Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China

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H I G H L I G H T S

- Annual pond drainage caused serious nutrient pollution in offshore environment
- Coastal shrimp ponds were strong and temporally variable atmospheric N_2O sources
- Harvested shrimp biomass and sedimentation were the main nutrient outputs
- Regular sediment removal can be a simple and effective mitigation strategy

A B S T R A C T

Aquaculture can cause serious environmental pollution in the coastal zone. The construction of nutrient budget can provide a scientific basis for understanding the fate of nutrients in the aquaculture systems to facilitate sustainable aquaculture management. In this study, we characterized the nitrogen (N) and phosphorus (P) budgets of coastal land-based aquaculture ponds practicing monoculture of whiteleg shrimps (*Litopenaeus vannamei*) at the subtropical estuarine zone in southeastern China. Our results showed that commercial feed was the main input of both N (> 90%) and P (> 95%) during the farming period. N output was mainly through biomass harvesting (43–49 %) and sedimentation (28–44 %), with N_2O emission only representing a small fraction of total N loss (≤ 0.03%). Similarly, most of the P was lost through sedimentation (56–68 %) and biomass harvesting (27–31 %). Despite the relatively high nutrient utilization efficiencies of the shrimp ponds, annual drainage of the ponds discharged 49.4 tons of N and 4.7 tons of P into the Min River Estuary, posing a serious threat to water quality. Based on the measured N_2O emissions in this study, coastal shrimp ponds in China were estimated to release ca. 1.2 Gg N_2O yr^{-1} to the atmosphere, contributing to 2.9% of the global aquaculture N_2O emission. We found that approximately 10% of our nutrient budgets remained unresolved, which might be related to volatilization, seepage and periphyton growth. Better feed formulation, optimized feeding practice and effective sediment management are suggested to help minimize the environmental impacts of the fast-expanding shrimp aquaculture sector in China. Future studies should compare N_2O emissions among aquaculture systems with different nutrient utilization efficiencies to

improve our assessment of the overall climatic impact of aquaculture operations.

Keywords: Nutrient budget; Nitrous oxide (N_2O) flux; Zone sampling; Aquaculture ponds; Subtropical estuary

1. Introduction

The demand for aquatic animal proteins, such as shrimps, has been growing rapidly around the world in recent years (FAO, 2018). The global yield of shrimps in 2015 alone was ca. 2.1 million tons, with the whiteleg shrimp (*Litopenaeus vannamei*) being widely cultivated in the coastal earthen ponds in the Asia-Pacific region (FAO, 2016). Coastal shrimp aquaculture can provide a number of benefits, such as job creation, improvement of rural economy and food security, etc. (Hu et al., 2012). While shrimp aquaculture production is maintained through a regular supply of feeds (Wang et al., 2018), only a small portion of the feeds is actually converted into animal biomass (Avnimelech and Ritvo, 2003; Chen et al., 2016; Sahu et al., 2013). A high ratio of feed quantity to biomass production, also termed as the feed conversion ratio (FCR), not only represents a loss of productivity, but also the accumulation of excess nutrients as wastes in the pond water and the sediment (Chen et al., 2016; Yang et al., 2017a). Nutrient-rich effluents discharged from the ponds can pose a threat to environmental quality in the neighboring areas (Herbeck et al., 2013; Mook et al., 2012; Zhang et al., 2016).

Of the various nutrient pollutants, nitrogen (N) and phosphorus (P) are of main interest because they are the key ingredients in aquaculture feeds and excreta, and contribute to eutrophication when being discharged into the coasts (Nhan et al., 2008). As such, N and P are the common currency to quantify the environmental impacts of coastal shrimp farms and assess the relative contributions of various pollution sources (Cao et al., 2007; Páez-Osuna, 2001). Studies in Mexico showed that while the total amounts of N and P nutrients discharged from the coastal shrimp farms were smaller than those from agricultural and municipal discharges, the environmental impact of shrimp farming could still be high in some local areas (Páez-Osuna et al., 1998; Páez-Osuna et al., 1999).

Previous studies of the environmental impacts of aquaculture tended to focus on nutrient dynamics in the water but overlook N loss via gaseous exchange. The organic residues such as excess feeds, fecal matters and detritus in the aquaculture ponds may provide an abundant supply of labile organic compounds that stimulate microbial decomposition and the subsequent production of greenhouse gases including N_2O (Bhattacharyya et al., 2013; Hu et al., 2012; Yuan et al., 2021). Recently, Yuan et al. (2019) estimated that freshwater aquaculture systems in the top 21 producers worldwide emit approximately 36.7 Gg N_2O yr^{-1} to the atmosphere. Similarly, coastal aquaculture ponds can be a source of N_2O (Yang et al., 2015). N_2O is a highly potent greenhouse gas with a sustained-flux global warming potential 300 times higher than that of carbon dioxide (CO_2) on a per unit mass basis over a 100-year period. Therefore, N_2O emission not only represents an alternative path for N loss in aquaculture systems, but also a potential environmental problem arising from aquaculture operation.

Rapid expansion of the aquaculture industry globally raises serious environmental concerns (MacLeod et al., 2020). In China, small-hold earthen shrimp ponds are among the fastest growing aquaculture operations (FAO, 2017) and are widely distributed in the tropical and subtropical coastal areas. In order to properly manage these aquaculture systems, improve productivity and mitigate environmental impacts, it is essential to measure the input and output of major nutrients, including N and P (Zhang et al., 2016; Zhang et al., 2018), as well as the feed conversion efficiency of farmed organisms within the system (Green and Boyd, 1995; Guo et al., 2017). In this study, the objectives were to: (i) determine the N and P budgets of earthen shrimp ponds at a subtropical estuarine zone in southeastern China by account for various input and output components; (ii) quantify the N_2O flux from the ponds to the atmosphere during the farming period; and (iii) assess the environmental impact of effluent discharge and N_2O emission arising from coastal shrimp aquaculture.

