT1, DT2 and DTR).

3. Materials and methods

3.1. Sediment sampling

The three stations were sampled in January 2008. At each sampling station, scuba divers collected samples with short corers (maximum penetration depth 60 cm, 90 mm in diameter). The first ten centimeters of each core were analyzed. The core samples provided material for chemical (total phosphorus and total nitrogen concentrations measurements) and granulometrical analyses, as well as for the foraminiferal studies.

After collection, each sediment core was vertically sectioned into 1 cm thick subsamples. Each subsample was divided on two equal parts. One part of each subsample was used for foraminiferal analyses. Granulometrical analysis, total phosphorus concentrations and total nitrogen concentrations were measured from the other part of each subsample.

3.2. Sedimentological analyses

For granulometrical analysis, each sediment sample was treated with 30% hydrogen peroxide to remove organic matter prior to the grain size analysis. The grain size of the sediment samples was analyzed by wet sieving using ASTM standard stainless steel sieves. The sediments were classified according to their gravel-sand-mud ratio (Folk, 1954). Silt/clay ratio was not analyzed because we supposed it did not impact the foraminiferal community composition. Our consideration was substantiated by a lack of papers reporting the impact of the silt/clay ratio on faunal composition or community structure.

3.3. Foraminiferal analyses

Living and dead foraminifera were differentiated using the Rose Bengal technique (Murray, 1991a). Rose Bengal was dissolved in distilled water (1 g into 1 l). Prior to staining, the samples were washed on 63 μm sieve. Residues were placed into the bowls and Rose Bengal solution was added. After 24 h, the samples were washed in the 63 μm sieve to remove surplus stain. The samples were then dried at 50 °C (Murray, 1991a). Stained individuals (protoplasm colored in bright red) were marked as "living" specimens, while unstained individuals were marked as "dead." At least 300 specimens were picked from each stained sample. Individuals were identified under a binocular magnifier (Nikon) following the generic classification of Loeblich and Tappan (1987) and Cimerman and Langer (1991). Qualitative (genera and species determination) and quantitative (number of "living" and "dead" specimens, total assemblage, absolute and relative abundance of species, dominant species) analyses of foraminiferal assemblages were performed.

An estimation of the species diversity was performed using the Shannon–Wiener index H, equitability index J, and Fisher α index (Buzas, 1979). Diversity indices were computed using PAST PROGRAM (http://folk.uio.no/ohammer/past). Because of the very small number of stained individuals, analyses were conducted on total assemblages (dead and living individuals). Species diversity and abundance data were compared with the results of chemical and granulometrical analyses.

3.4. Geochemical analyses

The quantitative determination of total nitrogen concentrations and total phosphorus concentrations in sediments was performed in all subsamples according to the standard methods given by the Croatian Standards Institute. A manual spectrometric method for detecting ammonium in water (ISO 7150-1:1984) was carried out for measuring total nitrogen concentrations. Total phosphorus concentrations were measured according to spectrophotometrical method for measuring total phosphorus concentrations in water (HRN ISO 6878:2001).

Prior to the analyses, each sediment subsample (~0.5 g) was digested with 5 ml of distilled water, 5 ml of digestion mixture, 2 ml of H_2SO_4, and 1 ml of HCl. The sample was subsequently heated. Afterwards, each sub sample was digested again with 5 ml of digestion mixture and 1 ml of 30% H_2O_2. Finally, the solution was treated with ~1 ml of phenolphthalein and ~1 ml 30% NaOH until it became a pale pink color.

3.5. Statistical analyses

A principal component analysis (PCA) was carried out to help interpret the large volume of data. PCA is the projection of a multivariate dataset onto a few dimensions in a way that preserves as much variance as possible (Krebs, 1998). Prior to PCA analysis, an additive logarithmic transformation $\log(x+1)$ was performed on standardized data (relative abundances of foraminiferal species) in order to reduce the importance of extreme values, to reduce the contributions of common species, to enhance the contributions of the rare species and to normalize the data (Krebs, 1998).

Because PCA is a procedure for finding hypothetical components that account for as much of the variance in multidimensional data as possible (Krebs, 1998) and does provide information about the variances, we correlated three different parameters (TN, TP and sediment type) with numerical values (values describing the position of each point – sub sample) of component 1 using linear modeling.

4. Results

4.1. Sedimentological analyses

The mud fraction (<63 μm) was very high at the station under the cages (DT 1) and at the station at the edge of the farm (DT 2). Throughout the cores from both stations, the mud fraction comprised 92–98% of the sediment. Because of their gravel–sand–mud ratio (Folk, 1954), sediments in DT1 and DT2 were classified as mud. Sediments at the reference station were classified as (slightly) gravely muddy sand according to the same classification scheme.

4.2. Foraminiferal analyses

The results for the foraminiferal analyses refer to the total ("living" and "dead") assemblage. "Living" specimens were scarce in sub samples (comprising ~10 specimens per sub sample) and therefore, unsuitable for statistical analysis or community interpretation.

Foraminiferal assemblages contained predominantly benthic species. Dominant (>4%) and accessory species were determined and counted at all stations and in all sub samples (Appendices A–F). In Table 1, percentages of suborders Textulariina, Miliolina and Rotaliina are presented.

A total of 72 species belonging to 44 genera were indentified at the station under the cages (DT 1). The first centimeter of sediment contained a high percentage of foraminifera belonging to suborder Rotaliina (97%), represented by *Epistominella exigua*, *Brizalina* sp., *Globocassidulina subglobosa*, and *Haynesina germanica*, while *Bulimina marginata*, *Neoconorbina terquemi*, *Elphidium* sp. and *Elphidium translucens* were subdominant (Appendices A and B). Downcore sediment samples show slight changes in foraminiferal composition. The majority of species were of the suborder Rotaliina, varying from 91% to 99% of the total number of species throughout the core. In the DT1 core, twelve species were of the suborder Miliolina, while specimens from the suborder Textulariina were rare. *Bulimina aculeata* was locally abundant (7.17% at 1–2 cm, 6.65% at 5–6 cm), while *E. translucens* was more common at 1–2 cm (6.49%) and at 4–5 cm (7.4%). *H. germanica* varied throughout the core, decreasing from the surface sediment (8.38%) to 4–5 cm (4.73%), and slightly increasing to 6.87% of the total assemblage farther down. There was a slight reduction in the number of *G. subglobosa* and *Brizalina* sp. downcore.

Table 1
Percentage of suborders Textulariina, Milioliina, Rotaliina.

Sediment section (cm)	Textulariina (%)	Milioliina (%)	Rotaliina (%)
Station DT1			
0–1	1.19	1.81	97
1–2	1.43	2.50	96.05
2–3	2.01	2.41	95.56
3–4	5.13	3.32	91.54
4–5	2.36	5.91	91.71
5–6	3.10	3.76	93.12
6–7	0	0.38	99.61
Station DT2			
0–1	0	4.18	95.81
1–2	2.55	1.98	95.45
2–3	0.28	2.54	97.16
3–4	3.89	2.09	94.01
4–5	0	3.24	96.75
5–6	0.30	3.31	96.38
6–7	1.12	0.56	98.30
7–8	1.20	10.13	94.29
8–9	1.17	2.81	96.01
9–10	1.42	3.57	95
Station DT R			
0–1	3.45	6.91	89.62
1–2	0.38	5.76	93.84
2–3	7.50	5.53	86.95
3–4	1.72	6.20	92.06
4–5	1.03	5.66	93.20
5–6	1.66	4.31	94.01
6–7	2.72	4.66	92.60
7–8	2.33	4.28	93.38
8–9	4.68	4.68	90.62

Table 2
Number of species, total number of specimens and diversity indices in each sample from station DT1.

	Sediment section (cm)						
	0–1	1–2	2–3	3–4	4–5	5–6	6–7
Taxa_S	38	42	38	46	43	45	26
Individuals	334	279	248	331	338	451	263
Shannon_H	3.08	3.11	3.10	3.31	3.24	3.24	2.53
Equitability_J	0.84	0.83	0.85	0.86	0.86	0.85	0.77
Fisher_alpha	11.04	13.73	12.52	14.51	13.07	12.44	7.16

Planktonic species made up 17% of the total assemblage in the surface sediment (0–1 cm) and the percentage varied throughout the core with maximum of 30% at 6–7 cm of the core.

Shannon–Wiener and equitability indices varied slightly throughout the core. The Shannon index ranged from 2.53 to 3.31 and equitability ranged from 0.77 to 0.86. The Fisher index was larger than five in all sub samples of the core, with a maximum at 3–4 cm (14.5) and a minimum at 6–7 cm (7.16). Altogether, bioindices implied normal marine conditions (Table 2).

