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Environmental response to long-term mariculture activities in the Weihai coastal area, China

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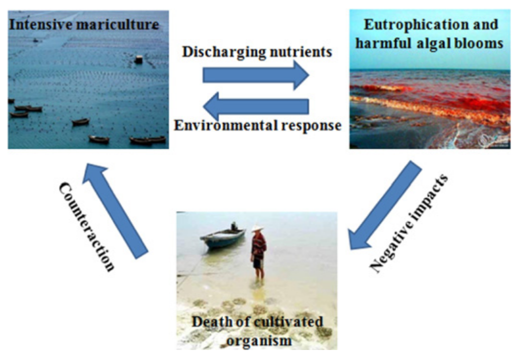
HIGHLIGHTS

- Water quality was impacted negatively by mariculture along the Weihai coast.
- Nitrogen concentrations and N/P ratio increased significantly during 2006–2014.
- Proportion of dinoflagellate in phytoplankton increased markedly during 2011–2014.
- The pH presented a potential declining trend since 2011.

GRAPHICAL ABSTRACT



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ABSTRACT

The environmental impacts of rapid expansion of mariculture have garnered worldwide attention. China is currently one of the largest countries to engage in this practice. In this study, a representative mariculture zone, the Weihai coastal area in China, was explored to determine the temporal variations in regional nutrients, N/P ratio, dissolved oxygen (DO), pH, chlorophyll *a* (Chl-a), and cellular abundance of diatoms and dinoflagellates in response to the rapid growth in mariculture activities between 2006 and 2014. The temporal variations in inorganic and organic nitrogen concentrations in the surface water presented significantly increasing trends during August, between 2009 and 2014. A marked increase in the ratios of dinoflagellate to diatom abundance, concurrently with ascending N/P ratios, was also observed during August between 2011 and 2014. In addition, dissolved inorganic nitrogen and phosphate variations revealed the highest concentrations during October and lower levels during May and August, which was attributed in part to the seasonal growth characteristics of kelp cultivated in the study area. Moreover, the nutrient concentrations in Sanggou, Rongcheng, Wulei, and Rushan bays were affected significantly by the various cultured organisms in these bays. The intensive mariculture activity in the Weihai coastal area is likely one of the causes of the negative effects on water quality, such as eutrophication and future ocean acidification. The exploration of effective strategies is quite necessary in the future for keeping good quality of coastal environment and sustainable mariculture development.

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1. Introduction

Mariculture has rapidly grown worldwide, largely in response to an increasing demand for high-quality protein for human consumption (Demirak et al., 2006; Herbeck et al., 2013; Shi et al., 2013). China has played a major role in this growth, representing ~62% of global marine fish production during 2014 (FAO, 2016). The annual production for mariculture increased from 1.4×10^7 t $year^{-1}$ in 2005 to 2.0×10^7 t $year^{-1}$ during 2015 (NBS, 2016). Intensive mariculture can negatively affect the environment through landscape modification, loss of biodiversity, and increasing risks to food safety (Mao et al., 2006; Zhou et al., 2006; Marinho-Soriano et al., 2009). For example, waste feed and faecal production can substantially increase nutrient loading inducing eutrophication (Tovar et al., 2000), which alters the pelagic and benthic community structure and potentially reduces the viability and productivity of the marine ecosystem including cultured biota (Zhang and Yang, 1999; Zhang et al., 2009; Wu et al., 2014).

In China, most mariculture activities are practiced in shallow inshore sheltered bays (Chang and Chen, 2008). The Weihai coastal area is a representative region with about a 50 year history of mariculture (Guo et al., 1999; Yang et al., 2004). It is also one of the largest mariculture production areas in China with kelp production accounting for >50% of the country's annual output. The Weihai coastal area is composed of four large bays including Sanggou, Rongcheng, Wulei, and Rushan bays, in addition to numerous small bays; all of them are used for mariculture. The various marine organisms cultivated in these bays include kelp (*Saccharina japonica*), scallops (*Chlamys farreri*), oysters (*Crassostrea gigas*), sea cucumber (*Apostichopus japonicus*), and fish, such as bass, turbot, and Japanese flounder (*Paralichthys olivaceus*) among others (Mao et al., 2006; Wang et al., 2014b). Although the impacts of mariculture activities on water quality in several individual bays, such as Sanggou Bay and Rushan Bay, have been previously studied (Mao et al., 2006; Shi et al., 2013; Jiang et al., 2015; Li et al., 2016c), the larger spatial and temporal scales along the entire Weihai coastal area have not been investigated thus far.

