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Effects of hypoxia on benthic organisms in Tokyo Bay, Japan: A review

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ABSTRACT

Bottom hypoxia (dissolved oxygen concentration $\leqslant 2\ \mathrm{ml\,l^{-1}}$) from anthropogenic eutrophication is a growing global concern. Here, we summarized characteristics of hypoxia and its effects on benthic organisms in Tokyo Bay. Despite recent decreases in nutrient inputs, hypoxia has been increasing in duration and spatial extent, suggesting that the substantial loss of tidal flats from reclamation is contributing to a decrease in the ability of Tokyo Bay to recycle nutrients. Hypoxia develops in the central to northern part of the bay and persists from spring to autumn, causing defaunation of benthic organisms. After the abatement of hypoxia in autumn, the defaunated area is recolonized, either through migration or larval settlement. Some megabenthic species with a spawning peak in spring and summer experience failure of larval settlement, which is probably due to hypoxia. The adverse effects of hypoxia are an impediment to recovery of benthic organisms in Tokyo Bay.

1. Introduction

Bottom hypoxia (dissolved oxygen [DO] concentration $\leqslant 2\ \mathrm{ml\,l^{-1}}$; Diaz and Rosenberg, 1995) caused by anthropogenic eutrophication is a major environmental problem occurring in a wide range of coastal systems and is a growing global concern (Diaz and Rosenberg, 2008). Adverse effects of hypoxia on aquatic organisms have been reported at the individual or population level in terms of mortality (Diaz and Rosenberg, 1995), growth (Zhou et al., 2001), reproduction (Thomas and Rahman, 2009; Thomas et al., 2006, 2007), settlement (Baker and Mann, 1992), spatial distribution (Pihl et al., 1991), and species interaction (Breitburg et al., 1997). There is also accumulating information regarding hypoxia and its effects on the benthic organisms in Tokyo Bay, Japan. The total abundance of the megabenthic species in the bay has been low since the late 1980s, and hypoxia is suggested to be one of the factors impeding recovery (Kodama et al., 2002), although the causal mechanism remains unclear. In this review, we describe the environmental characteristics of Tokyo Bay that contribute to the development of bottom hypoxia. We then consider the consequences of hypoxia on the benthic community in the bay in terms of habitat restrictions and population dynamics.

2. Environmental characteristics of Tokyo Bay

Tokyo Bay is located in central Japan and consists of inner and outer parts that are separated by a 6-km direct line between Cape Futtsu and Cape Kannonzaki (Furota, 1997; Unoki, 1993; Fig. 1). The outer part of the bay, also called Uraga Channel, faces the Pacific Ocean and has a depth ranging from 40 to more than 1000 m (Kaizuka, 1993). By contrast, the inner part of the bay is semi-enclosed with a mean depth of 19 m and a surface area of 922 $\mathrm{km^2}$ (Yoshikawa, 2011). The mean water retention period in the inner part of the bay is 31 days (Okada et al., 2007), indicating that its semi-enclosed state limits water exchange. In the present review, we consider only the inner part of the bay (referred to here as Tokyo Bay) because hypoxia is evident there.

Reclamation along the coast of the bay has been proceeding since the end of World War II; the 13,600 ha of tidal flats present in the 1940s was reduced to 1000 ha by the 1990s, a loss of 92.6%. This has led to deterioration of water and sediment quality (Kohno, 2006). It is unclear when hypoxia began to appear in Tokyo Bay, but a low DO concentration ($2.8\ \mathrm{ml\,l^{-1}}$) in the bottom water of the central part of Tokyo Bay was reported in April 1929 (Kobe Marine Observatory, 1931). During surveys of water quality in Tokyo Bay between 1948 and 2005, bottom water hypoxia was first observed in July 1955 in the central part of the bay and has since been increasing in its spatial extent as well as in its duration (Ishii et al., 2008). In 2004, hypoxia was found in the bay from April to November and showed a peak in its spatial extent—occupying 67% of the whole bay area—in July (Kodama et al., 2006a).

The sediment in Tokyo Bay consists primarily of sand in the southeastern area, whereas silt and clay are the main sediment constituents in other areas (Kodama et al., 2010a). Organic matter content is relatively higher in the silt and clay sediment (mean content of total organic carbon [TOC] in the sediment, $27.7\ \mathrm{mg\,g^{-1}}$) compared to that in the sandy sediment (mean sediment TOC content, $10.1\ \mathrm{mg\,g^{-1}}$) (Kodama et al., 2010a). In the north-central

