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Disturbance of recruitment success of mantis shrimp in Tokyo Bay associated with effects of hypoxia on the early life history

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ABSTRACT

We investigated effects of severe hypoxia (dissolved oxygen <1 ml l^{-1}) on recruitment of mantis shrimp *Oratosquilla oratoria* in Tokyo Bay. Ten-year field surveys were conducted to examine quantitative relationships in annual mean densities of larvae and juveniles, and spatial distribution of juveniles and severe hypoxia. There was no significant correlation between annual mean densities of larvae and juveniles, suggesting that mortality during larval or juvenile stages varies among years, which might have regulated abundance of young-of-the-year juveniles. Juvenile density was low in the severely hypoxic area, implying that hypoxia could affect survivals and spatial distribution of juveniles. Meanwhile, there are yearly fluctuations in juvenile density in normoxic areas of both northern and southern part of the bay. This evidence suggests that abundance of post-settled juveniles might have been determined by not only effects of hypoxia, but also other factors influencing mortality during the early life stages.

1. Introduction

Bottom hypoxia (dissolved oxygen, DO $\leqslant$ 2 ml l^{-1}) caused by anthropogenic eutrophication is one of the major environmental issues occurring in many coastal waters throughout the world (Diaz and Rosenberg, 1995, 2008). Exposure to environmental hypoxia has been shown to have deleterious effects on growth, metabolism, reproduction and development as well as population size in aquatic organisms (Wu, 2002; Thomas et al., 2007; Thomas and Rahman, 2009; Kodama et al., 2010a, 2012a; Kodama and Horiguchi, 2011). However, research concerning effects of hypoxia on population dynamics of aquatic organisms (such as relationship between hypoxia and year-class strength of benthic populations) is relatively scarce.

In Tokyo Bay, a substantial decline in the stock size of mantis shrimp *Oratosquilla oratoria* has been evident since late 1980s (Kodama et al., 2002, 2010b). In particular, the stock collapsed in 2005, and fishery that targets mantis shrimp has been suspended since then. The local fisheries cooperative association had earned maximum of 740 million JPY (CA. 7.3 million USD, as of April 28, 2014) in 1989 from mantis shrimp fishery, but the income have been completely lost due to the fishing suspension, resulting in serious economic problems for the local bottom trawl fishery. Reproductive season of mantis shrimp in Tokyo Bay lasts from spring to late summer, during which bottom hypoxia frequently or continuously present (Kodama et al., 2004, 2009a). Our previous studies have suggested a possibility that hypoxia may have adverse effects on recruitment success of mantis shrimp in Tokyo Bay (Kodama et al., 2006a, 2009b). In order to further examine this hypothesis, we investigated effects of hypoxia on the early life stages (i.e., spatial distribution and abundance of young-of-the-year juveniles, and mortality during pelagic larval or post-settled juvenile stages) by 10-year field surveys in the bay.

2. Materials and methods

2.1. Samples

We conducted monthly sampling surveys for larvae and juveniles of mantis shrimp in Tokyo Bay between May and December from 2004 to 2013. Details of the sampling procedure have been described previously (Kodama et al., 2006a, 2009b). Briefly, monthly sampling surveys for zooplankton were carried out at 15 sites by Kanagawa Prefectural Fisheries Technology Center (survey A; May–November in 2004–2013), 22 sites (survey B;

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September–December in 2004–2005) or 25 sites (survey C; May–August in 2004–2005, and May–December in 2006–2013) by Chiba Prefectural Fisheries Research Center and National Institute for Environmental Studies, and 10 sites by National Institute for Environmental Studies (survey D; Fig. 1). We conducted a vertical tow through the entire water column with a remodeled North Pacific (NORPAC) standard plankton net (net mouth area, 0.16 m^2; mesh size, 0.33 mm; Nippon Kaiyo, Tokyo, Japan) equipped with a flow meter during surveys A–C. We also collected plankton samples at each station during survey D (conducted in only 2006) by an oblique tow through the entire water column with a large plankton net (net mouth area, 1.32 m^2; mesh size, 0.33 mm; Rigo, Saitama, Japan) equipped with a flow meter. Plankton samples were fixed in 10% neutral-buffered formalin onboard. We sorted mantis shrimp larvae from the samples in the laboratory, and measured carapace length (CL; from the base of the anterolateral spine to the base of the posterolateral spine on the carapace) of the larvae to the nearest 0.1 mm.

We used data of larvae in the early pelagic stage ($0.9 \leqslant CL < 1.5$ mm) for analyses, because larvae in the prepelagic stages and late pelagic stages are present in the bottom layer and thus quantitative sampling for larvae at these stages is difficult using a remodeled NORPAC net (Hamano and Matsuura, 1987a; Ohtomi et al., 2006). The larval density (individuals m^{-3}) was calculated for the early pelagic stage at each site by dividing the total number of larvae collected by the volume of water sampled. Because the sampling procedure for plankton in survey D was different from that in surveys A–C, we transformed larval density values that were based on samples collected by the large-sized plankton net (X; individuals/m^3) to values comparable to the larval density based on the NORPAC net (Y; individuals/m^3) through a linear regression ($Y = 0.81X + 0.02$; given by Kodama et al., 2009b). We calculated monthly larval density by averaging the larval density over sampling sites in the southern bay in a month, because larvae in the early pelagic stage were not found in the northern bay (Kodama et al., 2009b). The annual larval density was calculated by averaging monthly larval density from June to October, the months when larvae in the early pelagic stage are present (Kodama et al., 2009b).

