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Eutrophication assessment and bioremediation strategy using seaweeds co-cultured with aquatic animals in an enclosed bay in China

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ABSTRACT

Intensive mariculture results in a rise in nutrient concentrations, then leads to serious eutrophication in coastal waters. Based on the sampling data obtained between August 2012 and July 2013, the eutrophication status in Yantian Bay was assessed, and the proportion of marine animals co-cultured with seaweeds was evaluated. The nutritional quality index (*NQI*) ranged from 4.37 to 13.20, indicating serious eutrophication conditions. The annual average ratio of nitrogen/phosphorus (N/P) was 25.19, indicating a nitrogen surplus in this system. DIN was selected as the best parameter to balance seaweed absorption and marine animal DIN production. *Gracilaria lemaneiformis* and *Laminaria japonica* were selected as co-cultured seaweeds. The optimal proportion of *G. lemaneiformis* production was assessed as 20074.14 tonnes. The optimal proportion of *L. japonica* production was evaluated as 15890.68 tonnes. High-temperature adapted seaweeds should be introduced for removing nutrients releasing by farmed aquatic animals in the summer in Yantian Bay.

1. Introduction

With declining catches in the marine fishery industry, mariculture has expanded and has had large impacts in recent years (Neori et al., 2004; Chen et al., 2014). There has been increasing output to meet the growing global demand for aquatic products (Halwart et al., 2007; Wilfart et al., 2013; Ferreira et al., 2014). Intensive mariculture is the predominant activity in bays or in coastal lagoons today (Muller-Feuga, 2000; Troell et al., 2003; Diana et al., 2013). During cultivation, a large quantity of organic pollutants are produced; organic waste from farming activities such as uneaten food and faeces are degraded into inorganic pollutants, which results in nutrient enrichment of water. (Maroni, 2000; Holmer et al., 2002; Carroll et al., 2003; Hu et al., 2013; Farmaki et al., 2014). The high nutritional status changes the characteristics of the ecosystem and causes a series of ecological events, including red tides, green tides and other disasters (Nagasoe et al., 2010; Glibert et al., 2011; Schumacher et al., 2014). Intensive mariculture is regarded as an important source of serious environmental deterioration (Karakassis et al., 2000; Rosa et al., 2002; Sara et al., 2004; Buschmann et al., 2006).

To deal with the eutrophication resulting from mariculture in sea areas, many methods have been proposed, among them integrated multi-trophic aquaculture (IMTA) which is increasingly popular as it can remove pollutants and increase the potential economic value (He et al., 2008). Integration of seaweeds with fish, shrimps and other aquatic animals has been suggested as a good method to counteract the release of dissolved nutrients (Nobre et al., 2010; Scherner et al., 2012). Dissolved nutrients are absorbed by seaweeds and result in increased biomass (Bolton et al., 2006). As a result, the concentration of dissolved nutrients is reduced and both seaweeds and cultured aquatic animals can be farmed (Ridler et al., 2006).

Sansha Bay in the Fujian province of China with a area of 714 km^2 is one of the most important aquaculture bases on the coast of the East China Sea. To date, the number of fish cages in the bay is 220,000, mainly for *Pseudosciaena crocea*, *Micropterus salmoides* (largemouth bass) and Sparidae (Su, 2009). The shape of each cage was $3 \times 3 \times 3$ m, and the mesh size was 2.0–4.5 cm. Most of Sansha Bay is suffering from severe eutrophication conditions (Cai et al., 2007). The purpose of the present study was to evaluate the environmental impacts of mariculture on the water column in Yantian Bay, one of enclosed bays in Sansha Bay, and suggest the appropriate proportion of marine animal to seaweeds

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to be co-cultured. The results would help in the decision on the number and size of marine animals that could be farmed in a particular water area, and may also contribute to the reduction of aquacultural self-pollution and the promotion of the IMTA system.

2. Materials and methods

2.1. Study area and survey methods

This study was conducted in the mariculture sea area of Sansha Bay (119°7′–119°9′E, 26°′7″–26°8′48″N), which is an enclosed bay in China; the sea area was 405.86 km^2 (Fig. 1). The exchange of water is mainly influenced by tides, so that the direction and velocities of the current are consistent with the tide. The tidal current pattern is semidiurnal with an average tidal range of 2.7–3.3 m and an average flow rate of 0.5–0.6 m s^{-1}. Animal production from July 2012 to August 2013 was determined. Based on our investigated data, *P. crocea* was cultured in approximately 15,520 cages in Yantian Bay, and the annual output was approximately 9670 tonnes. The annual output of other two aquatic animals, *Crassostrea gigas* and *Apostichopus japonicus*, was 5790 tonnes and 32.5 tonnes, respectively. Macroalgae *Gracilaria lemaneiformis* and *Laminaria japonica* were cultured in different seasons and the annual output was 21,820 tonnes and 1360 tonnes, respectively.

Samples were taken each month between August 2012 and July 2013 from ten sampling sites on each occasion (Fig. 1). Sampling site 1 was located in a non-mariculture sea area; sampling site 3 was located in a *C. gigas* cultured area; sampling site 4 was located in a *P. crocea* cage area; other sampling sites were distributed in the seaweed cultivation areas. Macroalgae *L. japonica* was mostly cultivated between January and November in Yantian Bay, and *G. lemaneiformis* was mostly cultivated between September and December. There were no macroalgae cultivated between June and August in Yantian Bay.