2. Materials and methods

2.1. Study area

The study was conducted in three earthen shrimp ponds at the Shanyutan Wetland, which is the largest tidal wetland (ca. 3120 ha) in the Min River Estuary, southeastern China (Fig. 1). The region is influenced by a subtropical monsoonal climate, with an annual mean temperature of 19.6 °C and an annual precipitation of 1,350 mm (Tong et al., 2010). The wetland is influenced by a typical semidiurnal tide with a tidal range of approximately 2.5–6 m. Its dominant vegetation species include the invasive *Spartina alterniflora*, and the native *Cyperus malaccensis* and *Phragmites australis*. Shallow aquaculture ponds, a common feature in the wetland, were created by removing the marsh vegetation (Yang et al., 2017b). They account for approximately 30% of the total area of the Shanyutan Wetland.

2.2. Shrimp pond preparation and management

The farming period was between May and November, with one crop of shrimps produced per year. The initial steps of pond preparation included cleaning and reinforcing the pond bank and draining the pond to dry the sediment. Next, lime (CaO) was added at a rate of 1.5 t ha^{-1} and the ponds were dried for 10 days. Afterward, brackish water from the adjacent estuary was pumped through a filter bag into the pond. Approximately 7 days after filling, the pond water was disinfected with trichloroisocyanuric acid (1.5 mg L^{-1}). A few days later, fertilizer (calcium superphosphate) was added at a rate of 1.5–2.0 kg 1000 m^{-3} daily for 7–10 days. Before stocking, probiotics (Zhengzhou Nongfukang Biotechnology Co., Zhejiang province, China) were added a dose of 200 mL 1000 m^{-2}. Basic physico-chemical parameters (e.g., pH, salinity, alkalinity, water color, etc.) of pond water were monitored to ensure they were within an appropriate range.

Each pond was stocked with juveniles (postlarvae) of *Litopenaeus vannamei* at a density of ca. 200 ind m^{-2}. The shrimps were fed with commercial feed pellets containing 42% crude protein (Yuehai™, Guangzhou, China) once in the morning (07:00) and once in the afternoon (16:00). Five paddlewheel aerators were activated four times a day (07:00–09:00, 12:00–14:00, 18:00–20:00, and 00:00–03:00) in each pond to facilitate aeration. During the farming period, pond water was not drained, but water was added twice to compensate for evaporation and seepage loss. After shrimp harvesting, water was discharged through the pond spillways. Further details of the three shrimp ponds are given in Table 1.

2.3. Field sampling

Each of the ponds was divided into three zones according to the microtopographic feature, water depth and management practices (Fig. S1) (Zhang et al., 2019). Zone N was the nearshore area, with a small amount of submerged vegetation. Zones F was a deep-water area (ditch) for feeding, while zone A was a shallow-water area (platform) where the aerators were located. Water depths in zone N, F and A were typically 0.3–0.5 m, 1.4–1.6 m and 0.7–1.1 m, respectively. In each pond, five sampling points were established along a transect from zone N to zone A. Taking into account the shrimp grow-out cycle as well as the need to minimize interference with the aquaculture operation, samples were collected two to three times every month during the farming period.

2.4. Environmental variables

Hydrographical variables (e.g., water temperature, pH, dissolved oxygen, and salinity) were measured *in situ* at two different water depths (i.e. ca. 20 cm below the water surface and 5 cm above the surface sediment). Water temperature and pH were measured by a submersible probe (IQ150, IQ Scientific Instruments, USA) with a precision of ±1.0%. Water salinity and dissolved oxygen (DO) concentrations were measured by a salinity meter (Eutech Instruments-Salt6, USA) and a multiparameter probe (550A YSI, USA), respectively. The detection limits for salinity and DO were 0.1 ppt and 0.1 mg L^{-1}, respectively. The relative standard deviations (RSD) of salinity and DO analyses were ≤ 1.0% and ≤ 2.0%, respectively.

2.5. Collection and analysis of water samples

Inflow and outflow water samples were collected from the inlet and outlet, respectively, in each pond using a 5-L Niskin sampler. Surface and bottom pond water samples were also collected. Precipitation was quantified by a rain gauge and rainwater samples were collected with a beaker five times over the entire study period. All the water samples were transferred into 200 mL polyethylene bottles, and 0.2 mL of saturated $HgCl_2$ solution was added to each bottle to inhibit microbial activities (Zhang et al., 2013). Water samples were kept dark and cold and transported back to the laboratory within 4–6 hr. In the laboratory, a portion of each water sample (about 50 mL) was filtered through a 0.45 μm cellulose acetate filter (Biotrans™ nylon membranes). The filtrates were stored in 50 mL polyethylene bottles and subsequently analyzed for NO_3^--N, NH_4^+-N, TDN (total dissolved nitrogen), PO_4^{3-} and TDP (total dissolved phosphorus) concentrations using a flow injection analyser (Skalar Analytical SAN^{++}, Netherlands). The detection limit and RSD were 0.6 μg L^{-1} and ≤3.0% for NO_3^-–N, 0.6 μg L^{-1} and ≤3.0% for NH_4^+–N and 3.0 μg L^{-1} and ≤2.0% for TDN. The detection limits and RSD were 0.2 μg L^{-1} and ≤2.0% for PO_4^{3-} and 0.3 μg L^{-1} and ≤3.0% for TDP.

2.6. Analysis of biomass, feed and sediment

Samples of the stocked animals (*L. vannamei*), feed and harvested animals were oven-dried at 60 °C for 24 h (Dien et al., 2018), and then ground and sieved with a sample sifter (pore size 0.15 mm). Sediment samples (0–20 cm) were collected monthly from all sampling points along each transect by a cylindrical metal corer (6 cm diameter) and kept dark and cold until analysis. In the laboratory, the sediment samples were freeze-dried, homogenized, and then ground into a fine powder for the analyses of nutrient content. NO_3^--N, NH_4^+-N and PO_4^{3-} were determined according to Laskov et al. (2007) and Tu et al. (2010). Total nitrogen (TN) and total phosphorus (TP) were measured by an elemental analyzer (Elementar Vario MAX CN, Germany) and molybdenum yellow spectrophotometry (NSMCC, 2002; Zhang et al., 2018), respectively.