At the station situated at the edge of the farm (DT2), a total of 50 genera and 87 species were identified and counted. The majority of foraminiferal species at station DT2 belonged to the suborder Rotaliina (74 species), with its percentage varying from 94% to 98% of total species throughout the core. In the DT2 core, the suborder Miliolina was represented with 11 species, comprising 4.2% of the total assemblage in surface sediment, with a slight decrease in percentage downcore. Species of the suborder Textulariina were absent from the surface sediment to rare downcore. The assemblage in the surface sediment (0–1 cm) at DT2 was dominated by *E. exigua* and *E. translucens.* Downcore sediments showed changes in foraminiferal composition. *G. subglobosa*, *Asterigerinata mamilla*, *Elphidium* sp. and *Elphidium gerthi* were accessory species in the surface sediment and showed an increase downcore (Appendices C and D). *H. germanica* was absent from the surface sample and appeared downcore. *Brizalina* sp. attained locally high values (6.5% at 2–3 cm and at 6–7 cm).

Planktonic species comprised 30% of the total assemblage in the surface sediment (0–1 cm) but the percentage decreased with core depth, hitting a minimum of 17% at 9–10 cm.

Shannon–Wiener and equitability indices varied slightly throughout the core. The Shannon index ranged from 2.74 to 3.12 and equitability ranged from 0.73 to 0.83. The Fisher index was larger than five in all sub samples of the core, reaching a maximum at 4–5 cm (15.45) and minimum at 9–10 cm (9.31). These bioindices pointed to normal marine conditions (Table 3).

At the reference station (DTR), a total of 74 species belonging to 45 genera were indentified. The majority of foraminiferal species at station DTR belonged to the suborder Rotaliina (56 species), with percentages varying from 86% to 94% of total species. Fifteen species belonging to suborder Miliolina made up 4–6% of the total assemblages. Suborder Textulariina was only represented by three species making up 3% of the total assemblage in the surface sediment and reaching a maximum of 7.5% at 2–3 cm. The foraminiferal assemblage in the surface sediment at station DTR was dominated by *Quinqueloculina* sp., *N. terquemi*, *Rosalina* sp., *Cibicides refulgens*, *A. mamilla*, *H. germanica* and *Asterigerinata* sp. (Appendices E and F). There was an evident reduction in *Quinqueloculina* sp. and *C. refulgens* downcore. *Cibicides* sp. and *Cibicides advenum* were rare or absent in the surface sediment, but their numbers increased downcore. *Ammonia parkinsoniana* and *Textularia bocki* attained locally high values (for *A. parkinsoniana*: 6.15% at 1–2 cm, for *T. bocki*: 5.14% at 2–3 cm). There was a reduction in the number of *Quinqueloculina* sp. downcore.

Planktonic species comprised 16% of the total assemblage in the surface sediment. Its proportion varied through the core with maximum of 27% at 5–6 cm of the core.

Diversity indices varied throughout the core. The Shannon index ranged from 2.83 to 3.18 and equitability ranged from 0.79 to 0.88. The Fisher index was larger than five in all sub samples, with a maximum at 0–1 cm (14.31) and a minimum at 1–2 cm (8.36). Bioindices implied normal marine conditions (Table 4).

4.3. Geochemical analyses

Total nitrogen concentrations (TN) were determined in all sub samples. In surface sediments, TN was the highest at DT1 (649.2 mg/kg) and decreased gradually moving towards the reference station. Farther down in the core at the station DT1, total nitrogen concentration varied with anomaly at 5–6 cm (2833.4 mgN/kg). At the station DT2, TN decreased downcore, with a minimum at 5–6 cm. At the station DTR, TN values also decreased downcore, with a minimum at 7–8 cm. There was a TN peak at 4–5 cm (611.9 mg/kg).

Total phosphorus concentrations (TP) were also determined in all sub samples. In surface sediments, TP decreased gradually from the cages (1112 mg/kg) to the reference station. At the station DT1, TP values varied downcore, with anomaly at 5–6 cm (4806.1 mgP/kg). At the station DT2, TP varied downcore, with anomaly at 4–5 cm (1222 mgP/kg). At the station DTR, TP values decreased downcore, with a minimum at 6–7 cm. The results of geochemical analyses are reported in Fig. 2.

Table 3
Number of species, total number of specimens and diversity indices in each sample from station DT2.

	Sediment section (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Taxa_S	40	40	42	39	47	42	38	42	44	32
Individuals	358	352	353	334	308	332	355	333	427	280
Shannon_H	2.81	2.93	2.74	3.06	2.95	2.76	2.80	3.12	2.96	2.76
Equitability_J	0.76	0.79	0.73	0.83	0.76	0.74	0.77	0.83	0.78	0.79
Fisher_alpha	11.54	11.62	12.42	11.45	15.45	12.73	10.78	12.72	12.31	9.31

Table 4
Number of species, total number of specimens and diversity indices in each sample from station DTR.

	Sediment section (cm)								
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Taxa_S	45	29	38	34	35	39	32	35	39
Individuals	318	260	253	290	265	301	257	257	256
Shannon_H	3.18	2.99	3.02	2.86	2.84	3	2.83	2.92	3.16
Equitability_J	0.83	0.88	0.83	0.81	0.79	0.81	0.81	0.82	0.86
Fisher_alpha	14.31	8.36	12.41	9.99	10.8	11.94	9.63	10.94	12.81

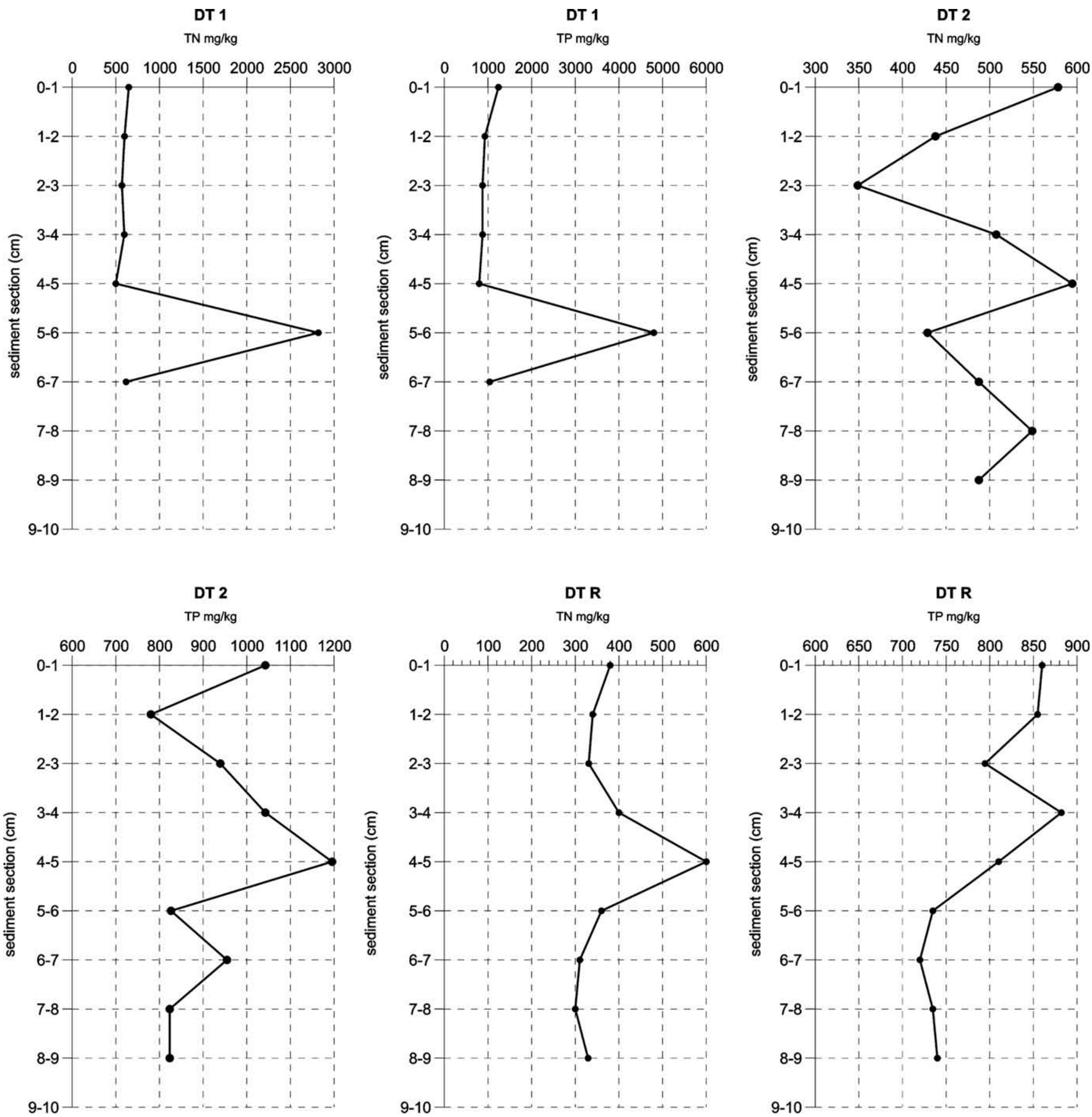

Fig. 2. Vertical profile of TN and TP in sediments under the cage (DT1), at the cage margin (DT2) and at the reference station (DTR).

