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Dynamics of dissolved nutrients in the aquaculture shrimp ponds of the Min River estuary, China: Concentrations, fluxes and environmental loads

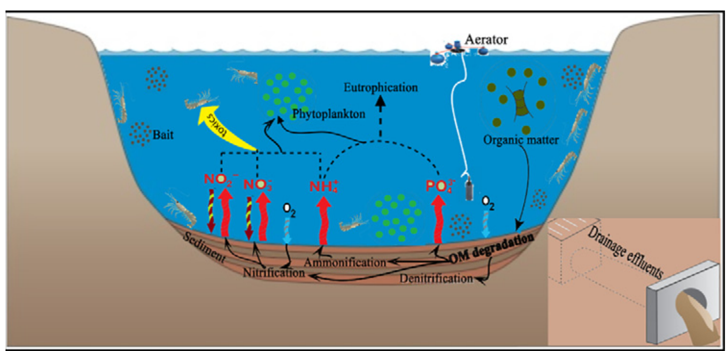
Ping Yang [a,b], Derrick Y.F. Lai [c], Baoshi Jin [a], David Bastviken [d], Lishan Tan [a], Chuan Tong [a,b,e,*]

[a] School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, PR China
[b] Key Laboratory of Humid Subtropical Eco-geographical Process of Ministry of Education, Fujian Normal University, Fuzhou 350007, PR China
[c] Department of Geography and Resource Management, and Centre for Environmental Policy and Resource Management, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China
[d] Department of Thematic Studies-Environmental Change, Linköping University, Linköping, Sweden
[e] Research Centre of Wetlands in Subtropical Region, Fujian Normal University, Fuzhou 350007, PR China

HIGHLIGHTS

- NH_4^+-N was the predominant species of dissolved inorganic nitrogen in shrimp ponds.
- Dissolved inorganic nutrients varied greatly among different shrimp growth stages.
- Aquaculture pond effluent is a key contributor to China's coastal water pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

Dissolved inorganic nutrients (NO_2^--N, NO_3^--N, NH_4^+-N, and PO_4^{3-}-P) play a critical role in the effective management of water quality and prevention of fish and shrimp diseases in aquaculture systems. In this study, dissolved inorganic nutrient concentrations in the water column and sediment porewater, and the fluxes across the sediment-water interface (SWI) were investigated in three intensive shrimp ponds with zero water exchange to examine nutrient cycling during the different growth stages of shrimps. Distinct changes in the dissolved inorganic nutrient concentrations in both the water column and sediment porewater were observed among the three growth stages. Average NO_2^--N, NO_3^--N, NH_4^+-N, and PO_4^{3-}-P concentrations in the sediment porewater were 3.53, 2.81, 29.68, and 6.44 times higher, respectively, than those in the water column over the study period, indicating that the pond sediment acted as a net source of nutrients to the water column. This was further supported by the net release of nutrients from the sediments to the water column observed during the incubation experiment. Nutrient fluxes were dominated by NH_4^+-N, while NO_x^--N (NO_2^--N and NO_3^--N) and PO_4^{3-}-P fluxes remained low. The high rates of NH_4^+-N release from the sediment highlight the need of taking into account the biogeochemical role of sediments in mitigating the problem of water quality degradation in coastal shrimp ponds. Based on a total water surface area of mariculture ponds and a total mariculture production of 2.57×10^6 ha and 2.30×10^9 kg, respectively, we estimated conservatively that approximately 4.77×10^4 tons of total nitrogen and 3.75×10^3 tons of total phosphorus are being discharged annually from the mariculture

* Corresponding author at: School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, PR China.
E-mail addresses: yangping528@sina.cn (P. Yang), tongch@fjnu.edu.cn (C. Tong).

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ponds into the adjacent coastal zones across China. Results demonstrated the importance of aquaculture pond effluent as a major contributor of water pollution in the coastal areas of China, and called for actions to properly treat these effluents in alleviating the eutrophication problem in the Chinese coastal zones.

1. Introduction

Global aquaculture production has increased dramatically over the past 50 years, with an average annual increase rate of 8.3% during the period of 1970–2008, to meet the rising demand around the world for protein (FAO, 2010). Intensive shrimp aquaculture (FAO, 2016), in which shrimp are raised at very high densities in closed or semi-closed systems with constant supply of oxygen, water, and food, is seen as an important component in sustaining a steady aquaculture production because of its short production cycles and high product values (Silva et al., 2013; Molnar et al., 2013). According to data from the Food and Agriculture Organization (FAO), global food shrimp (prawn) culture reached a total annual production of about 2.1 million tonnes in 2015 (FAO, 2016). Although intensive aquaculture has been very effective in responding to the ever-growing global demand for aquaculture food, it has also been linked to serious environmental problems.

