COMPARING NUTRIENT BUDGETS IN INTEGRATED RICE-SHRIMP PONDS AND SHRIMP GROW-OUT PONDS

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Abstract:

Saltwater intrusion has become a severe issue for the Mekong Delta in Vietnam, especially near the coastline. This issue has led to farmers diversifying from exclusively growing rice to adopting a mixed rice-shrimp system with rice only cultivated in the wet season. However, the nutrient (nitrogen, phosphorus and carbon) cycling and nutrient use efficiency of this system remain poorly understood. To address this knowledge gap, we examined nutrient budgets across 12 farms using integrated rice-shrimp ponds, and in some cases semi-intensive or intensive shrimp grow-out ponds (*Penaeus monodon* or *Penaeus vannamei*), over a two-year period (2014-2015). In terms of nutrient budgets, the main nutrient input (92% of the N input, 57% P and 95% C) in the integrated rice-shrimp ponds (IRSPs) came from intake water (excluding C from primary production), while water discharge accounted for the highest output (75% of N output, 41% P, 57% C, excluding C from respiration). The study showed that IRSPs had low dissolved oxygen and high nutrient concentrations which may affect shrimp production. Conversely, salinity levels in the wet season were too high for rice plants thereby affecting rice production. Shrimp survival in the IRSPs was low over the two years (6.3 ± 2.2%), which resulted in the low proportion of nutrients exported from the ponds as harvested shrimp (6% N, 5% P and 10% C). In contrast, the shrimp grow-out ponds (SGOPs), had much higher survival (77.1% for *P. vannamei* and 59.2% for *P. monodon*) in three of the six farms where the

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shrimp survived through to harvest. In these ponds, formulated feed was the highest nutrient input (*P. vannamei*: 82% N, 75% P and 85% C; *P. monodon*: 75% N, 55% P and 77% C) with approximately a third of the nutrients being in the shrimp harvest. In our study, nutrients in the IRSPs were used less efficiently than in SGOPs, hence mechanisms to improve shrimp survival and production in IRSPs are urgently needed.

Keywords: carbon; grow-out ponds; nitrogen; phosphorus; prawns; rice-shrimp ponds.

1. Introduction

Farmed shrimp are the most valuable commodity for Vietnam and account for 42% of the country's earnings from seafood production, and approximately 76% of Vietnam's shrimp production occurs in the Mekong Delta (ADB, 2013). The Mekong River and its tributaries are also critical areas for rice production, and the river system and its farmlands are known as the "Rice Bowl" of Vietnam (Dang and Danh, 2008). However, in recent decades, sea level rise, river flow regulation and increased water consumption have increased water salinity to the point where it is becoming a serious problem for rice production (Tho et al., 2013). Hence, in some regions, the canals and farms have freshwater in the rainy season but higher salinity in the dry season; consequently, rice is increasingly difficult to grow in the dry season. Integrated rice-shrimp farming has been promoted given that dry season conditions are suitable for shrimp production when rice crops might struggle or fail under higher salinities. This farming system involves farming rice in the wet season with shrimp culture in the same system during the dry season. This practice has increased from around 40,000 ha in 2000 (Brennan et al., 2002; Preston and Clayton, 2003) to 160,000 ha in 2016 and has been speculated a rise to 250,000 ha by 2030 (Tuan et al., 2016). Despite this, there have been few studies on the sustainability of these systems (Leigh et al., 2017).

An understanding of the nutrient budget, by quantifying nutrient inputs and outputs, and hence the efficiency of nutrient utilization, is critical to determine the sustainability of rice-shrimp farming systems. However, to date, this has not been addressed. There are many studies of nutrient budgets in a range of aquaculture systems, especially for shrimp ponds. For example, nutrient budgets have been determined for intensive shrimp ponds in Thailand (Briggs and Funge-Smith, 1994; Thakur and Lin, 2003), extensive shrimp ponds in Bangladesh (Rouf et al., 2012; Wahab et al., 2003), semi-intensive shrimp farms in

Mexico (Paez-Osuna et al., 1997; Paez-Osuna et al., 1999; Miranda et al., 2009), and semi-intensive shrimp farms in Australia (Jackson et al., 2003). These studies have found that feed was the primary source of nitrogen (N), phosphorus (P), and carbon (C) in these ponds with less than 17% being assimilated by shrimp (Briggs and Funge-Smith, 1994; Islam et al., 2004; Jackson et al., 2003; Miranda et al., 2009). In culture systems with low water exchange, waterborne loss of nutrients is less important than loss into the bed sediments of the pond due to the rapid accumulation of sludge (Audelo-Naranjo et al., 2010; Kittiwanich et al., 2012; Qi et al., 2001; Thakur and Lin, 2003). Hence, a significant proportion of nutrients received in ponds ends up settling on the pond bottom and being discharged (Huy and Maeda, 2015; Sun and Boyd, 2013; Xia et al., 2004).

