FORAMINIFERA AS INDICATORS OF ENVIRONMENTAL STRESS IN MARINE ECOSYSTEMS: NEW EVIDENCE FROM THE UKRAINIAN BLACK SEA SHELF

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Keywords: Danube, riverine discharge, superficial sediments, assemblage changes

Introduction

The marine environment is the ultimate destination of most terrestrial runoff, the majority of which comes from rivers that bring into the sea a vast amount of freshwater enriched with organic and inorganic compounds, including nutrients, waste products, and sediments. All this imposes enormous pressure, referred to here as environmental stress, on marine ecosystems. The stress influences taxonomic diversity, population structure, and productivity of marine organisms that depend on marine habitats for their life support.

The Black Sea bottom ecosystem is extremely sensitive to environmental stress. Any change in environmental parameters acts upon benthic organisms on the threshold principle, changing their taxonomic composition and assemblage structure. A reliable group of organisms is required to estimate the influence of stress on bottom ecosystems and trace its effects in space and time. Such organisms must be: benthic, taxonomically representative, widely distributed, hard-shelled, abundant, small-sized, and short lived. Together, these factors would provide a representative data-set to be successfully used for population statistics. Benthic foraminifera totally satisfy these requirements. They are ubiquitous in marine environments.

The main goal of this paper is to investigate the distribution of foraminifera on the Ukrainian shelf of the Black Sea in order to find out whether the benthic ecosystem here is under environmental stress, and if so what are the main factors responsible for it. To accomplish this goal, the following objectives were established: (1) to examine the taxonomic composition and quantitative distribution, of foraminifera, (2) to correlate them with environmental (oceanographic and sedimentological) parameters, (3) to identify the main factors responsible for the environmental stress and their priority, and (4) to identify assemblages and species-indicators of environmental stress.

Study area, materials, and methods

The study area includes the northwestern Black Sea shelf adjacent to the Ukrainian coast. Fifteen stations were sampled on board the Romanian research vessel “Mare Nigrum” on 17-21 May 2016 within the framework of the EMBLAS project (Fig. 1A) and compared with previously studied material (Fig. 1B, C).

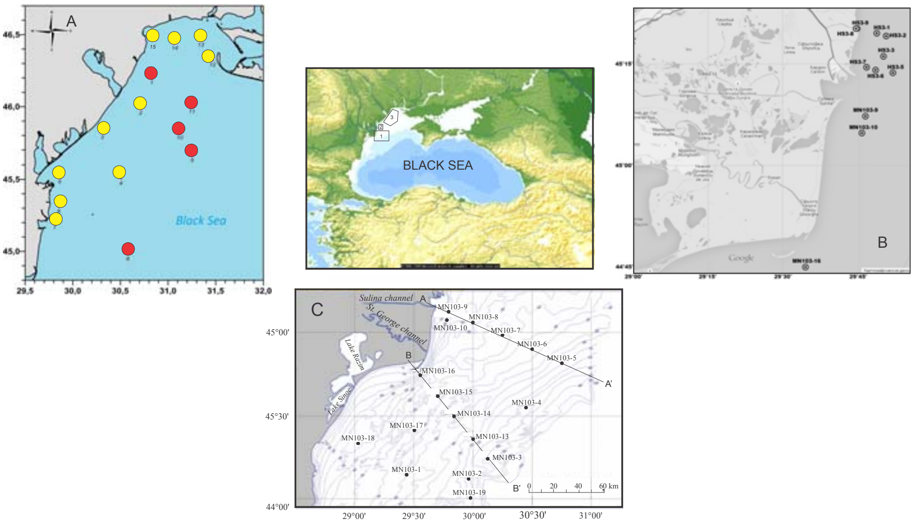


Figure 1. Study areas and location of sampled stations. A – present study in the framework of the EMBLAS project: yellow and red circles indicate stations of Cluster A and B (Fig. 6), respectively; B and C: previously studied areas in the framework of projects 40/13 and WAPCOAST, respectively.