2.7. Gas sampling and N_2O flux calculation

N_2O flux across the air-water interface was measured using the floating chamber method (Natchimuthu et al., 2016). Each chamber (opaque) had a base area of 0.1 m^2 and a volume of 5.2 L. It was covered with aluminum foil to minimize internal heating by sunlight, and fitted with styrofoam on the side for floatation. Gas flux measurements were taken at each of the transect points between 09:00 and 11:00 local time when the aeration system was off. Four individual gas samples inside the chamber headspace were extracted with a 60 mL syringe at 0, 15, 30 and 45 min after chamber deployment. The samples were then injected into pre-evacuated airtight gas sampling bags (Dalian Delin Gas Packing Co., Ltd., China) and returned to the laboratory in a cool box.

In the laboratory, N_2O concentrations were determined using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan) equipped with an electron capture detector (ECD) within 24 h after sampling. Three different concentrations of standard N_2O gas, namely, 0.3, 0.4, and 1.0 ppm, were used to calibrate the ECD. The detection limit for N_2O was

0.02 ppm, and the RSD of the measurements was ≤5.0% in 24 hr. N_2O flux across the air-water interface was calculated from the slope of the linear regression line between gas concentration and time, and expressed as μg m^{-2} h^{-1} (Yang et al., 2018).

2.8. Nitrogen and phosphorus budgets

N and P budgets in the shrimp ponds were calculated based on the inputs from inflow water and rainwater, stocked animals (shrimps) and feeds, and the outputs in the forms of discharged water, harvested shrimps and sediment accumulation (Sahu et al., 2013; Zhang et al., 2018). In addition, water-air N_2O exchange was included as a pathway of N output.

N and P inputs from each component (inflow water, rainwater, stocked animals, feed) were calculated as the product of the N and P concentrations and the total amount of each component.

N and P outputs via discharged water were calculated as the product of the total amount of water discharged and the N and P concentrations in the discharged water. N and P outputs via shrimp harvesting were calculated as the product of the total shrimp biomass and the N and P concentrations in the harvested shrimps. The amount of N and P accumulated in sediment was calculated as the product of the total amount of sediment and the change in N and P contents in the sediment. N output via air-water N_2O fluxes was determined as the product of the mean N_2O flux, the pond surface area (hectare), and the farming period (188 days).

The nutrient utilization efficiency of the cultured shrimp (%) was calculated as:

Total weight of harvested shrimps × Nutrient concentration in shrimp biomass / Total input of nutrient.

2.9. Data analysis

Data were tested for normality and homogeneity of variance. Two–way ANOVA was used to test for significant (p<0.05) effects due to sampling ponds, sampling time and their interactions on water quality parameters and N_2O flux, with the transect sampling points as a random variable. All statistical analyses were conducted in IBM SPSS statistics 22.0 (IBM, Armonk, NY, USA) and the significance level was set at $p < 0.05$. All plots were generated in OriginPro 8.0 (OriginLab Corp. USA).

3. Results

3.1. Water physicochemical parameters

The N and P levels in the ponds during the farming period are shown in Fig. 2. Sampling ponds and times and their interactions had significant effects on the mean concentrations of NO_3^--N (Fig. 2b), NH_4^+-N (Fig. 2c), TDN (Fig. 2d), PO_4^{3-} (Fig. 2e) and TDP (Fig. 2f) ($p < 0.01$; Table 2). Overall, the mean nutrient concentrations were highest in Pond II, followed by Pond I and then Pond III. However, there were no significant differences in mean water temperature (T_W), salinity, pH and DO among the ponds (p>0.05).

3.2. N_2O emission from shrimp ponds

Across all sampling dates and transect points, N_2O fluxes across the water-air interface differed significantly among the ponds (p<0.01; Table 2), with a range of 1.7–11.0, 1.6–20.3 and 1.8–17.6 μg m^{-2} h^{-1} observed in Ponds I, II and III, respectively (Fig. 3). The mean N_2O flux decreased in the order of Pond II (6.1±1.3 μg m^{-2} h^{-1}) > Pond III (5.1±1.1 μg m^{-2} h^{-1}) > Pond I (4.1±0.7 μg m^{-2} h^{-1}). N_2O fluxes also varied significantly over time (p<0.01; Table 2), with most of the high and low values being observed in June/September and July/August, respectively (Fig. 3). Overall, the shrimp ponds acted as a net source of atmospheric N_2O during the farming period.

3.3. Nitrogen budget

The N inputs and outputs in the shrimp ponds are presented in Table 3 and Fig. 4. Feeds accounted for 90.9–92.8 % of the total N input with a rate of 23.8–33.2 g m^{-2}. Inflow water accounted for 4.2–5.2 % of the total N input with a rate of 1.2–1.4 g m^{-2}. Stocked shrimp biomass and rainwater represented only a small fraction of the total N input (0.013–0.021 % and 3.0–3.8 %, respectively).

The main N output was the harvest of shrimp biomass, which accounted for 42.5–49.1 % of the total N output with a rate of 11.2 to 16.3 g m^{-2}. Sediment accumulation was the second largest pathway of N loss, contributing to 28.2–44.0 % of the total N output with a rate of 8.2 to 11.9 g m^{-2}. Outflow water and N_2O emission accounted for 7.8–13.3 % and 0.011–0.031 % of the total N output, respectively. The sources of the remaining 4.5–9.4 % of the total N loss were unidentified.

3.4. Phosphorus budget

The P budget and the percent contribution of various components are presented in Table 4 and Fig. 5. Feed was the main P input in the ponds with a rate ranging from 5.6 to 7.3 g m^{-2}, accounting for 95.4–96.4 % of the total P input. On the other hand, inflow water and rainwater accounted for 3.1–3.9 % and 0.6–0.7 % of the total P input, respectively. P input from stocked shrimp biomass was negligible, contributing to only 0.011–0.014 % of the total P input.

The main component of P output was sediment accumulation, accounting for 54.8–68.4 % of the total P output with a rate of 3.42 to 4.152 g m^{-2}. Harvesting of shrimp biomass was the second most important component of P output, accounting for 26.8–30.8 % of the total P output with a rate of 3.42 to 4.152 g m^{-2}. Water outflow and unidentified losses accounted for 4.9–5.3 % and 8.9–10.2 % of the total P output, respectively.