2.2. Water sample collection and nutrient concentrations determined

At each sampling site, the surface temperature, salinity and pH were measured in the field using a multi-parameter kit (MS5, HACH). Three water samples were taken at three places surrounding every site during the slack tide time at a depth of 15–20 cm below the surface using Niskin bottles and measured for levels of: ammonium (NH_4–N), nitrite (NO_2–N), nitrate nitrogen (NO_3–N), soluble reactive phosphorus (PO_4–P), chemical oxygen demand (COD), chlorophyll *a* (Chl *a*) and dissolved oxygen (DO). Seawater samples for dissolved inorganic nutrients measurements were filtered through cellulose membranes (0.45 μm) which were pre-immersed in 10% HCl for at least 10 h and rinsed with distilled water many times before use, and a small amount of Mercury(II) chloride was added. DO concentrations at different seawater depths were measured in the field using the Winkler method. Water samples used for Chl *a* determination were filtered onto GF/F glass-fiber filters. All seawater samples were transported to the laboratory under cold conditions and preserved in the freezer at −30 °C. In the laboratory, NH_4–N, NO_2–N, NO_3–N and PO_4–P concentrations were measured according to protocols of the Joint Global Ocean Flux Studies (1994). COD was measured directly by the marine water quality standard (GB17378.4-2007). Chl *a* samples were extracted using 90% aqueous acetone, and the concentration of Chl *a* was determined fluorometrically (Parsons et al., 1984) using a Turner Designs fluorometer.

2.3. Nitrogen content of L. japonica and G. lemaneiformis

From the beginning to the end of the macroalgae cultivation, 10–20 clusters of seaweeds were randomly collected in the cultivation area to measure the tissue nitrogen content. Samples collection of *L. japonica* and *G. lemaneiformis* were from September 2012 to December 2012 and from January 2013 to May 2013 monthly, respectively. After the collection, samples were rinsed and placed in oxygenated sealed plastic boxes filled with local seawater, kept under cool conditions, and transported to the laboratory. In the laboratory, samples were rinsed gently with running filtered seawater (0.45 mm filter membrane), rinsed with distilled water 3–4 times. Then the samples were dried in an oven at 60 °C, ground into powder using the experimental mill made by Christy and Norris, and the nitrogen content (%) was measured using an automatic Kjeldahl apparatus (KJELTEC2300).

2.4. Eutrophication assessment

The eutrophication assessment was based on whether the nutritional quality index (*NQI* value) was greater than or equal to 3 according to the nutritional quality index method (*NQI*) used elsewhere (Zhang et al., 2009). The *NQI* value was evaluated as follows: $NQI = C_{COD}/C'_{COD} + C_{DIN}/C'_{DIN} + C_{DIP}/C'_{DIP} + C_{Chl\ a}/C'_{Chl\ a}$, where C_{COD}, C_{DIN}, C_{DIP} and $C_{Chl\ a}$ were measured values, and values of C'_{COD}, C'_{DIN}, C'_{DIP} and $C'_{Chl\ a}$ were 2.0, 0.20, 0.015 mg L^{-1} and 5.0 μg L^{-1} according to the marine water quality standard (GB3097-1997), respectively.

2.5. Nitrogen balance determined

Nitrogen was selected as the balance parameter in this paper because of the surplus of nitrogen in mariculture sea areas of Yantian Bay according to the results of the present study. *L. japonica* and *G. lemaneiformis* were selected as the bioremediation species in the period December–May (winter and spring) and September–November (summer and autumn), respectively based on their biological characteristics. To balance the nitrogen excretion quantity by aquatic animals cultured and uptake quantity by seaweeds cultivated, the nitrogen balance equation can be represented as follows: $N_{(seaweed)} = N_{(excretion)} + N_{(feed\ \ residue)} + N_{(dead)}$ (Jiang et al., 2010). In the equation, the ammonium excretion rates of *P. crocea*, *C. gigas* and *A. japonicus* were measured in closed respiration chambers (Li et al., 2002; Mao et al., 2006), where $N_{(seaweed)}$ represents the nitrogen which was removed by the harvest of seaweeds.

2.6. Data analysis

All statistical analyses were performed using SPSS software (v.17.0SPSS Inc.). All data were displayed as the mean ± standard deviations and were multi-compared by one-way ANOVA. Differences were considered significant when $P < 0.05$.

3. Results

3.1. Hydrographic conditions and Chl a

Table 1 showed the monthly ranges of temperature, salinity, pH, DO, COD and Chl *a* during the monitoring period in Yantian Bay. The average temperature, salinity and pH was 20.74 °C, 24.01 ppt and 7.73 during the period, respectively, and was in the range of 12.49–30.17 °C, 19.03–27.74 ppt and 7.53–7.89, respectively. The geographical variation of the sea surface pH and salinity showed similar trends in different months, which indicated that pH and salinity increased from the inner bay to the mouth of the bay. The mean value of DO and COD was 7.15 mg L^{-1} and 0.84 mg L^{-1}, respectively, and was in the range of 6–8.14 mg L^{-1} and 0.48–1.72 mg L^{-1}, respectively. The average Chl *a* concentration was

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