Sediments were recovered using a 0.1 m^2 van Veen Grab. The transparency (Tr) was measured by Secchi disk. Other hydrological parameters were measured by Neil Brown Instrument Systems (CTD) with a General Oceanic rosette equipped with eleven Niskin bottles and electronic sensors: the water depth (D), salinity (S), temperature (T°C), pH, dissolved oxygen (DO), oxygen saturation index (SI), and oxygen-reduction potential (Eh). The grain-size analysis of the superficial (0-2 cm) sediment layer was performed by sieving and elutriation methods described in Logvinenko and Sergeeva (1986). Based on the results, the Median Diameter (Md) and Coefficient of Sorting (So) were calculated for each sample.

For the foraminiferal analysis, the sediment samples were collected from the superficial (0-2 cm) undisturbed sediment column recovered by grab. For staining of living forms, the samples were stored in 4% formalin solution buffered with sea water in the proportion 3:1 and 20 g of $Na_2B_4O_7$ per liter, then transferred to the laboratory where they were treated.

At each station, the total assemblage, including live (stained) and dead (empty) tests of foraminifera, was calculated together and expressed as the number of tests (abundance) per 50 g of dry sediment as described in Yanko and Troitskaya (1987) and Yanko et al. (1998). We used the total assemblage because (1) the very low number of living specimens did not allow a relevant statistical study of their distribution, (2) the presence of living specimens among all identified species indicated that they most probably live in the study area and therefore their empty tests are autochthonous, and (3) the total assemblage better characterizes the seasonal population dynamics (Debenay et al., 2001). Large samples were randomly split with a splitter into sub-samples. At least 300 specimens (for population statistics) whenever possible were picked up by hand under the binocular microscope. No heavy liquid for separation of tests from sediments was used. Broken forminiferal tests as well as their fragments and old tests (re-crystallized, worn down, filled with sediments) were considered as reworked and excluded from the analysis. For each species, the relative abundance was calculated and expressed as a percentage.

The grain-size analysis was performed in the laboratory of the Ukrainian Scientific Centre of Ecology of the Sea, while foraminiferal analyses were performed in the Micropaleontological Laboratory of Odessa I.I. Mechnikov National University, Ukraine.

In order to discover a possible interrelation between foraminiferal and environmental parameters, cluster, correlation, factor analyses, and multidimensional scaling were applied using the "Statistica 7" package. The correlations between parameters were considered as significant at $p < .05000$ and the 95% confidence limit, and only these correlation coefficients are provided in the paper.

Results and discussion

The factor analysis of hydrological parameters using the method of principal components followed by the varimax orthogonal rotation procedure (varimax normalized) identified two main factors with total eigenvalues of 78%. This value corresponds to a relatively high representation of the variables by the three factors model, and as such, it is statistically satisfactory. The contribution of each factor to the total eigenvalue is 47.7%, 17.5%, and 12.7%, respectively. The highest loadings to Factor 1 have Tr, DO, SI, and pH; Factor 2 – D and S; and Factor 3 – Eh and Chl. Factor 1 and Factor 2 are located in opposite corners on the Factor Diagram while Factor 3 occupies an intermediate position.

The most powerful is Factor 1. It has the highest loading to SI, which has positive correlation with Tr, T°C, DO, and pH but does not have any correlation with D. Transparency (Tr) is usually a function of turbidity. The area under study is under the strong influence of the Danube River discharge that accounts for about 75% of the total river discharge into the Black Sea. According to the model of Grégoire et al. (1998), most of the freshwater and fine suspended sediments initially move north in late spring-summer. This enables us to suggest that **Factor 1 is an influence of the Danube discharge on the marine bottom ecosystem.** Factor 2 has the highest loading to D and S. This enables us to suggest that Factor 2 is related to **distance from the shore and salinity**. Factor 3 has positive loading to Chl but negative to Eh, representing eutrophication of the bottom environment related to consumption of oxygen by decaying phytoplankton.

The grain-size distribution of the superficial sediments does not show any specific pattern and looks rather spotty (Fig. 2) except for the pelite fraction >0.005 that increases with depth (r=0.61).

