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Variations in macrobenthic community structures in relation to environmental variables in the Seto Inland Sea, Japan

Wataru Nishijima [a,*], Akira Umehara [a], Tetsuji Okuda [a], Satoshi Nakai [b]

[a] Environmental Research and Management Center, Hiroshima University, 1-5-3, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8513, Japan
[b] Graduate School of Science and Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

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ABSTRACT

A data set of 425 sites investigated by the Ministry of the Environment in 2001–2005 was used to evaluate the current sediment situation and its effect on macrobenthic community structure in the Seto Inland Sea, Japan. Cluster analysis and principle component analysis of sediments using physico-chemical parameters revealed that total organic carbon, mud, sulfide contents, and oxidation–reduction potential were important parameters influencing macrobenthic population size and biodiversity. A total organic carbon of 1 mg g^{-1} interval was highly negatively correlated with two biodiversity indices in the range of 1–20 mg g^{-1}. Overall, 42% of total sites were organically enriched with much lower macrobenthic population sizes and biodiversity, while 26% were characterized by sandy sediment with a high population size and high proportion of Arthropoda. *Nemertea* sp., *Glycera* sp., *Notomastus* sp. and *Ophiophragmus japonicus* were common macrobenthos, while *Theora fragilis* and Ptychoderidae were typical macrobenthos in organically enriched sediments.

1. Introduction

Enclosed and semi-enclosed seas have high fish and shellfish productivity, but are sensitive and vulnerable to anthropogenic stress. Many enclosed and semi-enclosed seas are subject to excess eutrophication and deterioration of water and sediment qualities (Larsson et al., 1985; Caddy, 2000). Three key elements of eutrophication are (1) increased nutrient levels leading to (2) production of particulate and dissolved organic matter and (3) degradation of organic matter leading to lowered oxygen concentration (Gray et al., 2002). Hypoxia and hydrogen sulfide production in the overlying water and sediments of systems with eutrophication have a crucial effect on macrobenthic communities (Powilleit and Kube, 1999; Seitz et al., 2009). Hypoxia and high hydrogen sulfide concentration in the sediment are frequently observed in eutrophic enclosed seas (Diaz and Rosenberg, 2008; Kodama et al., 2012; Baustian et al., 2013).

The Seto Inland Sea is a wide (23,203 km^2) and shallow (average depth of 38.0 m) semi-enclosed sea that was subject to severe eutrophication and pollution by industrialization and urbanization of the surrounding areas during the high economic growth period of the 1970s (Takeoka, 2002; Irizuki et al., 2011). However, organic and nutrient (nitrogen and phosphorus) loadings in these systems have been reduced in response to the Water Pollution Control Law (1970) and the Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea (1973). For example, the occurrence of a red tide was reduced by 46% from the 1970s to 2000s (http://www.jfa.maff.go.jp/setouti/akasio/nenkan/index.html) and transparency was improved from 6.4 m in the 1980s to 7.3 m in the 2000s (http://www.env.go.jp/water/heisa/heisa_net/setouchiNet/seto/kankyojoho/sizenkankyo/suisituodaku.htm). The Seto Inland Sea is divided into the following 10 sub-areas based on geographical and topographical features, each of which has quite a different environmental situation (Fig. 1): Kii Channel, Osaka Bay, Harima Nada, Bisan Seto, Bingo Nada, Hiuchi Nada, Aki Nada, Hiroshima Bay, Iyo Nada and Suo Nada. Hibiki Nada and Bungo Channel are also included in the Seto Inland Sea based on the Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea. According to a survey of the entire Seto Inland Sea in 1993–1994 (Hashimoto and Hashimoto, 1997), annual average dissolved inorganic nitrogen and phosphorus concentrations were quite different among sub-areas ranging from 1.2 μg-N l^{-1} to 11.2 μg-N l^{-1}, and 0.10 μg-P l^{-1} to 0.45 μg-P l^{-1}, while Secchi disc depths had a range of 2–20 m. Moreover, annual average chlorophyll a concentrations in the top 10 m of the water column had a range of about 10 mg m^{-2} in Kii Channel to about 50 mg m^{-2} in Osaka Bay and Hiroshima Bay. The occurrence of

* Corresponding author. Tel./fax: +81 82 424 6199.
E-mail address: wataru@hiroshima-u.ac.jp (W. Nishijima).

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red tide occurrence clearly decreased from the 1980s–1990s to the 2000s in Kii Channel, Harima Nada, and Aki Nada (http://www.jfa.maff.go.jp/setouti/akasio/gepou/index.html). For example, there was an average of 18, 16, 16, 9, and 5 red tide events in Kii Channel every 5 years from 1991 to 2010. Conversely, there were 9, 16, 18, 29, and 30 red tide events in Bungo Channel from 1991 to 2010. Hypoxia was frequently observed in Osaka Bay (Tsujimoto et al., 2008), Hiuchi Nada (Kasai et al., 2007) and Hiroshima Bay (Date and Seiki, 2006). Currently, the Seto Inland Sea is composed of eutrophic and eutrophic-to-oligotrophic sub-areas or regions.