4.4. Statistical analyses

PCA analysis was used to help visualize the data (relative abundance of the foraminiferal species). Two principal components (factors) were identified, together explaining 46.12% of the data variance. (35.07% from factor 1 and 11.05% from factor 2). Results separated the stations into two distinct groups (Fig. 3). The first group was composed of sediment sections from fish farm localities (DT1, DT2) and was located within a narrow range of positive values for component 1 (0–1). The second group consisted of sediment sections from reference station (DTR) and was characterized by negative values of component 1.

Three different parameters were correlated with numerical values of component 1. Total nitrogen concentrations (Fig. 4) and total phosphorus concentrations (Fig. 5) indicated a strong linear correlation with component 1. Linear modeling revealed no evident correlation between sediment type and component 1 (Fig. 6).

5. Discussion

This study analyzed the spatial and vertical relationships between foraminiferal community and organic enrichment indicators (TN, TP), with the goal of using foraminifera as bioindicators.

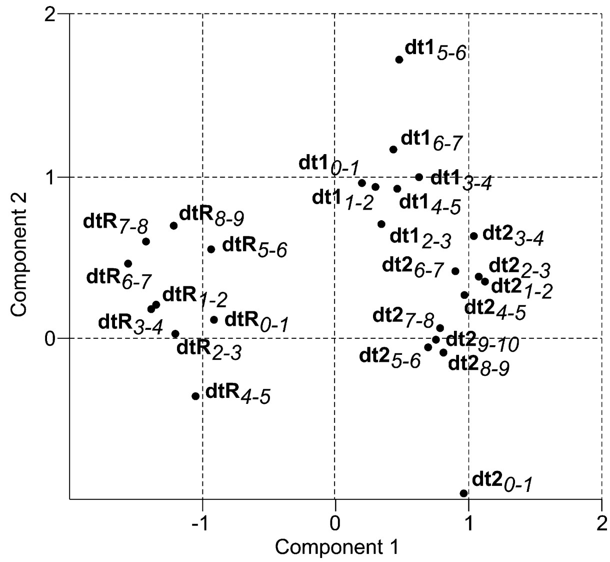

Fig. 3. PCA ordination diagram of sediment sections from stations DT1, DT2 and DTR.

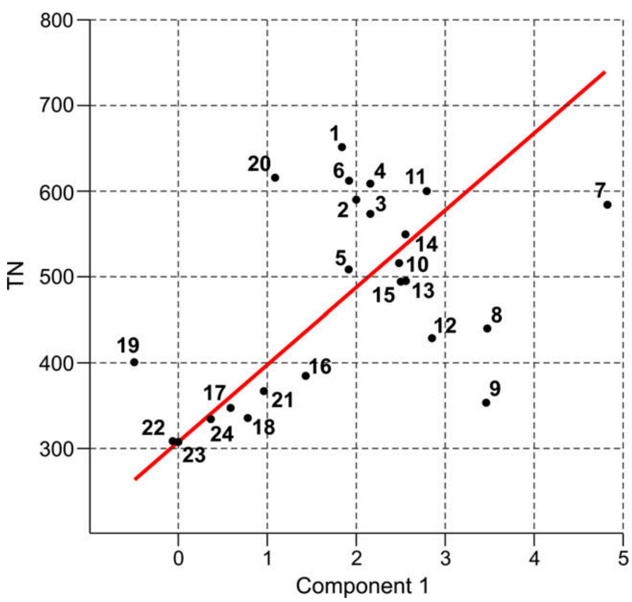

Fig. 4. Correlation of total nitrogen concentrations (TN) with numerical values of PCA component 1 (1. dt1 0-1; 2. dt1 1-2; 3. dt1 2-3; 4. dt1 3-4; 5. dt1 4-5; 6. dt1 6-7; 7. dt2 0-1; 8. dt2 1-2; 9. dt2 2-3; 10. dt2 3-4; 11. dt2 4-5; 12. dt2 5-6; 13. dt2 6-7; 14. dt2 7-8; 15. dt2 8-9; 16. dtR 0-1; 17. dtR 1-2; 18. dtR 2-3; 19. dtR 3-4; 20. dtR 4-5; 21. dtR 5-6; 22. dtR 6-7; 23. dtR 7-8; 24. dtR 8-9).

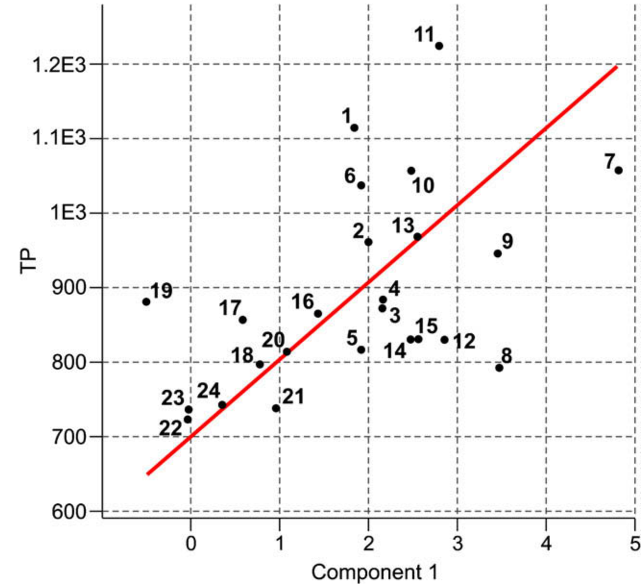

Fig. 5. Correlation of total phosphorus concentrations (TP) with numerical values of PCA component 1 (1. dt1 0-1; 2. dt1 1-2; 3. dt1 2-3; 4. dt1 3-4; 5. dt1 4-5; 6. dt1 6-7; 7. dt2 0-1; 8. dt2 1-2; 9. dt2 2-3; 10. dt2 3-4; 11. dt2 4-5; 12. dt2 5-6; 13. dt2 6-7; 14. dt2 7-8; 15. dt2 8-9; 16. dtR 0-1; 17. dtR 1-2; 18. dtR 2-3; 19. dtR 3-4; 20. dtR 4-5; 21. dtR 5-6; 22. dtR 6-7; 23. dtR 7-8; 24. dtR 8-9).

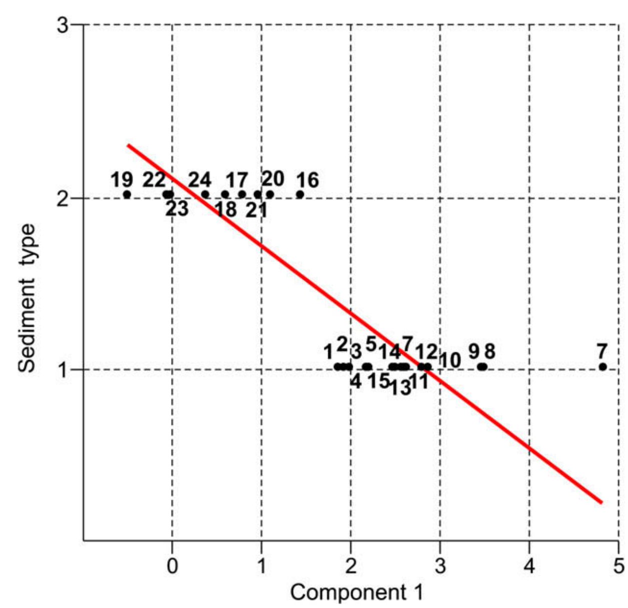

Fig. 6. Correlation of different sediment type with numerical values of PCA component 1 (1. dt1 0-1; 2. dt1 1-2; 3. dt1 2-3; 4. dt1 3-4; 5. dt1 4-5; 6. dt1 6-7; 7. dt2 0-1; 8. dt2 1-2; 9. dt2 2-3; 10. dt2 3-4; 11. dt2 4-5; 12. dt2 5-6; 13. dt2 6-7; 14. dt2 7-8; 15. dt2 8-9; 16. dtR 0-1; 17. dtR 1-2; 18. dtR 2-3; 19. dtR 3-4; 20. dtR 4-5; 21. dtR 5-6; 22. dtR 6-7; 23. dtR 7-8; 24. dtR 8-9).