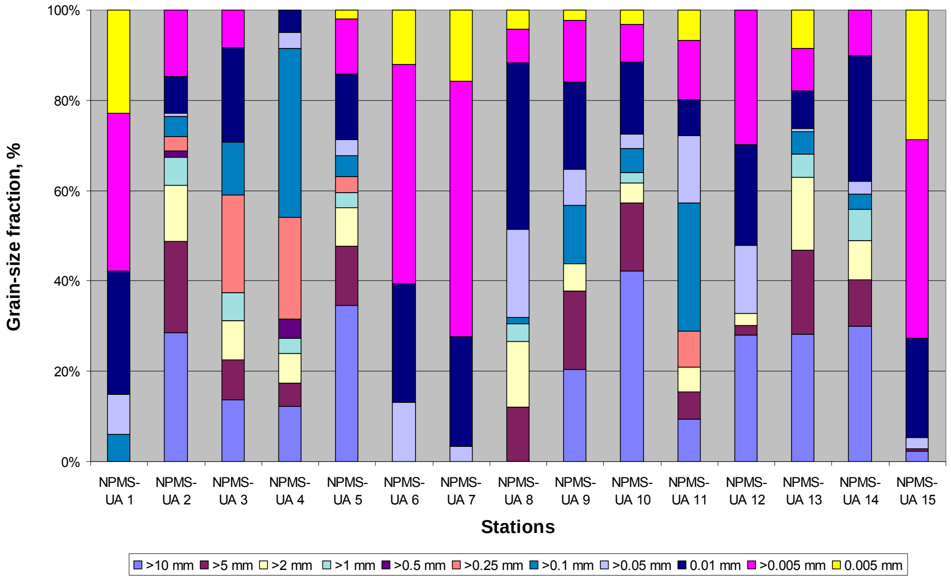


Figure 2. Grain-size distribution of sediments in the superficial (0-2 cm) layer of sediments.

Only benthic foraminifera were discovered. Their relative abundance per station along the depth gradient is shown in Fig. 3.

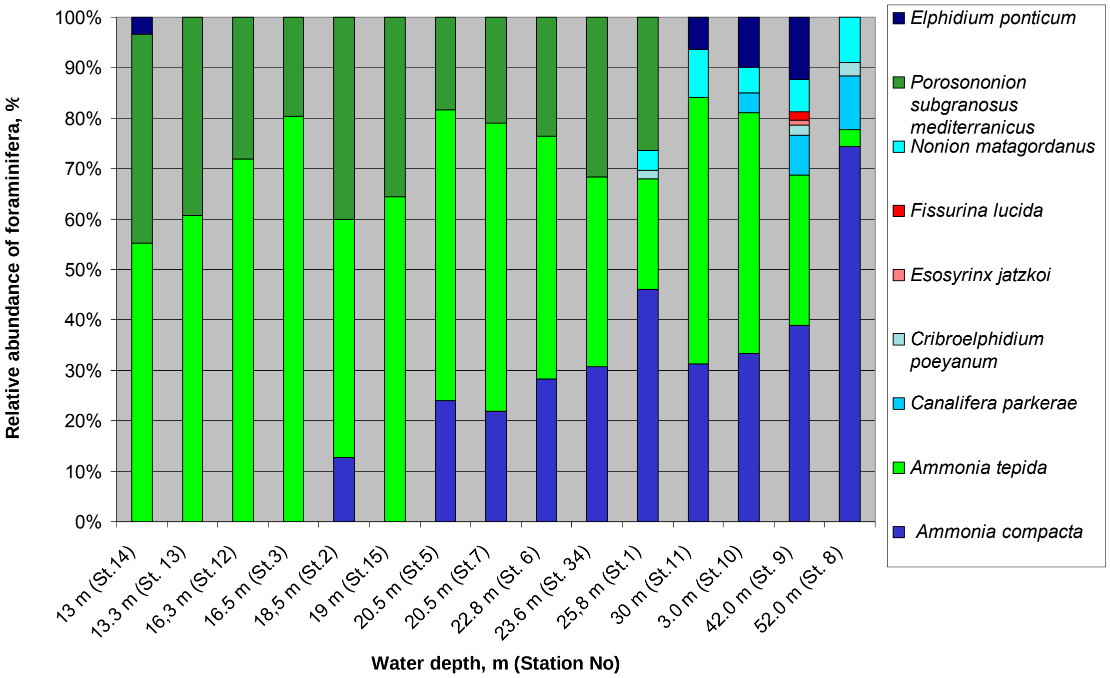


Figure 3. Relative abundance of foraminifera along the depth gradient: green – holeuryhaline (1-26 psu), blue – stricteuryhaline (11-26 psu), and red – polyhaline (18-26 psu) species.

Foraminifera are represented by nine species from two orders, and eight genera. All species are calcareous, no agglutinated forms are present.

