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Disturbance of benthic macrofauna in relation to hypoxia and organic enrichment in a eutrophic coastal bay

Keita Kodama*, Jeong-Hoon Lee, Masaaki Oyama, Hiroaki Shiraishi, Toshihiro Horiguchi

Center for Environmental Risk Research, National Institute for Environmental Studies, Onogawa, Tsukuba, Ibaraki 305-8506, Japan

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ABSTRACT

This study demonstrated the spatiotemporal patterns of the environmental conditions and benthic macrofauna in Tokyo Bay, Japan, and investigated the factors causing disturbances in the assemblage structure. In the north-central areas, the density and species diversity of the macrobenthos was low. Although hypoxia appeared in July, defaunation occurred in August. The delayed defaunation and recolonization soon after the abatement of hypoxia were attributed to several polychaete and bivalve species that were tolerant to the hypoxic environment. In the southeastern areas, however, the density and species diversity of the macrobenthos was high throughout the year, and no defaunation was recorded. Multivariate analyses showed that the disturbance in the macrofauna correlated with organic enrichment in the sediment and bottom-water hypoxia. There is a concern about further impairment of the macrofauna in the bay due to the expansion of sediment with high levels of organic matter towards the southern regions that could cause hypoxia and subsequent defaunation.

1. Introduction

Coastal waters are among the most productive environments in marine ecosystems due to high levels of primary production supported by the supply of nutrients from terrestrial areas (Ryther, 1969; Chapman and Wang, 2001). Macrobenthic assemblages are one of the key components of the biogeochemical cycle in coastal systems. For example, macrobenthic organisms contribute to the carbon cycle by decomposing organic matter in the sediment or bottom water through feeding and by serving as prey for organisms at higher trophic levels (Tamai, 1998). Coastal ecosystems are exposed to various stressors arising from human activities, such as the discharge of harmful chemical substances (Yogui et al., 2010), habitat destruction due to land reclamation and dredging (Suzuki, 2001), and eutrophication, including the deposition of organic matter in the bottom sediments (Boesch et al., 2001). Macrobenthic assemblages are likely to be susceptible to these anthropogenic stressors because most of the macrobenthic species are sedentary or less mobile and thus cannot avoid the environmental disturbances (Solan et al., 2004). Among these anthropogenic stressors, bottom hypoxia, defined as dissolved oxygen (DO) concentrations $\leq$2 ml l^{-1} and caused by organic enrichment in the sediment along with stratification of the water column, has been reported to be a major factor affecting disturbance in macrobenthic assemblages in eutrophic coastal systems throughout the world (e.g., Diaz and Rosenberg, 1995, 2008; Hyland et al., 2005; Magni et al., 2008).

Tokyo Bay, on the east-central coast of Japan, is one of the major eutrophic coastal systems in the world (Selman et al., 2008). Nutrient inputs to the bay have been decreasing due to regulations on nutrient loadings as specified by the Guiding Principle in Countermeasures for Eutrophication in Tokyo Bay in 1982, followed by the revision of the Water Pollution Control Law in 1993 (Kodama and Horiguchi, 2011). As a result, the amount of total nitrogen and phosphorus inputs into the bay and the concentrations of dissolved inorganic nitrogen and phosphorus in the bay have been decreasing since the 1980s (Kodama et al., 2010b; Nomura et al., 2011). However, the release of nutrients from sediments with high levels of organic matter has become another problem in the bay because the extra nutrients enhance primary production (Ogura, 1996). Consequently, Tokyo Bay is still considered eutrophic, and the frequency of red tides (massive algal blooms) in the bay has not decreased since 1979 (Ministry of Environment, 2005). Bottom hypoxia has been recorded since the 1950s in the central part of the bay and has since been increasing in its spatial extent and its duration (Ishii et al., 2008). These environmental conditions are likely to affect the biotic community in the bay. In fact, disturbance of the megabenthic assemblage, composed of fishes and large invertebrates, has been observed in Tokyo Bay concurrent with changes in environmental factors (Kodama et al., 2002, 2010a,b). To

* Corresponding author. Tel.: +81 29 850 2891; fax: +81 29 850 2673.
E-mail address: kodama.keita@04.alumni.u-tokyo.ac.jp (K. Kodama).

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understand the relationships between the changes of the biota and environment in Tokyo Bay, an investigation of the responses of the macrobenthic assemblage to environmental variations is necessary because, as mentioned earlier, the macrobenthos play an important role in the biogeochemical cycle of the Tokyo Bay ecosystem.

The objectives of this study were to characterize the spatiotemporal patterns of the environment and macrobenthic assemblage in Tokyo Bay and to estimate factors causing disturbance in the macrobenthic assemblage.