3.5. Feed conversion ratio and nutrient utilization efficiency

The feed conversion ratio of shrimps in Pond I, II, and III was 1.4, 1.3, and 1.3, respectively (Table 5). The utilization efficiencies varied over a range of 42.5–49.1% for N and 26.8–30.8% for P among the ponds (Table 5), with an average value of 46.9±2.2% and 29.4±1.3%, respectively.

4. Discussion

4.1. Nitrogen and phosphorus budgets in land-based shrimp aquaculture

Consistent with the findings of previous studies (e.g., Adhikari et al., 2012; Gál et al., 2003; Pouil et al., 2019), feed was the main input of N and P in our coastal shrimp ponds. Earlier studies have shown that sediment accumulation is a main component of nutrient outputs in aquaculture systems (e.g., Adhikari et al., 2012; Holmer et al., 2002; Zhang et al., 2020). Similarly, we found that sediment accumulation was a major pathway of P loss in our coastal shrimp ponds, but biomass harvesting was the largest contributor of total N output. This suggested relatively effective N incorporation into the shrimp biomass, which was further supported by the higher N utilization efficiency (UE) observed in our study than other studies (Table 6). The high UE makes whiteleg shrimp a preferred aquaculture species. Interestingly, we found no appreciable increase in UE when shrimp was co-cultured with other species (Table 6).

The percentages of N and P that were unaccounted for in our budgets were 4.5–9.4 % (Fig. 4) and 8.9–10.2 % (Fig. 5), respectively. The 'missing' nutrients could be attributed to several processes that were not measured in the present study, e.g. denitrification, seepage and volatilization. Previous studies have shown that denitrification and seepage can account for 6.9–30 % and 0.1–1.3 % of the total N output, respectively, in aquaculture systems (Boyd, 1985; Funge-Smith and Briggs, 1998; Gross et al., 2000). Some studies have also found that ammonia (NH_3) volatilization and periphyton growth also contribute to N output (Zhang et al., 2020).

The potential emission of nitrogenous gases such as NH_3 and N_2 from aquaculture systems have been studied previously (Brown et al., 2012; David et al., 2017; Hu et al., 2012). Brown et al. (2012) estimated that NH_3 volatilization and denitrification accounted for 38.4% of the N output in intensive catfish aquaculture systems, while Hu et al. (2012) estimated that about 20% of the N input to the aquaculture system could be lost as N_2. Yet, data on N_2O emission from aquaculture systems are still limited. In this study, we directly measured the N_2O fluxes from the coastal shrimp ponds and showed that N_2O emission during the farming period ranged from 0.16 to 0.22 kg N_2O ha^{-1}, which was equivalent to only 0.01-0.03 % of the total N output (Fig. 4). This suggested that N_2O emission only had a minor contribution to the total N loss in our shrimp ponds during the farming period.

4.2. Nutrient pollution from coastal shrimp ponds

Generally, the safety thresholds of nitrite and ammonia concentrations in the water column of shrimp aquaculture ponds in low-salinity conditions are 0.01 mg L^{-1} and 0.20 mg L^{-1}, respectively (Lai, 2014). Yet, we observed mean concentrations of NO_3^--N and NH_4^+-N in the three ponds that were considerably higher than the safety thresholds (Fig.2b and 2c), implying that the water quality could be harmful to the shrimp and reduce survival and growth through a variety of physiological dysfunctions (Hu et al., 2012; Kou et al., 2014). The N and P levels in the shrimp ponds reached 1.85–2.30 g m^{-3} and 0.15–0.24 g m^{-3}, respectively, near the end of the farming period (Fig. 2), which were 2–3 times higher than those observed in the adjacent coastal waters (Yang et al., 2017a).

Annual drainage after harvesting is a typical management practice for costal shrimp ponds in China (Herbeck et al., 2013; Yang et al., 2018, 2020). Extrapolating our measured dissolved nutrient levels to all shrimp ponds within the Min River estuary (ca. 1639 ha and average 1.5 m depth), we estimated that annual drainage would introduce 49.4±3.6 tons of N and 4.7±0.7 tons of P into the estuarine zone, creating serious water pollution and eutrophication problems (Yang et al., 2017a). Therefore, appropriate management strategies mitigating the discharge of nutrient-rich aquaculture wastewater from the shrimp pond systems into the adjacent waters are urgently needed.

4.3. N_2O emission from coastal shrimp ponds

Across the farming period, the average flux of N_2O emission from our shrimp ponds was 5.1±0.6 μg m^{-2} h^{-1} (Fig. 3). Exposure of the N-rich sediments to air after harvesting and pond drainage potentially increases N_2O production (Martikainen et al., 1993; Yang et al., 2013). Our previous study showed that the shrimp ponds acted as a net N_2O source with an average emission of 112.4 μg m^{-2} h^{-1} during the non-farming period, accounting for ca. 97% of the annual emission (Yang et al., 2020). Therefore, the combined annual N_2O emissions from our coastal shrimp ponds could be up to 515.1 mg N_2O m^{-2} yr^{-1}. N_2O production and emission could be even higher for aquaculture species with a lower nitrogen UE (Table 6). If we assume that our data were representative of all coastal shrimp ponds across China (total area 2.4×10^3 km^2, Bureau of Fisheries of the Ministry of Agriculture, 2019), we estimated that coastal shrimp aquaculture in China could potentially emit N_2O into the atmosphere at a rate of ca. 1.2 Gg yr^{-1}, which would be equivalent to ca. 2.9% of the global aquaculture N_2O emission (Yuan et al., 2019) and a total CO_2-equivalent emission of 383.2 Gg CO_2-eq over a 100-year time scale. Further comparison of N_2O emissions from aquaculture systems with different UE would improve our understanding of the overall climatic impact of aquaculture operations.