When compared with water quality, the sediment quality and population of benthic organisms has not been thoroughly characterized in the Seto Inland Sea. Water quality in the Seto Inland Sea has been monitored every season since 1982 at 229 sites (at present) by the Ministry of Land, Infrastructure, Transport and Tourism (http://www.pa.cgr.mlit.go.jp/chiki/suishitu/). However, monitoring of sediment quality is currently limited to 64 sites (at present) and does not include information regarding macrobenthic organisms. Large-scale monitoring of sediment quality and the macrobenthos population in the Seto Inland Sea was conducted in 1979–1984 by the Fisheries Agency (Fisheries Agency) and in 1991–1996 and 2001–2005 by the Ministry of the Environment. These investigations reported the spatial distribution of sediment parameters such as ignition loss (IL) and oxidation–reduction potential (ORP), as well as the species number and biodiversity index of macrobenthos (http://www.env.go.jp/water/heisa/heisa_net/setouchiNet/seto/kankyojoho/sizenkankyo/teisituodaku.htm/). However, macrobenthic community structure was not analyzed except for species number and the biodiversity index and macrofauna–habitat association with multiple physico-chemical factors was not clarified. Classification of sediments with multiple environmental properties and characterization of macrobenthic community structure in the classified sediments will improve our understanding of the benthic ecosystem in the Seto Inland Sea, Japan. We used a data set covering in 2001–2005 to evaluate the current sediment situation by classification and then investigated its effect on macrobenthic community structure in the Seto Inland Sea.

2. Materials and methods

2.1. Study sites

Sediment samples were obtained from 425 sites in the Seto Inland Sea (Fig. 1). Although Beppu Bay is generally included in Iyo Nada, they were treated separately in this study. Detail information regarding each sub-area is provided in Table 1. Sediments for macrobenthos analysis were not obtained from the three sites of Hibiki Nada.

2.2. Sample collection and analysis

Two sediment samples for physico-chemical and macrobenthic analyses were collected from the surface of the sediment at each sampling site in the summer during 2001–2004 using a Smith-McIntyre Grab sampler (0.1 m^2). The detailed schedule of sampling in each region and sites are shown in Table 1 and Fig. 1, respectively.

The upper 5 cm of sediments were subjected to temperature and ORP measurements on the ship, after which they were mixed and stored in plastic containers until further analysis for IL, total organic carbon (TOC), grain size, and sulfide content in the laboratory. The aforementioned analyses were carried out according to the sediment test method (Ministry of the Environment, 2001). Briefly, sediments for TOC and IL were centrifuged at 3,000 rpm for 20 min, after which supernatant was removed. The remaining sediments were then mixed well, dried at 105–110 °C for 2 h, and then sieved through a 2-mm mesh (dry sample). For TOC, the dried samples were treated with 1 mol l^{-1} of HCl solution for 1 day, washed repeatedly to remove carbonates, and then dried at 105–110 °C for 2 h. Next, samples were powdered and applied to a CHN analyzer to determine the TOC. For IL, dried samples were weighed to more than 5 g, ashed by combustion at 600 ± 25 °C for 2 h, and then reweighed. The IL was then determined from the weight lost during combustion.

Sediments used for grain size analysis were desalted by washing before being subjected to a series of processes without sieving

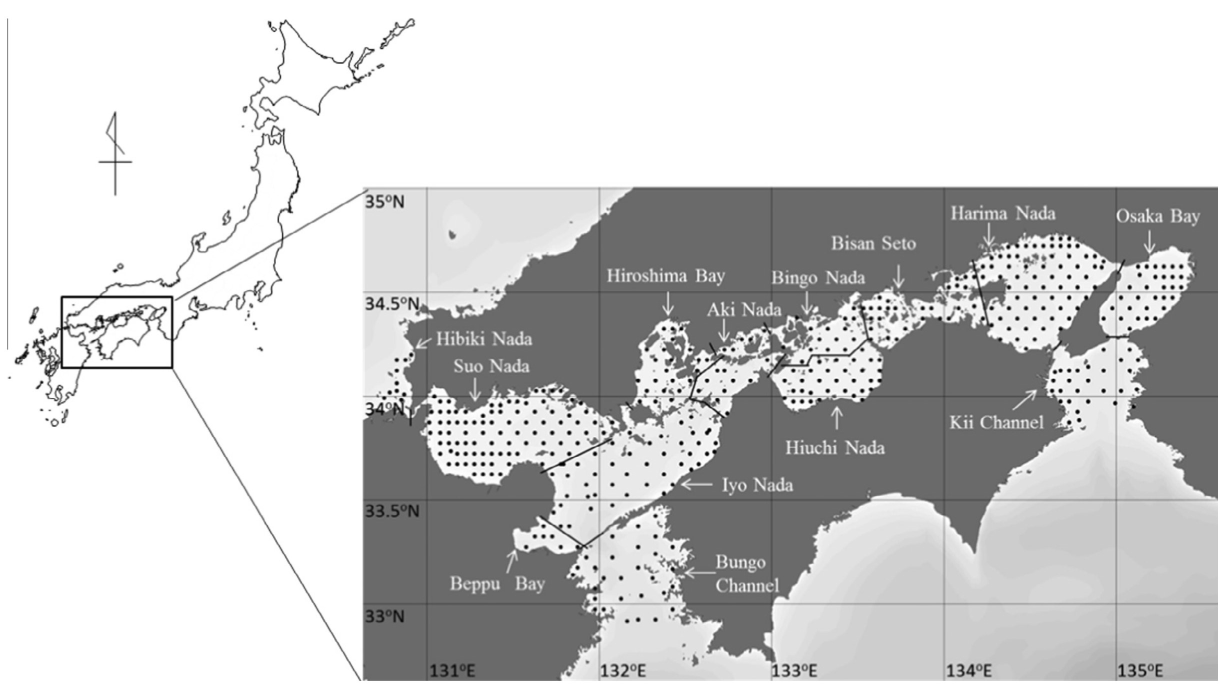

Fig. 1. Map of the study area in the Seto Inland Sea with sampling sites. The boundary lines between sub-areas are also shown.