2. Materials and methods

2.1. Field sampling

To investigate the spatiotemporal patterns of water quality, sediment quality, and macrobenthic community, monthly sampling surveys were carried out from April 2006 to March 2007 at ten sites across the bay (Fig. 1). The surveys were conducted during the day in two 5-t fishing boats. The water temperature, salinity, and DO concentrations (ml l^{-1}) were measured in the surface, at 0.5 m below the sea surface, and bottom layers, at 1 m above the sea bottom, using a conductivity, temperature, and depth (CTD) data logger with a DO sensor (model XR–420 CTD Marine, RBR Ltd., Ontario, Canada). Sediment samples were collected at each site with a Smith–McIntyre grab sampler (0.05 m^2; Rigo, Tokyo, Japan). Sediment sampling was repeated three times covering an area of 0.15 m^2 at each site. For macrobenthic samples, the whole amount of the sediment from the first two sediment samples and half of the third sediment sample were merged together (i.e., covering an area of 0.125 m^2) and were washed with seawater through a 0.5 mm mesh sieve. The sieved samples were fixed in 5% neutral buffered formalin. For the sediment quality measurement, a subsample of the sediment was taken from the surface of the other half of the third sediment sample in the grab sampler. The subsamples were transported to the laboratory in 280 ml stainless steel containers on ice.

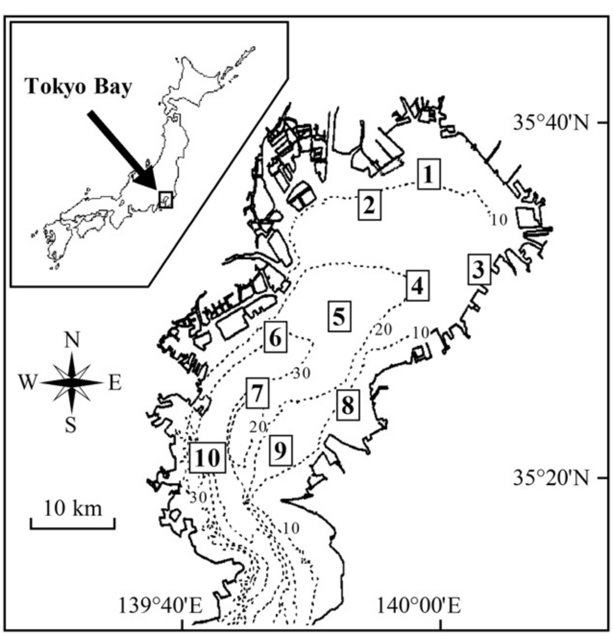

Fig. 1. Study site in Tokyo Bay, Japan. The measurements of water and sediment qualities and collection of macrobenthos were carried out monthly at ten sites from April 2006 to March 2007. Dotted lines and numbers show the depth contours in metres.

2.2. Water and sediment quality

We measured the loss on ignition (LOI) and the concentrations of total organic carbon (TOC), total nitrogen (TN), and total sulfide (TS) according to procedures as described by Kodama et al. (2010a). The grain size of the sediment samples was determined using laser diffractometry with an LMS-2000e (Seishin Enterprise, Tokyo, Japan), and the relative percentages of sand (0.075 to <2 mm in diameter), silt (0.005 to <0.075 mm), and clay (<0.005 mm) were determined.

2.3. Macrobenthic data

In the laboratory, the macrobenthos were sorted from the sediment samples under a binocular microscope and identified to the lowest taxonomic level possible (species, genera, or higher levels), and the number of individuals was counted for each taxon. The individual density was expressed as individuals per area collected by the Smith–McIntyre grab sampler (individuals m^{-2}).

2.4. Data analysis

Some datasets did not meet the assumptions of normality based on a Shapiro–Wilk test or of homogeneity of variance based on a Bartlett's test. Therefore, we used non-parametric statistical tests in the present study. A Kruskal–Wallis test was used to examine the spatial or temporal differences in the water temperature, salinity, DO concentration, LOI, and the concentrations of TOC, TN and TS. A chi-square test was conducted to examine the difference in the proportions of sand, silt and clay between sites.

The biotic relationship, in terms of the species composition and density, between any two stations was assessed with a Bray–Curtis similarity index (Bray and Curtis, 1957). Prior to the calculation of the Bray–Curtis similarity, the annual mean density data of each species at each station was square-root transformed to reduce the contribution of rare or highly abundant species (Clarke, 1993). The spatial pattern of the macrobenthic assemblage was examined by hierarchical agglomerative clustering with group-average linking on the Bray–Curtis similarity (Clarke and Warwick, 2001). We conducted a similarity profile (SIMPROF) test to detect significantly different site groups (Clarke and Gorley, 2006; Clarke et al., 2008). The annual means for the number of species and the Shannon's diversity index (Clarke and Warwick, 2001) were calculated for site groups delineated by the SIMPROF test.

To identify the water and sediment quality variables that showed a spatial pattern similar to that of the macrobenthic assemblage, we applied the BIO-ENV analysis (Clarke and Gorley, 2006). In the BIO-ENV analysis, a combination of water and sediment quality variables is identified whose Euclidean distance matrix shows the highest Spearman rank correlation coefficient (ρ_s) with the biotic Bray–Curtis similarity (Clarke and Warwick, 2001). The annual mean value at each site was used for the calculation of the Euclidean distance for all of the environmental variables of the bottom water or sediment, except DO. The mean DO between June and November was used for the analysis because bottom hypoxia was evident during that period. Several sets of the environmental variables, where no significant Spearman correlation was found between all combinations of the variables, were used for the BIO-ENV analysis (Clarke and Warwick, 2001).

The data analyses were conducted with the PRIMER 6 software (PRIMER-E, Plymouth, UK) or SPSS 11.5 software (SPSS Inc., Chicago, IL, USA).