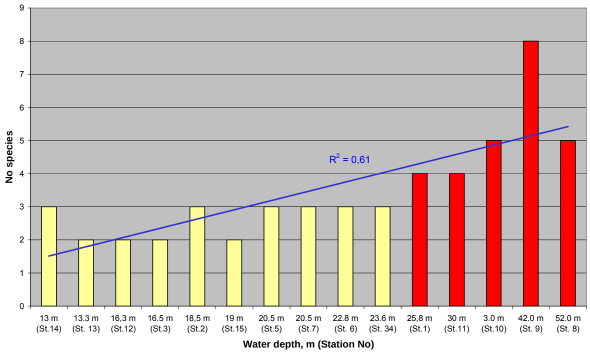


Figure 4. Number of foraminiferal species along the depth gradient. In yellow – stations of Cluster A.

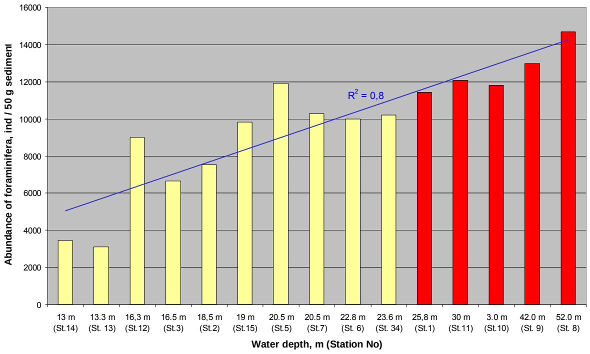
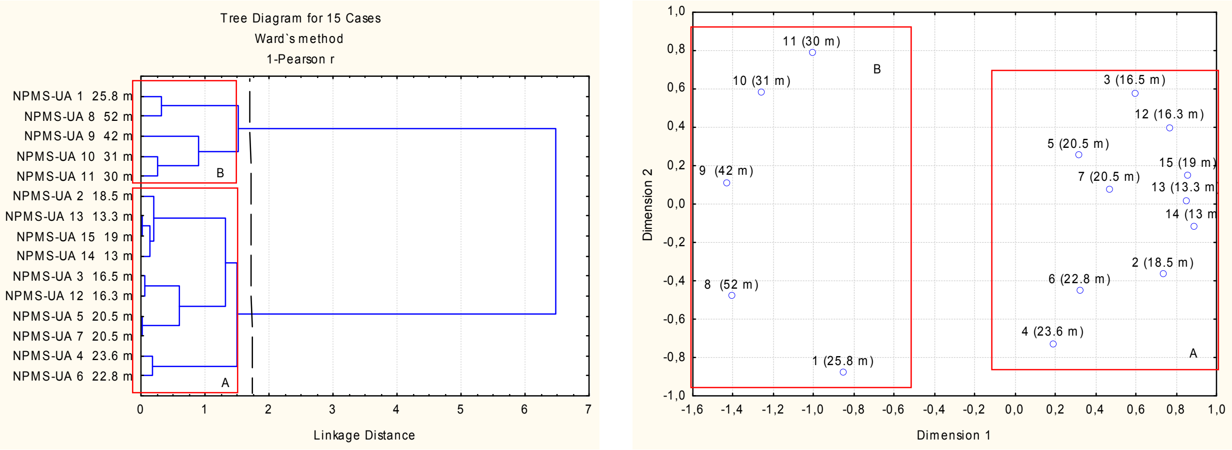


Figure 5. Abundance of foraminiferal species along the depth gradient. In red – stations of Cluster B.

The number of species increases from two to eight per station towards the sea (Fig. 4). Their abundance repeats this pattern, increasing from 3456 to 14,688 individuals per 50 g sediment (Fig. 5).

For groupings of stations that showed similar taxonomic compositions and quantitative characteristics of foraminifera, the Q-mode cluster analysis was applied. The data matrix consisted of 15 objects (stations) and nine variables (relative abundances of foraminifera), and it was standardized by objects. Ward's method was used to optimize the minimum variance within clusters. The Pearson's correlation coefficient was used as a measure of similarity. The resulting cluster dendrogram (Fig. 6a) and MDS plot (Fig. 6b) enabled us to distinguish Cluster A and Cluster B.



