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Red tides in Shiwha Bay, western Korea: A huge dike and tidal power plant established in a semi-enclosed embayment system

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ABSTRACT

To investigate red tides in Shiwha Bay, Korea, where a 12.7-km dike with two outlets (at the water gate and tidal power plant) was constructed, we measured physical, chemical, and biological properties at 3 fixed stations inside the dike on a monthly basis from May 2008 to July 2012. During the study period, red tides were present in Shiwha Bay during 33 of 46 (i.e., 72%) sampling events. Clearly, red tides are common in the bay. Red tides occurred 33, 12, and 10 times at Stations 1, 2, and 3, respectively. Restriction of water circulation at Station 1 (in the innermost part of the bay) may cause more frequent red tides due to phototrophic dinoflagellates than at Station 3, where water exchange between the inside and outside of the dike occurs through a water gate. After the world's largest tidal power plant was established in 2011, red-tide causative species switched from phototrophic dinoflagellates such as *Gymnodinium aureolum*, *Heterocapsa rotundata*, *Heterocapsa triquetra*, *Karlodinium veneficum*, *Paragymnodinium shiwhaense*, and *Prorocentrum minimum* to diatoms such as *Chaetoceros* spp., *Skeletonema costatum*, and *Thalassiosira* spp. Exchange of seawater between the inside and outside of the dike through the tidal power plant may have resulted in this change in the causative species. Inorganic nitrogen concentrations for the growth of phototrophic dinoflagellates and small flagellates during red tides were likely unlimited, but inorganic phosphorus concentrations may be limited. Thus, some phototrophic dinoflagellates and flagellates may acquire phosphorus from prey. The maximum grazing coefficients of the heterotrophic dinoflagellates *Pfiesteria piscicida*, *Gyrodiniellum shiwhaense*, *Gyrodinium dominans*/*Gyrodinium moestrupii*, and *Protoperidinium bipes* feeding on red-tide causative taxa including cryptophytes, *Eutreptiella gymnastica*, *P. minimum*, and *S. costatum*, were found to be 0.14–0.77 h^{-1}. Therefore, heterotrophic protistan grazers in Shiwha Bay may, at times, have considerable grazing impact on populations of co-occurring red-tide organisms.

1. Introduction

Red tides have occurred often in semiclosed bays and estuaries (Reid, 1980; Kishi and Ikeda, 1986; Choi et al., 1997; Huang and Qi, 1997; Xingyu et al., 2009; Jeong et al., 2013a), although huge red tides have also occurred in oceanic waters (Kononen, 1992; Cheng et al., 2005). Restricted water circulation and/or high nutrient load from freshwater in bays and estuaries have been known to be favorable for outbreaks of red tides (Balkis, 2003; Tsutsumi et al., 2003). In addition, seasonality of water temperature, precipitation, salinity, and/or nutrient loads in semiclosed bays and estuaries of temperate regions have resulted in seasonal changes in red-tide causative species (Honer et al., 1997; Smayda, 1997; Jeong et al., 2013a,b).

Water movements such as currents, turbulence, internal wave, and mixing are known to affect formation of red tide patches (Thomas and Gibson, 1990; Tynan, 1993; Fermin et al., 1996; Juhl et al., 2000; Smayda, 2002; Franks, 2005; Omand et al., 2011). Intense turbulence and/or vigorous mixing have been shown to prevent outbreaks of red tides in some cases (Smayda, 2002). Tidal currents in shallow-water regions, where tidal range is large, can produce high-intensity turbulence or vigorous mixing (Chen and Jirka, 1998; Jirka, 2001). Tidal range in the coastal waters of western Korea (i.e., the Yellow Sea side) is approximately 9–10 m. The frequency of outbreak of red tides in western Korea was much lower than that in southern Korea, where the tidal range is 2–4 m

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(Jeong et al., 2013b; Park et al., 2013). However, huge dikes constructed in the mouths or middles of bays and estuaries in western Korean prevent tidal excursion and restrict water circulation (Yoo et al., 2002; Yih et al., 2005). Since the construction of these dikes, red tides have occurred frequently in these waters. Bays and estuaries in western Korean act as nurseries for diverse marine organisms; in fact, some bays have been used for aquaculture farms (Kim, 1997, 1998). However, red tides in these regions have been known to cause great losses for the aquaculture industry (Kim, 1997, 1998).

Many red tides have occurred in Shiwha Bay, which is located on the west coast of central Korea (Choi et al., 1997; Baek et al., 2011). This bay is surrounded by 3 highly populated large cities: Ansan, Shiheung, and Hwasung. Several small streams enter the bay (Shin et al., 2000a,b), which is long and narrow, restricting water circulation inside the bay. In 1994, a 12.7-km dike with a 100-m water gate was constructed in the mouth of the bay. Thus, water exchange between inside and outside the dike occurred only through the water gate; water circulation was highly restricted and the tidal range inside the dike was reduced to 3–5 m. In addition, the world's largest tidal power plant was constructed in the middle of the dike in 2011. Water exchange began to occur through the turbines of the tidal power plant.

To explore the dynamics of red tides in Shiwha Bay, we took water samples at 3 fixed stations inside the dike on a monthly basis from 2008 to 2012 and measured physical, chemical, and biological properties. This study provides an improved understanding of red-tide dynamics in semiclosed bay systems, in waters with high tidal ranges, and in regions where the emplacement of artificial structures has resulted in restriction or relaxation of water circulation.