4.4. Management recommendations for shrimp aquaculture

In this study, the shrimp ponds were managed by commercial operators following their routine practices, including the type and amount of feeds added to the ponds. Based on our results, about half of the N input was not converted to shrimp biomass. Likewise, despite the fact that our shrimp ponds had considerably higher P UE than most studies (Table 6), still more than half of the added P was lost to the sediment, showing a low effectiveness in nutrient management. Poor utilization efficiency could be a result of low bioavailability of the feed constituents or suboptimal feeding practices (Avnimelech and Ritvo, 2003). Experimenting different feed formulations and feeding practices (e.g., changing feeding frequency; use of attractants) may improve UE (hence productivity) and reduce the discharge of nutrient-rich wastewater (D'Abramo and Sheen, 1994; Felix and Sudharsan, 2004; Bardera et al., 2019). On the other hand, the large accumulation of N and P in the sediment opens opportunities to improve aquaculture management and nutrient mitigation methods.

In traditional earthen pond shrimp farms along the Chinese coast, there is no regular removal of accumulated sediments. These aquaculture ponds therefore have a typical sediment layer that is several tens of centimeters thick, similar to other aquaculture ponds in SE Asia (Pouil et al., 2019). Draining the ponds between farming periods could release large amounts of the trapped nutrients in the sediment in dissolved forms, impacting water quality in the adjacent coasts (Páez-Osuna et al., 2017; Yang et al., 2017a; Zhang et al., 2020). Residue nutrients within the ponds may also negatively affect water quality for the subsequent farming periods (Avnimelech and Ritvo, 2003; Castillo-Soriano et al., 2013). Routine removal of the surface sediments between farming periods by dredging can be a simple and effective way to minimize the adverse environmental impacts of the aquaculture operation, while the nutrient-rich sediments could at the same time be used as fertilizers for (salt-tolerant) crops for added benefits (Pouil et al., 2019).

5. Conclusions

Given that the number of coastal aquaculture ponds and the intensity of the operation are likely to increase in the future for satisfying the growing food demand globally (FAO, 2018), their potentially adverse environmental impacts arising from aquaculture production need to be carefully considered and minimized. The present study analyzed the major sources and sinks of nutrients in the coastal earthen shrimp ponds in the Min River Estuary, southeastern China. Commercial feed was the main source of N and P, whereas harvested biomass and sediment accumulation were the main outputs for N and P, respectively. Despite the higher nutrient utilization efficiencies of our shrimp ponds than other aquaculture systems, less than half of the N and P inputs ended up in the shrimp biomass. N_2O emission was a relatively minor component of the N budget, accounting for only 0.01–0.03 % of the total N output.

Accumulated N and P in the water and sediment were the primary sources of pollution. Better feed formulation, optimized feeding practice and regular sediment removal can help attain more sustainable shrimp production in the coastal aquaculture systems by minimizing nutrient pollution and greenhouse gas production, improving pond productivity, and recycling key nutrients.

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Table 1

Characteristics of the shrimp (*L. vannamei*) ponds in the Min River Estuary.

	Pond I	Pond II	Pond III
Water depth (m)	1.3	1.3	1.3
Surface area (m^2)	14000	13000	12500
Stocking density (ind m^{-2})	214	215	216
Feed intake (kg m^{-2})	0.36	0.46	0.40
Body weight (g ind^{-1})	6.64	5.80	4.45
Survival rate (%)	70	80	75
Yield (kg m^{-2})	0.50	0.73	0.64

Table 2

Summary of the two-way ANOVA results examining the effect of sampling ponds, times, and their interactions on water quality parameters and N_2O fluxes.

	df	NO_3^--N		NH_4^+-N		TDN		PO_4^{3-}		TDP		N_2O fluxes	
		***F* values**	***p* values**	***F* values**	***p* values**	***F* values**	***p* values**	***F* values**	***p* values**	***F* values**	***p* values**	***F* values**	***p* values**
Sampling ponds	2	15.106	=0.002	17.787	=0.001	4.703	=0.045	6.398	=0.022	10.948	=0.005	9.084	=0.009
Sampling times	14	31.640	<0.001	45.028	<0.001	29.574	<0.001	4.030	<0.001	33.613	<0.001	6.087	<0..001
Sampling ponds× times	28	24.603	<0.001	14.658	<0.001	17.078	<0.001	2.695	<0.001	6.536	<0.001	14.118	<0..001

Table 3

Inputs and outputs of nitrogen (g m^{-2}) in the three shrimp ponds during the farming period.

Ponds	Nitrogen inputs					Nitrogen outputs					
	Inflow	Rainwater	Stocked biomass	Feed	Total	Outflow	N_2O emission	Harvested biomass	Sediment accumulation	Total	Others
Pond I	1.35±0.02	1.00	0.00002	23.82±0.36	26.20±0.38	2.34±0.15	0.003	11.15±0.17	11.53±0.33	25.02±0.58	1.18
Pond II	1.37±0.04	1.00	0.00002	30.78±0.45	33.17±0.49	2.60±0.12	0.010	16.28±0.21	11.86±0.27	30.75±0.61	2.42
Pond III	1.37±0.04	1.00	0.00002	26.68±0.38	29.06±0.42	3.86±0.17	0.006	14.27±0.18	8.20±0.19	26.34±0.52	2.72

Table 4

Inputs and outputs of phosphorus (g m^{-2}) in the three shrimp ponds during the farming period.

Ponds	Phosphorus inputs					Phosphorus outputs				
	Inflow	Rainwater	Stocked biomass	Feed	Total	Outflow	Harvested biomass	Sediment accumulation	Total	Others
Pond I	0.23±0.02	0.04	0.0007	5.64±0.16	5.92±0.13	0.31±0.01	1.58±0.08	3.42±0.28	5.31±0.32	0.61
Pond II	0.23±0.01	0.04	0.0007	7.29±0.21	7.57±0.19	0.43±0.03	2.32±0.12	4.15±0.22	6.90±0.37	0.67
Pond III	0.23±0.01	0.04	0.0008	6.32±0.17	6.59±0.18	0.32±0.01	2.03±0.10	4.03±0.21	6.38±0.29	0.21

Table 5

The feed conversion rate (FCR), and utilization efficiency (UE) of nitrogen and phosphorus by the cultured shrimps in the three ponds during the farming period.

Ponds	**FCR**	**UE of nitrogen**	**UE of phosphorus**
Pond I	1.42	42.54%	26.77%
Pond II	1.26	49.12%	30.60%
Pond III	1.26	49.10%	30.76%

Table 6

Utilization efficiency (UE) of nitrogen and phosphorus by different species in different aquaculture systems.