At Drvenik Island, TP and TN values were the highest at DT1 and decreased gradually as a function of distance from the cages. Low values at the reference station (DTR) highlight the localized influence of the farm. Total phosphorus values in sediments from the fish farm were higher than concentrations in sediments from the open sea and coastal water of the central and South Adriatic Sea (Barić et al., 2002). TP values determined at Drvenik Veliki fish farm were higher than those recorded from other fish farming areas (Matijević et al., 2006, 2008; Apostolaki, 2007).

Benthic foraminiferal assemblages showed spatial changes as a function of the distance from the cages and seem to be correlated with the measured geochemical characteristics of the sediment. PCA analysis provided support for the argument that fish farms have an impact on the environment, grouping fish farm stations (DT1, DT2 sub samples) and separating them from the reference station (DTR) sub samples (Fig. 2). Linear modeling showing strong a correlation for TN (Fig. 4) and TP (Fig. 5) with component 1 confirmed that TN and TP were factors controlling the grouping of sub samples in PCA, thereby influencing benthic foraminiferal assemblages at the Drvenik Veliki fish farm. Sediment type differed between the stations and could be one of the factors influencing the distribution of foraminiferal assemblages. Linear modeling (Fig. 6) revealed no evident correlation between sediment type and component 1 (Fig. 6), so we can conclude that sediment type is not factor controlling the distribution of benthic foraminiferal assemblages at the Drvenik Veliki fish farm.

The benthic epifaunal species *E. exigua* (Murray, 1991a) had the highest abundance (~18%) near the edge of the farm (DT2), high abundance (~10%) under the cages (DT1) and very low abundance (~4%) at the reference station, which indicates that *E. exigua* was the most abundant species in conditions with constant organic input. The abundance data are consistent with previous studies reporting that the species prefers environments enriched with organic matter (Sun et al., 2006; Eberwein and Mackensen, 2006).

The abundance of *G. subglobosa* (Murray, 1991a) showed the same distributional pattern as *E. exigua*. *G. subglobosa* had a higher abundance in the sediments under the cages, while the species became less frequent towards the reference station. These findings reveal that *G. subglobosa* is tolerant to organic enrichment in sediments, and can be used as indicator of fish farming. The results for *G. subglobosa* are in accordance with previous studies reporting that *G. subglobosa* occurs in regimes with high food input (Sun et al., 2006; Eberwein and Mackensen, 2006; Panieri and Sen Gupta, 2008).

The genus Bulimina (Murray, 1991a) including species *B. aculeata*, *Bulimina elongata*, *B. marginata* and genus *Brizalina* (Murray, 1991a) including species *Brizalina dilitata*, *Brizalina spathulata*, *Brizalina striatula*, *Brizalina* sp. were dominant in samples under the cages and at the edge of the farm (with higher abundance under the cages) and were present with very low abundance at the reference station, reflecting their dependence on a rather continuous abundance of organic matter. Species belonging to genus *Elphidium* reveal the same trend in distribution as those in the genera *Bulimina* and *Brizalina*. Murray (1991a) found that *Elphidium* can occupy more than one habitat, changing from epifaunal to infaunal, suggesting that keeled individuals have an epifaunal mode of life, while non-keeled individuals prefer an infaunal mode. Our study found that the appearance of *Elphidium*, *Bulimina* and *Brizalina* is positively correlated with food-enriched sediments. Such findings are in accordance with previous studies (Donnici and Serandrei Barbero, 2002; Hayward et al., 2004; Eberwein and Mackensen, 2006; De Nooijer et al., 2008; Mojtahid et al., 2008).

The highest abundance for *H. germanica* (Murray, 1991a) was under the cages (DT1). According to the geochemical analyses, it was the area experiencing the strongest impact from the fish farms. Thus, as in previous studies (Debenay et al., 2001; Armynot du Châtelet et al., 2004; Romano et al., 2008), *H. germanica* can be considered a species tolerant to high abundances of organic matter.

On the other end of the spectrum, trochospiral and epifaunal species *A. mamilla*, *Rosalina* sp. and *N. terquemi* (Murray, 1991a) were dominant at the reference station and were present with very low abundances in the samples under the cages and at the edge of the farm. Most trochospiral and epifaunal species are considered opportunistic (Jorissen, 1999) but not are restricted to a eutrophic regime. Due to the fact that *A. mamilla*, *N. terquemi* and *Rosalina globularis* are associated with vegetated sea-bottoms (Panieri et al., 2005; Frezza and Carboni, 2009), their absence at stations DT1 and DT2 might be the consequence of the degraded vegetation cover in the fish farm area (Petricioli et al., 2006).

Representatives of the epiphyte genus *Cibicides* (Langer, 1993): *C. advenum* and *C. refulgens* were only dominant at the reference station. They were absent from stations DT1 to DT2 possibly due to the degraded community of seagrass *Posidonia* (Petricioli et al., 2006). *Cibicides* species have a relatively high oxygen requirement (Sen Gupta et al., 2007), which means that even the slightest oxygen depletion caused by enhanced nutrient input could be the explanation for their absence from sediments under the fish farm. On the other hand Szarek et al. (2006), used *Cibicides* species as indicators of strong bottom-water currents. Occurrence of *Cibicides* species may be the result of different hydrodynamic conditions indicated by the difference in sediment type (gravely muddy sand) at the station. It is not easy to determine which parameter is limiting for the *Cibicides* species distribution considering that for each species, in variable environments, different factors may be limiting (Murray, 1991b).

In addition to the spatial changes of foraminiferal composition, we analyzed the difference in the foraminiferal assemblage from the opening of the fish farm in 1998 (sediments at the bottom of the core) to the present (surface sediments).

At DT1 station, *G. subglobosa* and *H. germanica* had the highest abundance in the surface layer and decreased with core depth. Knowing that *G. subglobosa* occurs in regimes with high food input (Sun et al., 2006; Eberwein and Mackensen, 2006; Panieri and Sen Gupta, 2008) and that *H. germanica* is tolerant to enhanced nutrient input (Debenay et al., 2001; Armynot du Châtelet et al., 2004; Romano et al., 2008), the appearance of these species in the surface layer is presumably the consequence of enhanced nutrient input attributable to fish farm activities. At the same station in the surface layer, the abundance of *A. mamilla* was very scarce and increased with core depth. The disappearance of *A. mamilla* in the surface layer probably coincides with the degradation of the community of seagrass *Posidonia* (Petricioli et al., 2006). Knowing that *A. mamilla* is associated with vegetated environments (Frezza and Carboni, 2009; Panieri et al., 2005), its disappearance is probably a consequence of the above mentioned degradation. The same trend in abundances of *A. mamilla* was observed at the edge of the farm (DT2), presumably as a consequence of the same vegetation degradation.

In this paper, we analyzed the impacts of fish farming on foraminiferal community composition and diversity at each station. We also compared the faunal characteristics between the stations and at each station through time. Results from this study demonstrate no notable difference in diversity indices between the stations. The Shannon–Wiener index H and the equitability index J showed a similarity in species abundance (high biodiversity) and the Fisher α index indicated normal marine conditions. The above findings lead to the conclusion that there is no perceptible correlation between foraminiferal diversity and organic enrichment caused by fish farm activities. We conclude that these faunal parameters are not suitable indicators of the aforementioned environmental conditions. Similar findings have been reported for attempts to use the macrobenthic community as biological indicators of fish farming (Aguado-Giménez et al., 2007). However, the presence or absence of foraminiferal species as well as changes in species abundance can be used as indicators of environmental changes caused by fish farming.