One of the key environmental concerns regarding intensive aquaculture is the accumulation of nutrients (especially inorganic nitrogen and phosphorus), which can cause water quality problems within ponds (Hargreaves and Tucker, 2004; Castillo-Soriano et al., 2013; Hu et al., 2014) and subsequently shrimp diseases. In general, intensive aquaculture shrimp ponds are maintained through daily supply of feeds. However, only a small proportion of these nutrient inputs are being converted into shrimp biomass, as the feed utilization efficiency is only about 4.0–27.4% (Su et al., 2009; Chen et al., 2016). Consequently, the majority of the nutrients in the residual feeds are retained in the pond water. Once the accumulation of nutrients in pond water exceeds the tolerance threshold, adverse effects in the form of harmful algae blooms and water quality deterioration could be seen in the aquaculture ponds (Huang et al., 2016; Yang et al., 2017a). More importantly, high concentrations of nutrients (especially ammonia and nitrite) in the water column can stimulate the release of corticosteroid hormones into the venous circulation of shrimps (Hu et al., 2014), which may be hazardous to shrimp health and thus cause a reduction in shrimp productivity. Understanding the nutrient dynamics of intensive aquaculture ponds therefore is critical for proper pond management and improvement of shrimp yield.

Another key environmental concern regarding intensive aquaculture is the discharge of pond effluents into the water bodies of the nearby coastal zones. In general, the water column is the main habitat for animals in aquaculture ponds, and its conditions are closely associated with the healthy growth of fish, shrimp, and other organisms (Yang et al., 2017b). Complete drainage of pond water is typically done at the end of each aquaculture production cycle, in order to aerate the bottom soils and discard the water polluted with nutrients and wastes in preparation of the next round of aquaculture production (Wang and Wang, 2007; Wu et al., 2014). During this process, large quantities of water enriched with nutrients are discharged into the adjacent ecosystem over a very short period of around a month (Wu et al., 2014). Such practice can rapidly alter the nutrient levels and quality of nearby waters, and thus create eutrophication problems in the coastal ecosystems. Impacts of the discharge of aquaculture effluents on the water quality in coastal creeks (Wolanski et al., 2000; Burford et al., 2003; Costanzo et al., 2004) and mangrove swamps (Molnar et al., 2013; Cardoso-Mohedano et al., 2016a, 2016b) have already received great attention. However, very few studies have investigated the effects of aquaculture pond effluents on the trophic status of receiving coastal waters (Herbeck et al., 2013).

In the Asia-Pacific region where approximately 90% of the world's aquaculture production takes place, land-based aquaculture pond culture is the most important method of shrimp production in freshwater and brackish water systems (FAO, 2010). China has the world's largest mariculture industry, with a total mariculture pond area and total aquaculture production of 2.57×10^6 ha and 2.30×10^9 kg, respectively, in 2015 (Chen et al., 2016). In view of this, studying the nutrient dynamics of aquaculture ponds in China is essential for promoting the sustainable development of the aquaculture industry and assessing the likely risks of eutrophication of coastal water bodies. The main objectives of this study were to: (1) investigate the temporal variability of dissolved inorganic nutrients in the water column and sediment porewater of aquaculture shrimp ponds in China at different growth stages of shrimps, (2) assess the nutrient fluxes across the sediment-water interface (SWI) of these ponds, and (3) evaluate the impact of effluent discharge from these aquaculture ponds on the trophic status of receiving coastal waters.

2. Materials and methods

2.1. Study area description

The study site is located in Shanyutan wetland (ca. 3120 ha) of the Min River estuary in southeast China (Fig. 1). The area has a subtropical monsoon climate, which is relatively warm and wet, with a mean annual temperature of 19.6 °C and a mean annual precipitation of ~1350 mm (Tong et al., 2010). Shrimp ponds are a dominant landscape feature in the Min River estuary (Yang et al., 2015). The total area of shrimp ponds in the Shanyutan wetland is about 234 ha. These ponds were converted in 2011 by complete removal of all marsh vegetations. Aquaculture production in the majority of the shrimp ponds occurs between June and November.

2.2. Shrimp pond system and management

As the optimal water temperatures for the growth of shrimp (*Litopenaeus vannamei*) are 22 to 35 °C, only one crop of shrimps can be produced per year in our study site. Prior to shrimp production, the ponds were filled with estuarine water from the Min River estuary using a submerged pump. The water first passed through a 2 mm mesh bag in order to prevent to the entry of predators and competitors (Guerrero-Galván et al., 1999). Additional input of freshwater into the ponds took place occasionally during rainfall events. No water was discharged from the spillways of the ponds until the end of shrimp harvesting. The water depth in the shrimp ponds over the culture period ranged between 1.1 and 1.5 m, with a mean of 1.4 m.

To assess nutrient cycling during the culture period, water and sediment samples were collected from three commercial shrimp ponds in the Shanyutan wetland (26°01′49″ N, 119°37′39″ E) of the estuary (Fig. 1). The basic details of the three ponds are shown in Table 1. Before stocking, each shrimp pond was fertilized with 37.5 kg ha^{-1} of urea (46% N) and 5.2 kg ha^{-1} of phosphate fertilizer (38% P_2O_5). Postlarval (PL) *Litopenaeus vannamei* shrimps of approximately 0.9–1.2 cm in length were successively stocked in the ponds from mid- to late-May, and feeding was initiated simultaneously. The shrimp production cycle began on May 15, and lasted for about 163 days. *L. vannamei* were fed with artificial feeds containing 42% of crude protein (Yuehai™, Guangzhou, China) twice per day at 07:00 and 16:00 (local standard