Aquaculture systems	Cultured animals	UE of nitrogen (%)	UE of phosphorus (%)	Reference
Monoculture	Shrimp	42.54−49.12	26.77−30.76	**Present study**
	Crucian carp	27.78	6.48	Chen et al., 2015
	Shrimp	27.40	8.95	Su et al., 2009
	Shrimp	22.40	10.50	Li et al., 2012
	Shrimp	24.00	13.00	Briggs and Funge-Smith, 1994
	Fish	6.1	--	Flickinger et al., 2019
	Prawn	23.7	--	Flickinger et al., 2019
	Giant gourami	5.00–19.00	1.00–5.00	Pouil et al., 2019
	Largemouth bass	37.47–39.53	24.63–25.98	Zhang et al., 2020
	Haliotis discus hannai	30.75	12.83	Gao et al., 2019
Polyculture	Shrimp and tilapia	36.00−47.00	14.80−18.10	Li et al., 2012
	Snakehead and bighead carp	30.11−32.90	13.13−14.28	Zhang et al., 2018
	Jellyfish, shellfish, fish, and prawn	21.03−70.19	46.95−50.14	Guo et al., 2017
	Shrimp, tilapia, and constricted tagelus	23.40	14.70	Tian et al., 2001
	Tambaqui and prawn	28.90	--	Flickinger et al., 2019
	Tilapia and prawn	22.00	--	David et al., 2017
	Abalone, and sea cucumber	28.93−45.89	9.89−19.59	Gao et al., 2019

"–" indicates no data.

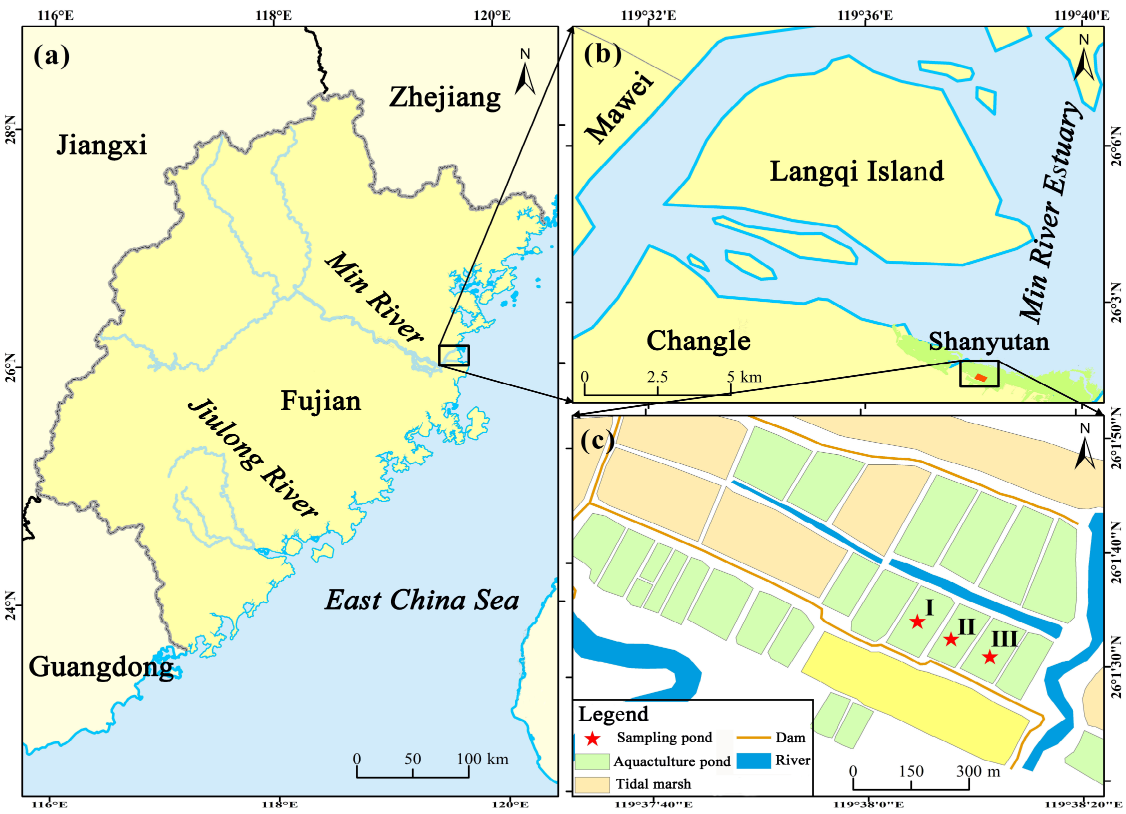

Figure 1. Location of the shrimp ponds in the Shanyutan Wetland of the Min River Estuary, southeastern China.