6. Conclusions

This paper attempted to describe the impact of fish farming on foraminiferal communities in the Central Dalmatian offshore area. Surveying the foraminiferal community (assemblage composition and diversity indices) together with measurements of the granulometrical and geochemical properties of the sediment, we came a few basic conclusions:

– Benthic foraminiferal assemblages showed spatial changes as a function of the distance from fish cages, presumably correlated with the geochemical characteristics of the sediment.
– *E. exigua*, *G. subglobosa* and *H. germanica*, as well as the genera *Elphidium*, *Bulimina* and *Brizalina* are tolerant to enhanced nutrient input, and can be used as indicators of fish farm activities.
– Trochospiral and epifaunal species *A. mamilla*, *Rosalina* sp. and *N. terquemi* were absent from the fish farm stations as a consequence of degraded vegetation cover in the monitored area.
– Epiphyte species *C. advenum* and *C. refulgens* were absent from the fish farm stations, probably due to the degraded community of the seagrass *Posidonia*.
– At the fish farm stations, there has been an increase in the abundance of *G. subglobosa* and *H. germanica* since the establishment of the farm.
– Foraminiferal species diversity did not show any changes caused by the fish farming and is not a suitable indicator of organic enrichment caused by fish farming,
– Community composition (presence or absence of species, changes in species abundance) can be used as an indicator of organic enrichment caused by fish farm activities.

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Appendix A. Relative abundance of foraminiferal species in each sample from station DT1

Species	Sediment section (cm)						
	0–1	1–2	2–3	3–4	4–5	5–6	6–7
Textularia agglutinans	0.60	1.43	2.02	3.32	0.89	2.22	0.00
Textularia bocki	0.60	0.00	0.00	1.81	1.48	0.89	0.00
Adelosina mediterranensis	0.00	0.00	0.00	0.30	0.30	0.00	0.00
Siphonaperta aspera	0.00	0.36	0.00	0.00	0.00	0.00	0.00
Siphonaperta hauerina	0.00	0.00	0.00	0.00	0.59	0.00	0.00
Siphonaperta irregularis	0.00	0.00	0.00	0.00	0.30	0.00	0.00
Cycloforina sp.	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Quniqueloculina sp.	0.90	0.00	1.61	1.21	3.25	2.88	0.00
Quinqueloculina laevigata	0.00	0.00	0.40	1.51	0.89	0.00	0.00
Quinqueloculina seminula	0.00	1.08	0.00	0.30	0.30	0.22	0.00
Pseudotriloculina laevigata	0.00	0.36	0.00	0.00	0.00	0.00	0.00
Pyrgo sp.	0.30	0.00	0.00	0.00	0.00	0.00	0.00
Triloculina tricarinata	0.00	0.72	0.00	0.00	0.00	0.00	0.00
Sigmoilinita sp.	0.60	0.00	0.40	0.00	0.30	0.44	0.38
Lagena sp.	0.00	0.36	0.00	0.30	0.00	0.00	0.00
Lagena striata	0.00	0.36	0.00	0.00	0.00	0.22	0.00
Fissurina sp.	2.10	3.23	2.82	2.11	1.18	2.88	1.90
Palliolatella orbignyana	0.30	0.00	0.00	0.00	0.00	0.00	0.00
Epistominella exigua	9.28	11.47	14.92	15.11	13.02	6.43	14.83
Neogloboquadrina dutertrei	0.30	0.00	1.21	0.00	0.00	0.00	0.00
Globigerina bulloides	0.30	0.36	0.81	1.21	0.59	1.33	0.76
Globigerina calida	1.80	0.72	1.21	0.60	1.78	0.89	1.14
Globigerinoides ruber	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Globorotalia sp.	0.30	0.00	0.00	0.00	0.00	0.00	0.00
Orbulina universa	16.47	17.92	15.32	10.27	10.36	12.64	30.80
Hastigerina pelagica	0.00	0.00	0.81	0.30	0.00	0.00	0.00
Bolivina sp.	0.00	1.79	0.40	0.00	1.18	0.00	0.00
Bolivina pseudoplicata	0.00	0.36	2.02	2.42	0.00	0.00	0.00
Bolivina variabilis	0.00	0.00	0.00	2.11	2.37	2.00	3.04
Brizalina sp.	7.19	3.58	2.42	4.83	5.03	4.43	2.28
Brizalina dilitata	2.10	1.08	0.00	4.53	2.37	2.66	6.46
Brizalina striatula	0.60	0.00	0.00	0.00	0.00	0.00	0.00
Cassidulina laevigata	0.00	0.72	0.40	0.00	0.00	0.00	1.14
Globocassidulina subglobosa	5.69	2.87	6.85	3.32	2.66	2.88	4.18
Rectuvigerina sp.	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Bulimina aculeata	2.99	7.17	4.03	3.02	3.55	6.65	1.90

Appendix B. Relative abundance of foraminiferal species in each sample from station DT1-continued

Species	Sediment section (cm)						
	0–1	1–2	2–3	3–4	4–5	5–6	6–7
Bulimina elongata	0.60	0.36	0.40	0.91	0.00	0.22	0.00
Bulimina marginata	4.19	6.81	5.24	5.44	7.69	5.99	2.28
Uvigerina sp.	0.30	1.08	0.81	0.60	0.89	0.00	0.00
Uvigerina mediterranea	0.90	0.00	1.61	0.60	0.59	0.89	0.00
Reussela spinulosa	0.30	1.08	0.00	0.60	0.89	0.89	0.00
Cassidella	0.90	0.00	0.00	0.00	0.00	0.00	0.00
Gavelinopsis praegeri	0.00	1.08	0.00	0.30	0.00	0.22	0.00
Neoconorbina terquemi	4.19	2.87	1.61	0.91	2.07	1.11	1.14
Rosalina sp.	2.69	2.51	3.63	0.30	0.30	0.00	1.14
Rosalina bradyi	0.30	0.00	0.00	0.00	0.00	1.77	0.00
Rosalina globularis	0.00	0.00	0.40	0.60	0.59	0.89	0.38
Cornobella patelliformis	0.00	0.00	0.00	0.30	0.00	0.00	0.00
Cibicides sp.	1.80	0.72	1.21	0.30	0.30	2.88	3.04
Cibicides advenum	0.90	0.00	0.40	1.81	2.07	0.89	0.00
Cibicides refulgens	0.00	2.51	1.21	0.91	0.30	0.44	0.00
Lobatula lobatula	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Planorbulina mediterranensis	0.00	0.72	0.00	0.00	0.00	0.00	0.00
Asterigerinata sp.	2.10	3.94	3.63	2.42	2.66	2.44	6.08
Asterigerinata mamilla	1.80	0.00	0.40	0.00	0.59	0.00	0.00
Nonionella opima	0.00	0.72	2.82	0.91	0.30	0.44	0.76
Nonionella turgida	0.00	0.00	0.81	1.21	1.18	0.00	0.00
Melonis pompiloides	0.00	0.00	0.00	0.00	0.00	1.11	0.00
Aubignyna planidorso	0.00	1.43	0.00	1.21	0.00	0.00	0.00
Buccella sp.	0.00	1.08	0.00	0.00	0.00	0.00	0.00
Ammonia sp.	2.10	3.94	0.00	0.00	0.00	5.32	0.38
Ammonia beccarii	0.00	0.72	0.81	0.60	0.00	0.00	0.00
Ammonia parkinsoniana	2.99	0.36	1.61	1.21	1.48	1.33	1.14
Ammonia tepida	0.00	0.36	0.00	2.42	2.96	0.22	0.00
Elphidium sp.	4.19	1.43	5.24	2.42	4.44	8.65	3.80
Elphidium crispum	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Elphidium gerthi	4.49	1.08	1.61	3.63	2.07	2.44	2.66
Elphidium macellum	0.60	0.36	0.00	0.30	0.30	0.22	0.38
Elphidium translucens	3.89	6.45	3.23	5.44	7.40	2.66	1.52
Porosononion sp.	0.00	0.00	0.00	0.00	0.00	0.22	0.00
Haynesina germanica	8.38	2.51	4.44	3.63	4.73	6.87	6.46
Haynessina depressula	0.00	0.00	1.21	0.60	0.89	0.00	0.00

Appendix C. Relative abundance of foraminiferal species in each sample from station DT2