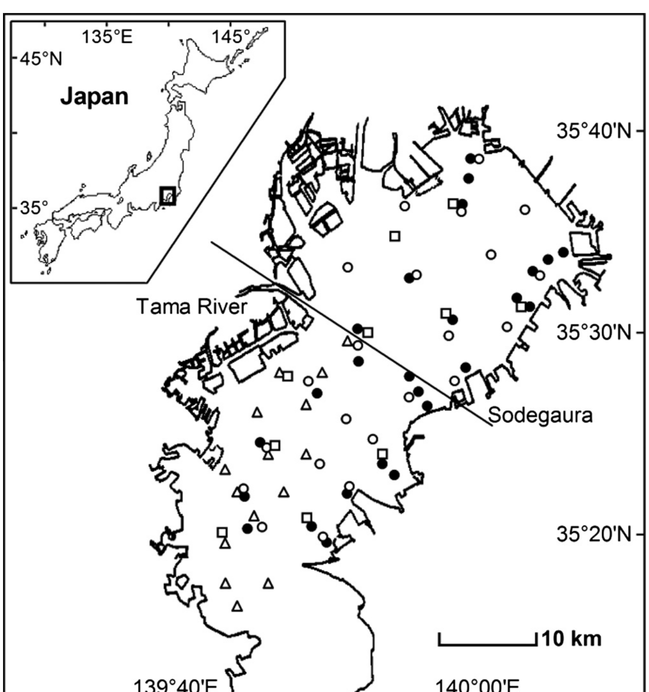

Fig. 1. Locations of sampling sites in Tokyo Bay, Japan. Sampling of *Oratosquilla oratoria* larvae was conducted during surveys A (white triangles), B (white circles), C (black circles) and D (white squares). Sampling of juveniles was conducted during surveys B and C. The line between Tama River and Sodegaura separates the bay into north and south areas.

Juveniles of mantis shrimp were collected during surveys B and C (Fig. 1) using a dredge trawl (cod-end mesh size, 1.8 cm; net mouth, 0.4 m high and 1.2 m wide), and the towed distance (m) was recorded for each site. We measured body length (BL; from the base of the rostrum to the anterior edge of the median notch of the telson) on board or in the laboratory to the nearest 0.1 cm without using any fixative solution, and counted number of individuals at each site. We regarded individuals <8 cm BL as juveniles (Kodama et al., 2006a). The juvenile density (individuals m^{-2}) was calculated at each site by dividing the total number of juveniles collected by the towed area (i.e., width of the dredge trawl [1.2 m] × towed distance [m]). We calculated mean juvenile density over all sampling sites in December as the annual juvenile density, because larval settlement is completed by December (Kodama et al., 2009b). A total of 1932 juveniles was collected during December of the survey periods (mean BL 4.6 cm, range 2.3–7.9 cm). We estimated the date of settlement of the juveniles collected, by backcalculating the number of days after settlement from mean BL of juveniles in December using the growth equation of juveniles (Hamano and Matsuura, 1987b; refer to Kodama et al., 2009b for detailed procedures).

2.2. Hypoxic data

To examine the spatial distribution of hypoxia in Tokyo Bay, we used DO contours at the bottom (<1 m above the sea bottom) published by the Chiba Prefectural Fisheries Research Center (accessed April 28, 2014; www.pref.chiba.lg.jp/lab-suisan/suisan/suisan/suikaisokuhou/index.html).

Adult of mantis shrimp is tolerant to relatively moderate hypoxic conditions (1–2 ml DO l^{-1}, Kodama et al., 2012b), and larvae could also tolerate DO concentration as low as 1 ml l^{-1} (Kodama et al., unpublished preliminary data). Therefore, we revised the DO contours so that the maps only display severely hypoxic areas (<1 ml DO l^{-1}).

Examination of hypoxia and juvenile data on the same date is not enough for assessing effects of hypoxia on the spatial distribution of juveniles, because spatial distribution of hypoxia in Tokyo Bay shows large fluctuations due to estuary circulation, or occasional wind events such as typhoons (Kodama et al., 2006a). Thus, we obtained DO contours after the estimated date of settlement of juveniles, and merged those DO contours to display the past existence of severe hypoxia after juveniles started the benthic life. Area fraction of regions where there had been severe hypoxia since the estimated date of settlement of juveniles in the northern part of the bay were calculated on the merged DO contour for each year by dividing the number of pixels of the severely hypoxic area by the total number of pixels in the northern part of the bay (the area above the line in Fig. 1)) and multiplying by 100, using Image J software (ver 1.43; National Institute for Health, USA).

2.3. Data analysis

Differences in the annual mean densities of larvae and juveniles in the whole bay area, northern area and southern area among all combinations of years were examined by the Tukey–Kramer test (Sokal and Rohlf, 1981). To investigate the quantitative relationship between larvae and juveniles, we calculated Pearson's correlation coefficient (r) between the annual mean densities of larvae and juveniles. We also calculated r between area fraction of severe hypoxia and juvenile densities in the whole, northern or southern

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