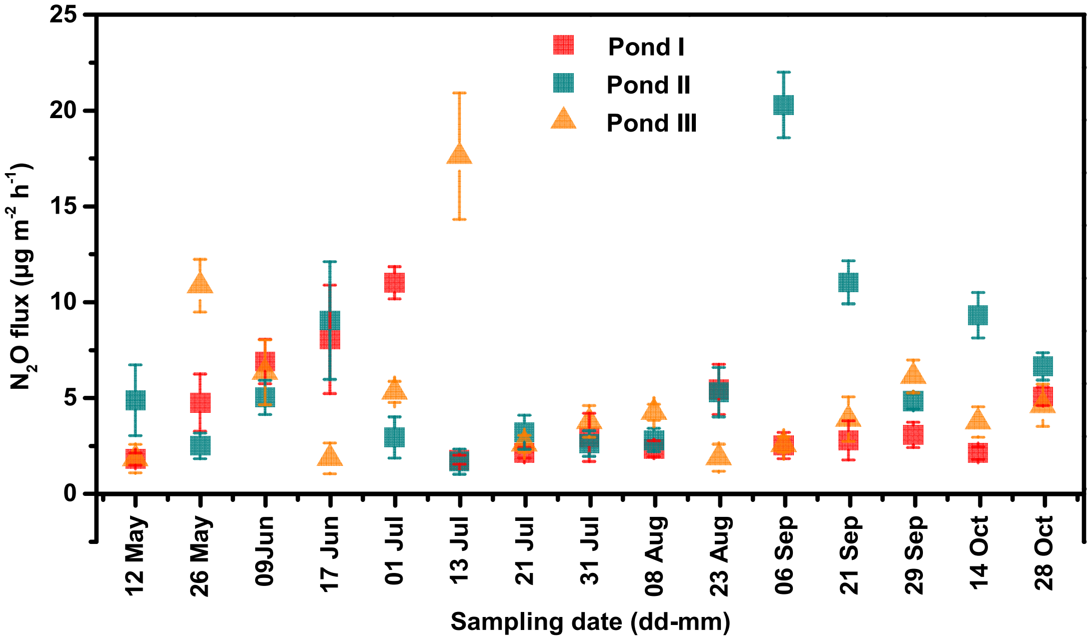

Figure 3. N_2O flux across the water-air interface in the three shrimp ponds during the farming period (May-October). Error bars represent standard error (*n* = 5).

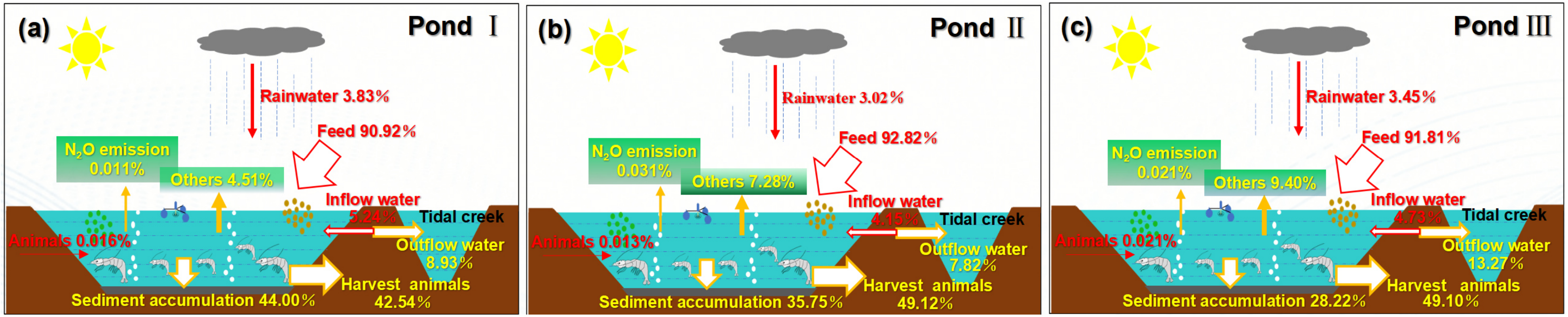

Figure 4. Percent contribution of each component in the nitrogen budget of the three shrimp ponds during the farming period (May-October).

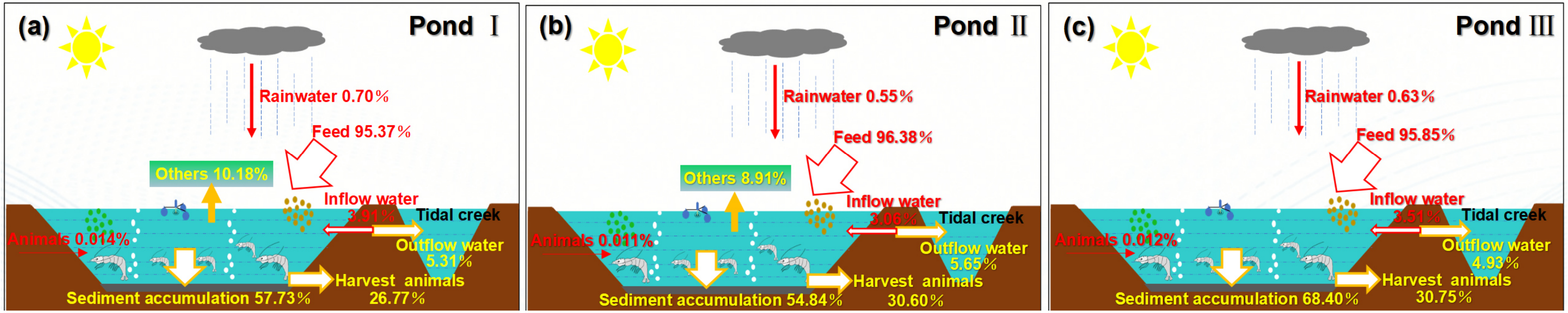

Figure 5. Percent contribution of each component in the phosphorus budget of the three shrimp ponds during the farming period (May-October).

Supporting Information for

Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China

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Supporting Information Summary

No. of pages: 5 No. of Figures: 2 No. of tables: 0

Page S3: Fig. S1 A diagram showing the locations of sampling sites (red dots) within the pond. Zones N, F, and A are nearshore, feeding, and aeration areas, respectively.

Page S4: Fig. S2 Water quality parameters in the shrimp ponds during the farming period (May-October): (a) salinity, (b) NO_3^--N, (c) NH_4^+-N, (d) TDN (Total Dissolved Nitrogen), (e) PO_4^{3-}, (f) TDP (Total Dissolved Phosphorus). Error bars represent standard error (n = 5).