Species	Sediment section (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Textularia agglutinans	0.00	1.99	0.28	2.10	0.00	0.30	0.56	0.60	0.70	0.71
Textularia bocki	0.00	0.57	0.00	1.80	0.00	0.00	0.56	0.60	0.47	0.71
Cornuspira foliacea	0.00	0.00	0.00	0.00	0.32	0.30	0.00	0.30	0.00	0.36
Adelosina Mediterranensis	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spiroloculina sp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00
Siphonaperta aspera	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Cycloforina tenuicollis	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Quniqueloculina sp.	1.12	0.00	0.00	0.30	0.32	0.60	0.00	0.60	0.70	2.50
Quinqueloculina dutemplei	0.00	0.28	0.28	0.30	0.00	0.00	0.00	0.30	0.00	0.00
Quinqueloculina laevigata	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Quinqueloculina seminula	0.00	0.00	0.85	0.00	0.97	0.00	0.00	0.00	0.00	0.00
Triloculina sp.	0.00	0.00	0.00	0.30	0.00	0.60	0.00	0.00	0.00	0.00
Sigmoilinita sp.	2.79	1.70	1.42	1.20	0.65	1.81	0.56	3.30	1.87	0.71
Lenticulina sp.	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(*continued on next page*)

Appendix C (*continued*)

Species	Sediment section (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Lagena doveyensis	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Lagena striata	0.00	0.00	0.57	0.00	0.65	0.00	0.00	0.00	0.00	0.00
Glandulina sp.	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Glandulina rotundata	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.23	0.00
Fissurina sp.	0.00	0.85	1.70	0.60	0.32	0.60	0.56	0.30	0.70	0.00
Fissurina lucida	0.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Epistominella exigua	18.72	14.20	24.65	14.07	17.53	21.39	23.38	7.81	19.91	22.86
Neogloboquadrina dutertrei	0.56	0.28	0.57	0.00	0.00	1.20	0.00	0.00	0.23	0.00
Globigerina sp.	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globigerina bulloides	0.28	0.00	0.00	0.30	0.65	0.00	0.28	1.20	0.70	0.00
Globigerina calida	4.19	1.70	0.57	0.90	1.30	0.90	1.69	1.20	1.64	1.07
Globigerina glutinata	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globigerinella aequilateralis	0.28	1.70	0.00	0.00	0.65	0.00	0.56	0.30	0.23	0.00
Globorotalia sp.	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orbulina universa	25.98	21.31	21.53	12.87	20.45	20.48	14.93	12.31	15.46	16.79
Hastigerina pelagica	0.00	0.00	0.28	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Bolivina sp.	0.28	0.57	0.00	0.90	0.32	0.60	0.85	0.60	2.11	1.79
Bolivina pseudoplicata	3.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bolivina variabilis	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Brizalina sp.	2.23	3.69	6.52	3.59	3.25	3.01	6.48	1.80	1.87	2.50
Brizalina dilitata	2.23	1.42	1.42	3.29	3.90	1.20	1.97	1.80	1.87	2.86
Brizalina spathulata	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	1.43
Brizalina striatula	2.51	0.85	0.00	0.00	1.30	1.20	0.00	0.30	2.34	1.43
Cassidulina laevigata	0.00	0.28	0.00	0.60	0.32	0.30	0.28	0.60	0.23	0.00
G. subglobosa	1.96	2.84	3.40	3.59	3.57	4.52	2.25	4.20	2.58	4.64
Floresina sp.	0.28	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Rectuvigerina sp.	0.28	0.57	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00
Bulimina sp.	0.00	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bulimina aculeata	0.00	0.00	1.98	1.80	0.32	0.30	0.85	0.90	0.00	0.00

Appendix D. Relative abundance of foraminiferal species in each sample from station DT2-continued

Species	Sediment section (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Bulimina elongata	0.56	0.57	0.28	0.30	0.65	0.60	0.28	0.30	0.94	0.71
Bulimina marginata	3.63	3.13	1.98	1.80	1.95	3.01	2.82	2.70	3.51	3.57
G. pseudospinences	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uvigerina sp.	0.00	0.00	0.28	0.00	0.00	0.60	0.28	0.00	0.00	0.36
Uvigerina mediterranea	0.00	0.57	0.28	0.30	0.00	0.00	0.00	0.30	0.47	0.36
Reussela spinulosa	1.12	1.14	1.13	1.50	0.97	0.00	1.41	0.90	1.41	0.71
Eponides sp.	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stomatorbina concentrica	0.00	0.00	0.00	0.30	0.00	0.90	0.00	0.00	0.00	0.00
Gavelinopsis praegeri	0.84	0.00	0.00	0.00	0.00	0.00	0.00	3.00	1.17	0.00
Neoconorbina sp.	0.00	0.85	0.57	0.30	0.00	0.00	0.00	0.00	0.00	0.00
Neoconorbina terquemi	0.56	0.00	0.00	0.00	0.00	1.51	1.69	1.20	3.98	4.64
Rosalina sp.	1.68	0.28	1.42	0.00	1.95	0.00	0.85	0.90	0.70	1.07
Rosalina floridensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.00
Rosalina globularis	0.00	0.00	0.00	1.20	0.32	0.60	0.00	0.00	0.00	0.00
Cornobella erecta	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00
Cornobella patelliformis	0.00	0.00	0.28	0.00	0.32	0.30	0.28	0.00	0.00	1.07
Discorbinella bertheloti	0.00	1.14	0.00	0.00	0.00	0.00	0.00	0.60	0.47	0.00
Hyalinea balthica	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.23	0.00
Cibicides sp.	0.00	2.27	1.70	2.40	2.60	0.90	2.54	2.70	1.87	0.71
Cibicides refulgens	0.00	0.00	0.00	0.00	0.32	0.30	0.28	1.20	0.23	0.00
Lobatula lobatula	0.00	0.00	0.28	0.00	0.32	0.60	0.28	0.30	0.00	0.00
Asterigerinata mamilla	1.96	1.42	4.25	7.19	6.17	6.63	7.89	11.11	9.84	5.36
Nonionella sp.	0.00	0.85	0.85	0.00	1.30	0.90	0.85	0.00	0.00	0.00
Nonionella opima	1.96	0.00	0.57	1.50	0.00	0.30	0.28	0.60	0.94	1.07
Nonionella turgida	1.12	0.00	1.42	0.60	0.32	0.30	0.85	0.60	0.47	0.36

Appendix D (*continued*)

Species	Sediment section (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Melonis sp.	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00
Gyroidines sp.	2.23	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G. lamarckiana	0.00	0.28	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aubignyna planidorso	0.00	1.70	1.13	0.60	0.65	0.00	1.13	0.60	0.94	0.00
Buccella sp.	2.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia sp.	0.28	0.85	0.57	1.20	1.62	0.90	1.41	1.20	0.23	0.00
Ammonia parkinsoniana	0.00	0.00	0.00	2.69	0.32	0.00	0.00	0.00	0.23	0.00
Ammonia tepida	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium sp.	0.28	4.55	2.27	6.89	3.25	0.00	6.76	6.61	4.68	6.79
Elphidium sp. 3	1.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium depressulum	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00
Elphidium gerthi	1.96	10.23	2.55	5.39	3.57	7.23	4.23	6.31	2.34	2.14
Elphidium macellum	0.00	0.57	0.00	0.00	0.32	0.00	0.00	0.00	0.23	0.00
Elphidium translucens	5.31	5.68	1.70	5.39	5.19	6.02	1.97	4.20	2.11	2.14
Porosononion sp.	0.00	0.00	0.00	1.50	0.65	0.30	0.56	0.60	0.23	0.00
Haynesina germanica	0.00	5.40	7.08	8.38	6.82	6.02	6.48	10.51	7.26	7.50
haynesina sp. 1	2.51	0.00	0.28	1.50	1.30	0.00	0.85	2.10	0.70	0.71
Haynesina sp. 3	0.00	0.85	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haynessina depressula	0.84	1.42	1.13	0.30	0.00	0.90	0.00	2.40	0.00	0.36

Appendix E. Relative abundance of foraminiferal species in each sample from station DTR