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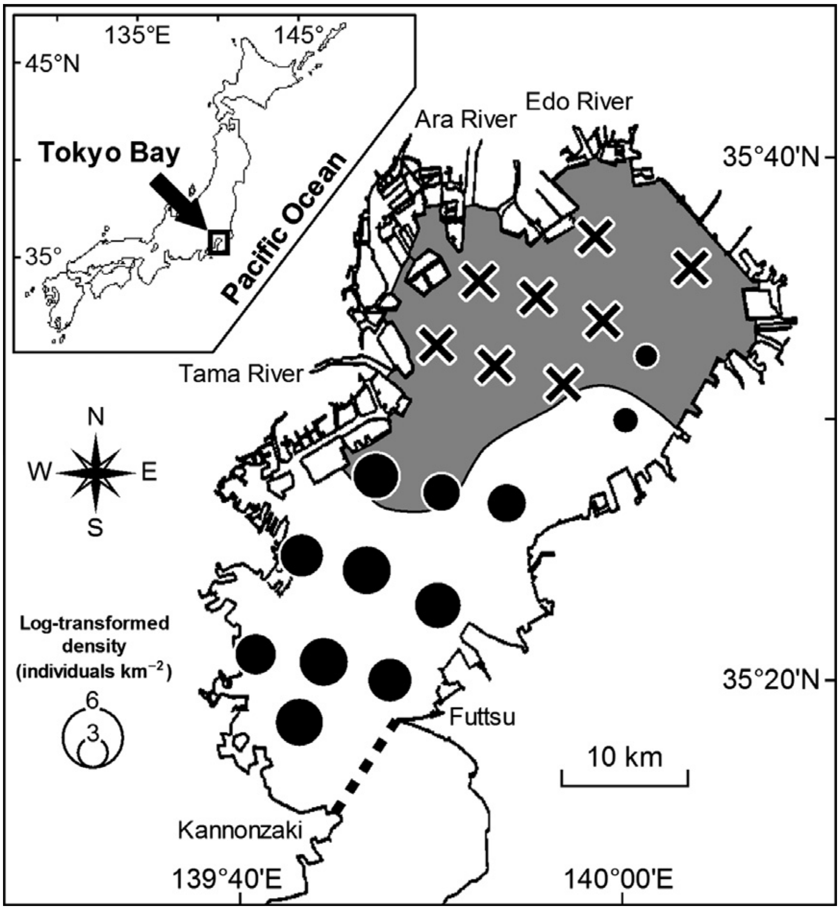

Fig. 1. Map of Tokyo Bay, Japan. The dashed line between the two capes (Kannonzaki and Futtsu) divides the bay into two parts: inner (above the line) and outer (below the line). The spatial distribution of bottom hypoxia (dissolved oxygen concentration 2 ml l^{-1} or less; shaded area) and individual density of the megabenthos (black circles) in August 2005 are also shown. No megabenthos occurred in some hypoxic sites (crosses). Modified from Kodama et al. (2010a).

part of Tokyo Bay where levels of organic matter in the bottom sediment are high, hypoxia is sustained by thermal and salinity stratification during the summer (Kodama et al., 2010a).

Nutrient loading from the adjacent terrestrial areas is considered to be one of the major contributors to the development of hypoxia (Diaz and Rosenberg, 1995). Excessive nutrient input into the catchment area enhances phytoplankton production, which results in dead phytoplankton accumulating on the sea bottom, followed by depletion of oxygen in the bottom water from microbial respiration during the decomposition of organic matter. In Tokyo Bay, household wastewater from the surrounding metropolitan area contributes 65% and 68% of loadings of total nitrogen (TN) and total phosphorus (TP), respectively (data from 2004 in Anon., 2009). 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. TN and TP loadings were 364 and 41.2 t day^{-1}, respectively, in 1979, 319 and 25.9 t day^{-1} in 1989, and 208 and 15.3 t day^{-1} in 2004 (Anon., 2009). In addition, concentrations of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) at the surface and DIN, but not DIP, at the bottom of Tokyo Bay have been decreasing since the 1980s (Kodama et al., 2010b). Levels of organic matter, as represented by chemical oxygen demand, in the surface and bottom water of the bay slightly decreased from 1977 to 2007 (mean between 1977 and 2007, 3.7 mg l^{-1} at the surface and 2.1 mg l^{-1} at the bottom; the slope of the linear regression line, −0.03 mg l^{-1} year^{-1} at both the surface and bottom; $P < 0.01$ for both; data from the National Institute for Environmental Studies, http://www.nies.go.jp/igreen/index.html). Despite these decreases in nutrient levels, the spatial extent and duration of hypoxia in Tokyo Bay has been increasing (Ando et al., 2005; Ishii et al., 2008).

In Mikawa Bay, Japan, bottom hypoxia is considered to be caused primarily by an impaired ability of the bay to recycle nutrients due to the reclamation of shallow water areas, including tidal flats, rather than by nutrient loading to the bay (Suzuki, 2001). Tokyo Bay has also experienced a substantial loss of tidal flats due to reclamation, and this loss may contribute substantially to the development of hypoxia in the bay. In addition, release of nutrients from the bottom sediment enhances primary production in Tokyo Bay (Ogura, 1996). Release of nutrients increases under hypoxic conditions (Matsumura et al., 2004) and most likely causes further primary production, followed by deposition of dead plankton on the sea floor and further development of bottom water hypoxia. Ishii et al. (2008) suggested that the trend of increasing water temperature in the bay in autumn and winter is one of the factors causing prolonged temperature stratification, resulting in a greater duration of bottom water hypoxia.

3. Effects of hypoxia on spatial distribution of the benthic community

Hypoxia alters the spatiotemporal community structure of macrobenthic and megabenthic organisms in the bay. Defaunation of the macrobenthic community was first recorded in Tokyo Bay in 1941 (Masui, 1943); we were unable to find any records prior to