Intensive mariculture generates diverse effects on the environment. Good seawater quality can greatly contribute to the development of mariculture; however, poor environmental conditions adversely affect the survival of cultivated organisms (Cardoso-Mohedano et al., 2016; Urbina, 2016). The magnitude and consequences of these environmental effects caused by mariculture are embodied in several environmental characteristics including seawater temperature, salinity, pH, dissolved oxygen (DO), tidal influence, hydrodynamic characteristics, depth, and nutrient availability (Brooks and Mahnken, 2003). In particular, changes in nutrient availability can further lead to a variety of effects, such as the enhancement of chlorophyll *a* (Chl-a) concentration, the possible occurrence of anoxia and hypoxia events, ocean acidification, and toxic algal blooms (CENR, 2000; Piñón-Gimate et al., 2009; Teichberg et al., 2009). The co-occurrence of harmful algae blooms with these environmental stressors can aggravate such effects (Burridge et al., 2010; Morgan et al., 2012). Hence, water quality parameters, such as nutrients and nutrient ratios, DO, pH, Chl-a, and cell abundances of diatoms and dinoflagellates, were selected to assess the environmental effects of local mariculture activities on seawater quality in the Weihai coastal area.

The present study aims to evaluate nine years of the above mentioned water quality parameters recorded between 2006 and 2014 and to assess the environmental effects of local mariculture activities on seawater. Our working hypothesis is that long-term mariculture can produce a negative impact on the ecosystem water quality and can cause potential ecological risk in the Weihai coastal area. This work demonstrates the need for monitoring the environmental quality in marine organism cultivation areas. The results of this study are crucial for developing sustainable fisheries in coastal ecosystems and for enhancing food security on a global scale.

2. Materials and methods

2.1. Study area

The Weihai coastal area (36°30′–37°54′ N, 121°6′–123°6′ E) is located at the east end of Shandong Peninsula, China (Fig. 1A and B), and is surrounded by the Yellow Sea in the north, east, and south with a 986 km total coastline (Li et al., 2016b). The average and maximum water depths in this coastal area are 13 m and 45 m, respectively (Li et al., 2016a).

Rongcheng, Sanggou, Wulei, and Rushan bays are located along the Weihai coast (Fig. 1C; Supplementary Fig. S1). Rongcheng and Sanggou bays contain multi-trophic mariculture involving mainly shellfish and kelp culturing (Jiang et al., 2015), whereas only a single type of shellfish is farmed in Wulei and Rushan bays. Only 6–12% of the total mariculture area was used for sea cucumber or fish farming in the four bays (MEB, 2012). Areas occupied by mariculture in Sanggou, Wulei, Rushan, and Rongcheng Bays were 15×10^3 ha, 10×10^3 ha, 3×10^3 ha, and 2.8 $\times 10^3$ ha, respectively (MEB, 2014). Many small bays used for marine organisms' cultivation in the Weihai coastal area include Weihai, Shidao, and Jinghai bays (Fig. 1C).

Well known for its high primary productivity in Chinese coastal areas, Sanggou Bay (37°01′–37°09′ N, 122°24′–122°35′ E), with a mean depth of 7.5 m, is a semi-enclosed bay which occupies the largest mariculture area among the above four bays (Li et al., 2016c). Thus, the water qualities of its mariculture and non-mariculture zones were selected for study. Most local mariculture is floating raft and long-line cultures within the bay (Zhang et al., 2009; Zeng et al., 2015). Filter-feeding shellfish, such as scallops and oysters are cultivated in Sanggou Bay from May to November, whereas kelp is grown in the bay from late autumn to spring, November to May, and is harvested from late spring to summer, late May to July (Fang et al., 1996). The annual production of the main cultivation species in Sanggou Bay during 2011, including kelp (*Saccharina japonica*), oyster (*Crassostrea gigas*), and scallop (*Chlamys farreri*), was 84,500 tons (dry weight), 60,000 tons (wet weight), and 15,000 tons (wet weight), respectively (Rongcheng Fishery Technology Extension Station, 2012). To assess the water quality under long-term mariculture conditions, a mariculture zone was defined on the basis of long-time mariculture activities and occupied areas in Sanggou Bay (Ning et al., 2016). An offshore region along the mariculture zone was subsequently defined as a non-mariculture zone (Supplementary Fig. S2).

2.2. Data sources

Historic mariculture area and production data from 2006 to 2014 were collected from the Bureau of Statistics of Weihai city (http://www.stats-wh.gov.cn/). In addition to the above two parameters, all surface water quality parameters including dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP or PO_4-P), total dissolved nitrogen [TDN = DIN + dissolved organic nitrogen (DON)], total dissolved phosphorus [TDP = DIP + dissolved organic phosphorus (DOP)], the N/P ratio (=DIN/DIP), DO, pH, and Chl-a were measured in this study during nine cruises (Cruise Nos. 1, 2, 3, 4, 5, 7, 10, 13, 16; Supplementary Table S1) in August every year between 2006 and 2014 (Supplementary Fig. S3). The results were used to analyse the temporal variations in the different parameters. The abundances of diatoms and dinoflagellates were also determined during four August cruises between 2011 and 2014 (Cruise Nos: 7, 10, 13, 16; Supplementary Table S1). The seasonal patterns of the water quality parameters were assessed from data collected during 12 cruises in May, August, and October of 2011–2014 (Cruise Nos.: 6–17; Supplementary Table S1). For comparison, water quality data of the four mariculture bays (i.e. Rongcheng, Sanggou, Wulei, and Rushan bays) were analysed from water collected during the aforementioned 12 cruises in these bays in May, August, and October every year during 2011–2014 (Cruise