Species	Sediment section (cm)								
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Haplophragmoides sp.	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Textularia agglutinans	1.57	0.00	2.37	0.69	0.38	0.33	1.56	2.33	3.52
Textularia bocki	1.57	0.38	5.14	1.03	0.75	1.33	1.17	0.00	1.17
Adelosina sp.	0.00	0.00	0.79	0.00	0.00	0.33	0.00	0.00	0.00
Adelosina carinata-striata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00
Spiroloculina sp.	0.00	0.00	0.40	1.03	0.00	0.00	0.00	0.00	0.00
Siphonaperta sp.	0.31	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Siphonaperta irregularis	0.00	0.00	0.00	1.03	0.38	0.00	1.17	0.39	0.78
Cycloforina villafranca	0.00	0.00	0.00	0.00	0.00	0.66	0.00	0.00	0.00
Quniqueloculina sp.	4.09	4.23	1.19	0.00	3.02	1.66	2.33	0.78	0.78
Quinqueloculina berthelotiana	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Quinqueloculina seminula	0.00	0.00	0.40	0.34	0.00	1.33	0.00	0.00	0.00
Millionella sp.	0.31	0.00	0.79	2.07	0.00	0.00	0.00	0.78	0.78
Pyrgo sp.	0.31	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.39
Triloculina adriatica	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00	0.00
Triloculina tricarinata	0.00	0.00	0.00	0.69	0.38	0.00	0.39	1.17	0.39
Sigmoilinita sp.	0.94	1.15	1.98	1.03	1.89	0.00	0.78	0.78	1.17
Peneroplis pertusus	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39
Lagena doveyensis	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fissurina sp.	1.26	2.31	0.40	0.00	0.00	1.66	0.78	1.56	0.39
Epistominella exigua	3.77	3.46	3.56	2.41	3.77	3.65	3.11	1.95	5.47
Neogloboquadrina dutertrei	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00
Globigerina bulloides	0.00	0.00	0.79	1.03	0.00	0.66	0.39	0.00	0.00
Globigerina calida	2.20	1.92	1.58	0.69	0.75	1.99	0.39	1.95	2.73
Globigerinella aequilateralis	0.00	0.77	0.79	0.00	0.00	0.00	0.00	0.00	0.00
Globorotalia sp.	0.63	0.00	0.00	0.00	0.00	2.99	0.00	0.00	0.00
Orbulina universa	14.15	10.00	16.60	19.66	24.53	23.26	9.73	7.39	12.89
Bolivina sp.	0.94	2.69	0.40	0.00	0.00	0.00	0.00	0.00	0.00
Bolivina variabilis	0.00	0.00	0.00	0.00	0.00	1.33	0.78	0.78	1.17
Brizalina sp.	2.52	3.08	0.79	1.72	1.89	1.99	1.17	1.56	3.91
Brizalina dilitata	0.00	1.54	0.40	0.00	0.00	1.00	0.00	0.00	0.39
Brizalina striatula	1.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cassidulina laevigata	0.63	0.00	0.40	0.34	0.38	0.00	0.39	0.00	0.00

(*continued on next page*)

Appendix E (*continued*)

Species	Sediment section (cm)								
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Globocassidulina subglobosa	3.46	3.08	1.98	2.76	1.89	2.33	0.78	1.56	1.17
Bulimina aculeata	0.00	0.38	0.00	0.00	0.75	0.00	0.39	0.00	0.39
Bulimina elongata	0.00	0.00	0.00	0.00	0.00	0.66	0.00	0.78	0.00
Bulimina marginata	0.63	0.00	0.40	0.00	0.75	0.00	0.00	0.00	0.00

Appendix F. Relative abundance of foraminiferal species in each sample from station DTR continued

Species	Sediment section (cm)								
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Uvigerina sp.	0.00	0.00	0.79	0.00	0.00	0.00	0.00	0.00	0.00
Uvigerina mediterranea	0.31	0.00	0.00	0.00	0.00	0.33	0.39	0.39	1.17
Reussela spinulosa	0.63	0.00	1.19	0.69	0.75	0.33	0.00	1.95	0.78
Stomatorbina concentrica	0.00	0.00	0.00	1.03	0.00	1.33	0.00	0.00	0.00
Gavelinopsis praegeri	0.63	0.77	0.00	0.00	0.75	0.33	0.00	0.00	0.00
Nveoconorbina terquemi	12.58	14.62	13.44	17.93	13.21	11.63	21.79	21.01	12.89
Rosalina sp.	5.97	3.85	5.53	3.79	6.04	3.65	8.95	1.95	5.47
Rosalina bradyi	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rosalina floridensis	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rosalina globularis	0.00	0.00	0.00	0.00	0.00	2.66	0.78	1.17	1.17
Rosalina macropora	0.00	0.00	0.00	0.00	1.89	0.00	0.00	0.00	0.00
Cornobella patelliformis	0.00	0.00	0.40	0.00	0.00	0.33	0.00	0.00	0.00
Cibicides sp.	3.77	2.69	1.19	2.41	0.38	0.66	4.67	5.84	5.47
Cibicides advenum	0.00	5.77	1.98	4.14	5.66	4.65	4.67	4.67	2.73
Cibicides refulgens	5.35	6.15	5.53	1.72	3.02	2.33	3.89	1.17	3.13
Lobatula lobatula	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78
Planorbulina mediterranensis	0.00	0.00	0.40	0.34	0.00	0.00	0.00	0.78	0.39
Cibicidella variabilis	0.00	1.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Asterigerinata sp.	6.29	10.38	6.72	8.62	7.55	3.65	6.23	10.12	7.03
Asterigerinata mamilla	5.35	3.46	8.30	4.83	4.15	1.33	4.67	8.17	3.91
Nonionella opima	0.00	0.00	0.40	0.00	0.38	0.33	0.00	0.00	0.00
Melonis pompiloides	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.39
Aubignyna planidorso	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Buccella sp.	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.78
Ammonia sp.	0.63	0.00	3.16	0.34	0.00	0.00	1.17	1.17	2.73
Ammonia beccarii	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00
Ammonia parkinsoniana	1.57	6.15	0.79	3.45	3.02	3.65	2.72	3.11	2.73
Ammonia tepida	0.63	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00
Elphidium sp.	0.63	0.38	0.00	0.00	1.89	1.66	0.00	0.39	1.95
Elphidium crispum	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.39	0.39
Elphidium gerthi	1.26	1.54	0.79	2.76	2.26	3.32	4.28	3.50	4.30
Elphidium macellum	0.00	1.15	1.98	2.41	0.38	0.66	0.78	0.78	1.17
Elphidium translucens	3.46	3.08	2.77	2.41	2.26	1.66	1.17	0.78	0.00
Porosononion sp.	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haynesina germanica	5.35	2.69	3.56	5.17	0.00	7.64	8.17	8.17	2.73
Haynesina sp. 1	0.00	0.00	0.00	0.00	2.26	0.00	0.00	0.00	0.00
Haynessina depressula	0.31	0.00	0.00	0.34	0.75	0.33	0.00	0.00	0.00

References

Aguado-Giménez, F., Marín, A., Montoya, S., Marín-Guirao, L., Piedecausa, A., García-García, B., 2007. Comparison between some procedures for monitoring offshore cage culture in western Mediterranean Sea: sampling methods and impact indicators in soft substrata. Aquaculture 271, 357–370.

Angel, D.L., Verghese, S., Lee, J.J., Saleh, A.M., Zuber, D., Lindell, D., Symons, A., 2000. Impact of a net cage fish farm on the distribution of benthic foraminifera in the northern Gulf of Eliat (Aqaba, Red Sea). Journal of Foraminiferal Research 30, 54–65.

Apostolaki, E.T., Tsagaraki, T., Tsapakis, M., Karakassis, I., 2007. Fish farming impact on sediments and macrofauna associated with seagrass meadows in the Mediterranean. Estuarine, Coastal and Shelf Science 75, 408–416.

Armynot du Châtelet, E., Debenay, J.P., Soulard, R., 2004. Foraminiferal proxies for pollution monitoring in moderately polluted harbors. Environmental Pollution 127, 27–40.

Barić, A., Kušpilić, G., Matijević, S., 2002. Nutrient (N, P, Si) fluxes between marine sediments and water column in coastal and open Adriatic. Hydrobiologia 475 (476), 151–159.

Benitez-Nelson, C., 2000. The biogeochemical cycling of phosphorus in marine systems. Earth-Science Reviews 51, 109–135.

Bouchet, V.M.P., Debenay, J.P., Sauriau, P.G., Radford-Knoery, J., Soletchnik, P., 2007. Effects of short-term environmental disturbances on living benthic foraminifera during the Pacific oyster summer mortality in the Marennes-Oléron Bay (France). Marine Environmental Research 64, 358–383.

Buzas, M.A., 1979. The measurement of species diversity. In: Lipps, J.H., Berger, W.H., Buzas, M.A., Douglas, R.G., Rossc, A. (Eds.), Foraminiferal Ecology and Palaeoecology. Society of Economic Paleontologists and Mineralogists, Washington, pp. 3–10 (Short course 6).

Cimerman, F., Langer, M.R., 1991. Mediterranean foraminifera. Razred za naravoslovne vede, Classis IV: Historia naturalis 30, pp. 118 + 93 pls. Slovenska akademija znanosti in umetnosti, Ljubljana.