A B

Figure 6. Grouping of stations with similar compositions of foraminiferal species: A. Dendrogram from a Q-mode cluster analysis based on species population in which the separation of three clusters including A and B can be recognized; B. MDS plot of stations showing groups distributed on a metric scale suggesting that the dendrogram of Figure 6a should be "trimmed" at Linkage Distance 1.8 (dotted vertical line). For clarity, the cruise number "NPSM-UA" has been omitted from the station numbers.

Cluster A includes stations NPMS-UA 2, 3, 4, 5, 7, 12, 13, 14, and 15 located closer to the shore at water depths of 13-23.6 m that are mostly affected by Factors 1 and 3, i.e., the Danube discharge and eutrophication. Cluster B includes stations NPMS-UA 1, 8, 9, 10, and 11 located farther from the shore at water depths of 25.8-52 m that are mostly affected by Factors 2, i.e., salinity. Compared to Cluster B, Cluster A is characterized by the lowest average values of Tr, DO, SI, and S, and a lower number of species (2-3) compared to Cluster B (4-8), as well as a lower average abundance of foraminifera (8192 ind/50 g sediment) compared to Cluster B (12,591 ind/50 g sediment). The species *Ammonia tepida* dominates in Cluster A, while *Ammonia compacta* dominates in Cluster B, providing the name for the assemblages, respectively. The former expresses negative correlation with depth (r=0.81), while the latter positively correlates with depth (r=0.9), salinity (r=0.56), and silt (r=0.6) fraction (>0.05 mm).

There is almost no correlation of foraminiferal distribution with type of substrate. Out of nine species, only *Elphidium ponticum* and *Fissurina lucida* show positive correlation (r=0.52-0.61) with the silt fraction, while *Nonion matagordanus*, on the contrary, negatively correlates with it (r=-0.52). Abundance of foraminifera positively correlates with the silt fraction (r=0.58) but negatively (r=-0.61) to the coarse sand fraction. This is related to the amount of food, which is more abundant in a silty substrate.

Foraminiferal chracteristics in both Clusters show that all stations are located in the area of permanent environmental stress. This is indicated by low number of species and dominance of holeuryhaline species well adapted to stressful conditions. This stress is caused by the Danube discharge, which brings a vast amount of organic material upon which phytoplankton, and particularly dinoflagellates (Mudryk et al., this volume), quickly reproduce. The stress decreases towards the sea but only to a certain extent.

The shallow foraminiferal assemblage of Cluster A is identical to the assemblage of the Danube delta front (5-25 m depth) in its Ukrainian and Romanian parts (Fig. 1B and C). The relatively deep foraminiferal assemblage of Cluster B is very similar to that of the Danube prodelta (Fig. 1C) (Yanko et al., 2014, in press; Kondaryuk et al., 2015).

Conclusions

Foraminiferal characteristics show that the Danube discharge of water and sediments enriched with organic and inorganic compounds imposes environmental stress on the bottom ecosystem. The stress is expressed in a decrease in diversity and species richness as well as dominance of few holeuryhaline species (*A. tepida* and *P. subgranosus mediterranicus*) that appear to be tolerant of the stress. The intensity of the stress is a function of distance from the shore and turbidity: the closer to the shore, the more intense is the environmental stress—strong (assemblage *A. tepida*), weak (assemblage *A. compacta*). The boundary between the first and second degree of intensity of the riverine influence on bottom ecosystems can be located at isobath -25 m, which coincides with the distal zone of the delta front. This study is still in progress and will be reported elsewhere.

Acknowledgments

This paper is a contribution to the projects: EMBLAS “Environmental Monitoring in the Black Sea,” BS-ERA.NET 076 “Water Pollution Prevention Options for Coastal Zones and Tourist Areas: Application to the Danube Delta Front Area,” WAPCOAST (2010-2012), and “Control of observation during the operation of deep water navigable course of the Danube-Black Sea: sea part" under agreement No. 40/13 with the Ukrainian Scientific Research Institute of Ecological Problems, Kharkov. It also contributes to the IGCP 610 project “From the Caspian to Mediterranean: Environment change and human response during the Quaternary.” The authors thank Georgiy Zolotarev from the Ukrainian Scientific Centre of Ecology of the Sea for providing data on grain-size analysis. The second author thanks the staff of “Mare Nigrum” for their help in obtaining sediment material.

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