Page S5: References

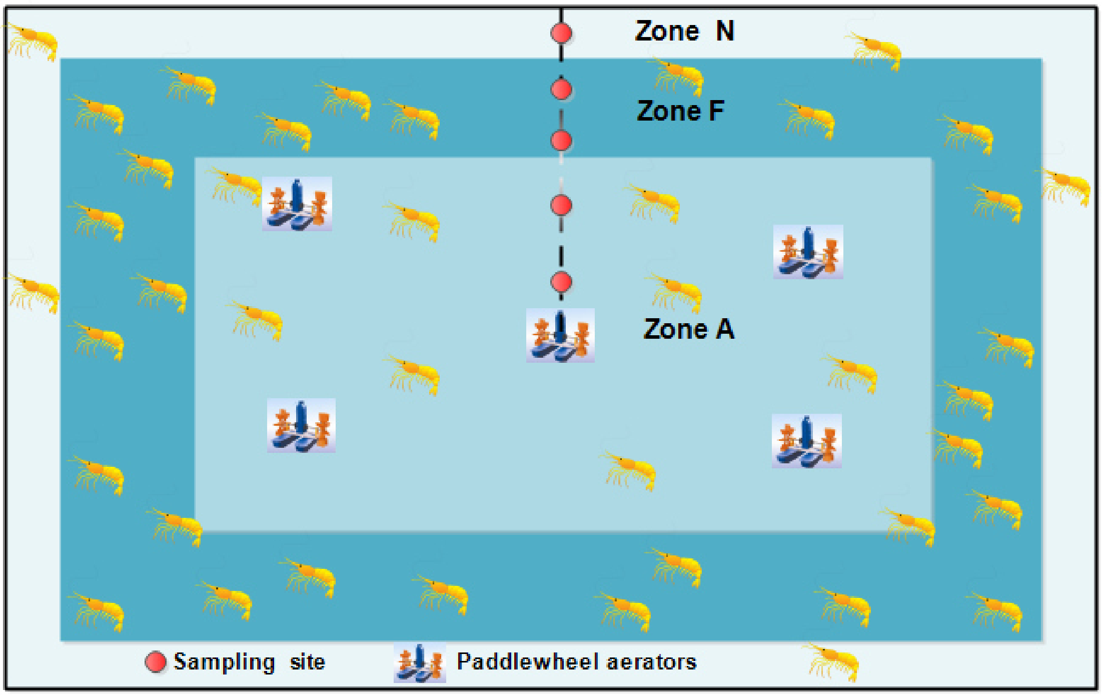

Fig. S1. A diagram showing the locations of sampling sites (red dots) within the pond. Zones N, F, and A are nearshore, feeding, and aeration areas, respectively (modified after Zhang et al., 2019).

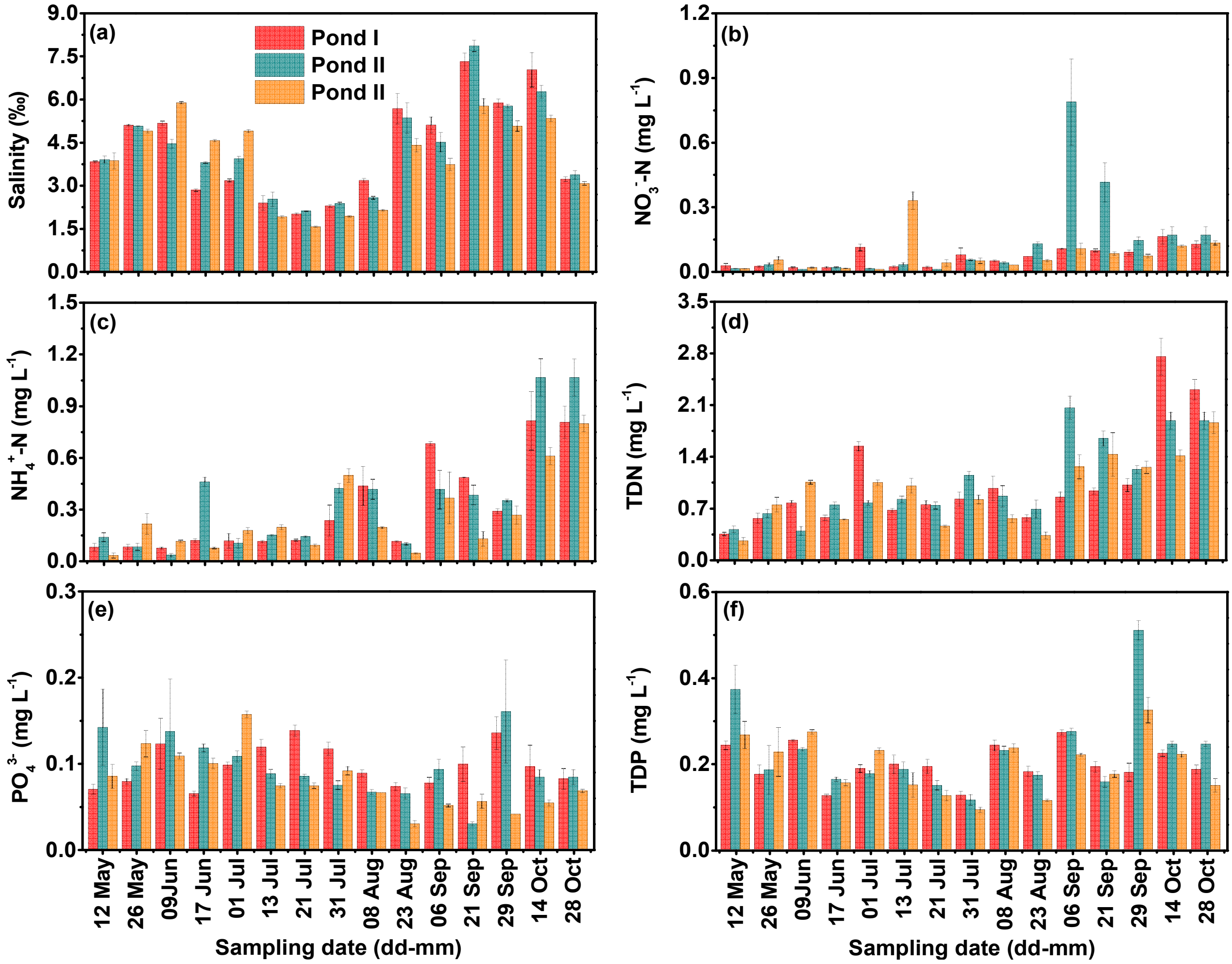

Fig. S2. Water quality parameters in the shrimp ponds during the farming period (May-October): (a) salinity, (b) NO_3^--N, (c) NH_4^+-N, (d) TDN (Total Dissolved Nitrogen), (e) PO_4^{3-}, (f) TDP (Total Dissolved Phosphorus). Error bars represent standard error (n = 5). Data are taken from Zhao et al. (2020).

References

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