2. Materials and methods

2.1. Abundances of protists and bacteria in Shiwha Bay

Shiwha Bay (43.8 km^2 in area) is located on the western coast of the central Korean peninsula (Fig. 1). A 12.7-km dike crossing the mouth of the bay was constructed in 1996, and water passed through a 100-m-long water gate before the world's largest tidal power plant was constructed in April 2011. Approximately half the water inside the Shiwha Bay (i.e., ~150 of 320 million tons waters) daily passes through ten 7.5-m diameter turbines of the tidal power plant (Bae et al., 2010). The speed of the water passing the turbines is 12–13 m s^{-1}. We explored red tides at 3 different fixed stations inside the dike: Station 1 (St. 1) was located in the innermost part at the point of entry of a small stream, Station 2 (St. 2) near the tidal power plant, and Station 3 (St. 3) near the water gate. Water depths at St. 1, St. 2, and St. 3 were 3.5–6.0 m, 11.3–13.0 m, and 5.5–10.0 m, respectively, depending on the tide (Fig. 1).

Water samples were taken at the surface at each station with water samplers during high tides every month from May 2008 to July 2012, except in frozen months (December 2009–February 2010 and January–February 2011). In addition, nutrient data were unavailable in November 2008 and January and July 2009 and pH data in July and August 2011

Plankton samples for counting were poured into 500-ml polyethylene (PE) bottles and preserved with acidic Lugol's solution (for diatoms, phototrophic dinoflagellates, cryptophytes, raphidophytes, euglenophytes, prasinophytes, and heterotrophic protists), Bouin's solution (for ciliates), or glutaraldehyde (for nanoflagellates, picoeukaryotes, and bacteria). Dominant species of protists were isolated and established in clonal cultures for identification using morphological and DNA sequencing analysis.

To determine the abundances of diatoms, phototrophic dinoflagellates, heterotrophic protists, and diverse flagellates (cryptophytes, raphidophytes, euglenophytes, etc.), samples preserved with acidic Lugol's solution were concentrated by 1/5–1/10 using settling and siphoning methods (Welch, 1948). After thorough mixing, all (or a minimum of 100) cells of each protist species in one to ten 1-ml Sedgwick–Rafter counting chambers were counted under a light microscope.

Small phototrophic or heterotrophic dinoflagellates *Gyrodiniellum shiwhaense*, *Karlodinium veneficum*, *Paragymnodinium shiwhaense*, *Pfiesteria piscicida*, *Stoeckeria algicida*, *Woloszynskia cincta*, *Azadinium* cf. *poporum*, and *Gymnodinium aureolum* were only 10–20 μm in cell length and all displayed very similar morphologies (Ballantine, 1956; Jeong et al., 2005b, 2006, 2010b; Kang et al., 2010, 2011a, 2011b; Potvin et al., 2012); thus, one species could not be distinguished from the others using only light microscopy. Therefore, we identified these species using their DNA sequences and quantified their abundance using a quantitative PCR (qPCR) method (Park et al., 2009). Total abundances of these dinoflagellates in fixed samples were enumerated and then compared to abundances quantified using the qPCR method. For qPCR analysis, aliquots of 100–250-ml water samples were gently filtered through GF/C filters and preserved at −72 °C until DNA extraction. After the genomic DNA was extracted with phenol chloroform isoamyl alcohol (25:24:1), qPCR was carried out with Platinum qPCR SuperMix-UDG (Invitrogen, Eugene, Oregon, USA) on a Rotor-Gene qPCR detection system (Rotor-Gene 3000, Corbett Research, Sydney, Australia).

In order to determine the abundance of bacteria, picoeukaryotes, and nanoflagellates, aliquots of the water samples were poured into 100-ml PE bottles and preserved with glutaraldehyde (final conc. = 1%, v/v). Three to twelve 1-ml fixed aliquots were stained with 4′,6-diamidino-2-phenylindole (DAPI, final conc. = 1 μM) and then filtered onto 0.2-μm-pore-size polycarbonate (PC) black membrane filters. Bacteria were enumerated under an epifluorescent microscope with ultraviolet light excitation (Porter and Feig, 1980). Additionally, three 1–5-ml fixed aliquots were stained with DAPI and then filtered onto 0.2-μm-pore-sized PC black membrane filters. Phototrophic nanoflagellates (PNFs; 3–6 μm cell length) that exhibited orange-colored autofluorescence under an epifluorescent microscope with blue light excitation were also enumerated.

We measured the carbon content for each of many protists species cultured in our laboratory using a CHN analyzer (Jeong et al., 2013a). For noncultured species or taxa, the length and width of cells preserved in 5% acidic Lugol's solution were measured using a light microscope and cell volume was then calculated according to geometry. The carbon content for each species of protists was calculated from the cell volume according to Menden-Deuer and Lessard (2000).

During the study period, red-tide patches were generally visible when the biomass of total red-tide causative species exceeded 200 ng C ml^{-1}. In fact, when the biomass of red-tide organisms exceeds 200 ng C ml^{-1}, a red-tide warning is announced by the National Fisheries Research and Development Institute, Korea (NFRDI, 2012). Thus, we defined red tides here as the biomass of one or sum of the top 3 causative species ≥200 ng C ml^{-1}.

2.2. Physical and chemical properties in Shiwha Bay

Water temperatures and salinities in surface waters were measured using a YSI 30 (YSI, LA, USA) and pH and dissolved oxygen (DO) was measured using pH-11 (Schott HandyLab, Mainz, Germany) and Oxi 197i (WTW, Weilheim, Germany), respectively. For inorganic nutrient analysis, the water samples were gently filtered through GF/F filter papers and moved to the laboratory and