Debenay, J.P., Guillou, J.J., Redois, F., Geslin, E., 2000. Distribution trends of foraminiferal assemblages in paralic environments: a base for using foraminifera as bioindicators. In: Martin, R. (Ed.), Environmental Micropaleontology: The Application of Microfossils to Environmental Geology. Springer, p. 481.

Debenay, J.P., Tsakiridis, E., Soulard, R., Grossel, H., 2001. Factors determining the distribution of foraminiferal assemblages in Port Joinville Harbor (Ille d'Yeu, France): the influence of pollution. Marine Micropaleontology 43, 75–118.

De Nooijer, L.J., Dujinstee, I.A.P., Bergman, M.J.N., Van der Zwaan, G.J., 2008. The ecology of benthic foraminifera across the Frisian Front, southern North Sea. Estuarine, Coastal and Shelf Science 78, 715–726.

Donnici, S., Serandrei Barbero, R., 2002. The benthic foraminiferal communities of the northern Adriatic continental shelf. Marine Micropaleontology 44, 93–123.

Eberwein, A., Mackensen, A., 2006. Regional primary productivity differences off Morocco (NW-Africa) recorded by modern benthic foraminifera and their stable carbon isotopic composition. Deep-Sea Research I 53, 1379–1405.

Ecoina, d.o.o., 1999. Konačna studija o utjacaju na okoliš kod uzgajališta tuna (*Thunnus thynnus* L.) kod Drvenika Velog. Monitoring Report, Zagreb, Croatia.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. Journal of Geology 62, 344–356.

Frezza, V., Carboni, M.G., 2009. Distribution of recent foraminiferal assemblages near the Ombrone River mouth (Northern Tyrrhenian Sea, Italy). Revue de Micropaléontologie 52, 43–66.

Haq, B.U., Boersma, A., 1998. Introduction to Marine Micropaleontology. Elsevier, New York.

Hargrave, B.T., Phillips, T.A., Doucette, L.I., White, M.J., Milligan, T.G., Wildish, D.J., Cranston, R.E., 1997. Assessing benthic impacts of organic enrichment from marine aquaculture. Water Air Soil Pollution 99, 641–650.

Hayward, B.W., Grenfell, H.R., Nicholson, K., Parker, R., Wilmhurst, J., Horrocks, M., Swales, A., Sabaa, A.T., 2004. Foraminiferal record of human impact on intertidal estuarine environments in New Zealand's largest city. Marine Micropaleontology 53, 37–66.

Holmer, M., Marba, N., Diaz-Almela, E., Duarte, C.M., Tsapakis, M., Danovaro, R., 2007. Sedimentation of organic matter from fish farms in oligotrophic Mediterranean assessed through bulk and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analyses. Aquaculture 262, 268–280.

Jorissen, F.J., 1999. Benthic foraminiferal microhabitats below the sediment-water surface. In: Sen Gupta, B.K. (Ed.), Modern Foraminifera. Kluwer Academic Publishers, Dordrecht, pp. 161–179.

Kalantzi, I., Karakassis, I., 2006. Benthic impacts of fish farming: meta-analysis of community and geochemical data. Marine Pollution Bulletin 52, 484–493.

Krebs, C.J., 1998. Ecological Methodology. Addison Wesley Longman, Menlo Park, California. p. 620.

Langer, M.R., 1993. Epiphytic foraminifera. Marine Micropaleontology 20, 235–265.

La Rosa, T., Mirto, S., Mazzola, A., Danovaro, R., 2001. Differential responses of benthic microbes and meiofauna to fish-farm disturbance in coastal sediments. Environmental Pollution 112, 427–434.

Loeblich Jr., A.R., Tappan, H., 1987. Foraminiferal genera and their classification. Van Nostrand Reinhold, New York. p. 869.

Matijević, S., Kušpilić, G., Bogner, D., Barić, A., 2004. Fish farming influence on physical and chemical properties of sediment and water column in the middle Adriatic. In: Proceedings of the Rapport du 37th Congrès de la CIESM, p. 222.

Matijević, S., Kušpilić, G., Barić, A., 2006. Impact of a fish farm on physical and chemical properties of sediments and water column in the middle Adriatic Sea. Fresenius Environmental Bulletin 15, 1058–1063.

Matijević, S., Kušpilić, G., Kljaković-Gašpić, Z., Bogner, D., 2008. Impact of fish farming on the distribution of phosphorus in sediments in the middle Adriatic area. Marine Pollution Bulletin 56, 535–548.

Mojtahid, M., Jorissen, F., Pearson, T.H., 2008. Comparison of benthic foraminiferal and macrofaunal responses to organic pollution in the Firth of Clyde (Scotland). Marine Pollution Bulletin 56, 42–76.

Murray, J.W., 1991a. Ecology and palaeoecology of benthic foraminifera. John Wiley and Sons Inc., New York. p. 397.

Murray, J.W., 1991b. The niche of benthic foraminifera, critical thresholds and proxies. Marine Micropaleontology 41, 1–7.

Panieri, G., Gamberi, F., Marani, M., Barbieri, R., 2005. Benthic foraminifera from a recent, shallow-water hydrothermal environment in the Aeolian Arc (Tyrrhenian Sea). Marine Geology 218, 207–229.

Panieri, G., Sen Gupta, B.K., 2008. Benthic foraminifera of the Blake Ridge hydrate mound, Western North Atlantic Ocean. Marine Micropaleontology 66, 91–102.

Paytan, A., Cade-Mehun, B.J., McLaughlin, K., Faul, K.L., 2003. Selective phosphorus regeneration of sinking marine particles: evidence from ^{31}P-NMR. Marine Chemistry 82, 55–70.

Petricioli, D., Trajbar, S., Stagličić, N., 2006. Uzgajališta tuna na lokacijama kod otokâ Kluda i u Uvali Mala Luka na otoku Drvenik Veliki. Monitoring Report, Oikon d.o.o., Zagreb, Croatia.

Resig, J.M., 1960. Foraminiferal ecology around ocean outfalls off Southern California. In: Pearson, P.A. (Ed.), Waste Disposal in the Marine Environment. Pergamon Press, London, pp. 104–121.

Risgaard-Petersen, N., Nielsen, L.P., Rysgaard, L.P., Galsgaard, T., Meyer, R.L., 2003. Application of the isotope paring technique in sediments where anammox and denitrification coexist. Limnology and Oceanography: Methods 1, 63–73.

Romano, E., Bergamin, L., Finoia, M.G., Carboni, M.G., Ausili, A., Gabellini, M., 2008. Industrial pollution at Bagnoli (Naples, Italy): benthic foraminifera as a tool in integrated programs of environmental characterisation. Marine Pollution Bulletin 56, 439–457.

Schafer, C.T., Winters, G.V., Scott, D.B., Pocklington, P., Cole, F.E., Honig, C., 1995. Survey of living foraminifera and polychaete populations at some Canadian aquaculture sites: potential for impact mapping and monitoring. Journal of Foraminiferal Research 25, 236–259.

Scott, D.B., Schafer, C.T., Honig, C., Younger, D.C., 1995. Temporal variations of benthic foraminiferal assemblages under or near aquaculture operations: documentation of impact history. Journal of Foraminiferal Research 25, 224–235.

Sen Gupta, B.K., Smith, L.E., Lobegeier, M.K., 2007. Attachment of Foraminifera to vestimentiferan tubeworms at cold seeps: refuge from seafloor hypoxia and sulfide toxicity. Marine Micropaleontology 62, 1–6.

Sun, X., Corliss, B.H., Brown, C.W., Schowers, W.J., 2006. The effect of primary productivity and seasonality on the distribution of deep-sea benthic foraminifera in the North Atlantic. Deep-Sea Research I 53, 28–47.

Sutherland, T.F., Levings, C.D., Petersen, S.A., Poon, P., Piercey, B., 2007. The use of meiofauna as an indicator of benthic organic enrichment associated with salamonid aquaculture. Marine Pollution Bulletin 54, 1249–1261.

Szarek, R., Kuhnt, W., Kawamura, H., Kitazato, H., 2006. Distribution of recent benthic foraminifera on the Sunda Shelf (South China Sea). Marine Micropaleontology 61, 171–195.

Watkins, J.G., 1961. Foraminiferal ecology around the Orange County, California, ocean sewer outfall. Micropaleontology 7, 199–206.

Zalesny, E.R., 1959. Foraminiferal ecology of Santa Monica Bay, California. Micropaleontology 5, 101–126.