Nutrient budgets provide a means to quantify potential impacts of a pond management strategies to improve the efficiency of production. There remains a gap in our knowledge of nutrient budgets for integrated rice-shrimp ponds (IRSPs). Therefore, in this study, we compared nutrient budgets in shrimp grow-out ponds (SGOPs) with adjacent IRSPs to determine dominant nutrient inputs and outputs, and the relative effectiveness of nutrient utilization by shrimp. This information is a fundamental step in improving food utilization efficiency, water quality and biogeochemical processes of the farming practices.

2. Materials and methods

2.1. Study area

The study focused on 12 farms along a canal in the Cai Nuoc District, Ca Mau Province, Vietnam from February 2014 to January 2016 (Fig. 1). There were six farms (C1-C6) using only IRSPs, with a platform (70-80% of area) for rice growing, and surrounding ditch (20-30% of area) for water management and shrimp farming. An additional six farms (M1-M6) were used to trial a combination of the IRSPs, plus newly constructed SGOPs with shrimp grown from semi-intensive to intensive conditions. IRSPs ranged in size from 1.2 to 3.5 ha, with water depth in the ditch typically 1.0-1.4 m, and for the platform 0.1-0.4 m. The SGOPs were 0.2-0.3 ha in area, and 1.1-1.5 m deep (Fig. 2).

There are two main seasons in the region: the dry season from December to April, and the wet (rainy) season from May/June to October/November (Leigh et al., 2017). The hottest period is typically between April and May, while the wettest period is from September to October/November. During the rainy season, water salinity in this region drops gradually from around 20 to 4, and may become fresh (Hoanh et al., 2016). The area experiences annual flooding due to its low elevation. The air temperature ranges from 24 to 34^{0}C, and the average monthly rainfall ranges from 0 mm in the dry season to 250 mm in the wet season, with annual rainfall around 2300 mm (ADB, 2013).

2.2. Pond management

The first steps of preparation for the IRSP included cleaning and reinforcing the pond bank, discharging the water in the ditch through a sluice gate, and transferring sludge in the ditch to the platform. After that, lime was added to the pond (using calcium oxide, a dose of 1 t ha^{-1} ditch^{-1} and 500 kg ha^{-1} platform^{-1}), then the platform was dried for 5-7 days. Approximately 15-20 days later, water was added from the canal via a filter bag if the salinity of the supply channel was suitable (> 10) or via a settling pond. Unwanted fish were killed using Rotenone, and water was disinfected using iodine added at 0.5 mg L^{-1}.

Before shrimp stocking, the SGOP was also prepared by cleaning and reinforcing the bank, draining the pond to dry the sediment, and removing sludge on the bottom layer. Next, the pond was fenced with nets to prevent small crabs from entering before it was limed (using calcium oxide, dose: 1-2 t ha^{-1}), and dried from 7-10 days. The total time for pond preparation (removing sludge, drying pond and liming) was one month. When salinity of the supply channel was suitable, water was pumped through a filter bag into the pond. The depth of water was about 1.2 to 1.6 m. From 3 to 5 days after filling, water was disinfected by using benzalkonium chloride (1.5 mg L^{-1}). A few days later, fertilizer was added (using di-ammonium phosphate or nitrogen phosphorus potassium, dose: 2-3 kg 1,000 m^{-3}), and conducted continuously within 2-3 days. Lime and dolomite were typically added. A few days before stocking, probiotics (BioShrimp-RIA2, dose: 1.0 L 1,000 m^{-2}) were also added, and some basic physico-chemical parameters were monitored to ensure they were in an appropriate range: pH (7.5-8.5), alkalinity (80-120 mg L^{-1}), salinity (> 8 for stocking black tiger shrimp), Secchi disc depth (25-35 cm), and colour of water (light blue, light yellow, blue yellow, yellow green, and light brown) (Boyd, 1995).

A key difference between the SGOPs and the IRSPs was the shrimp stocking density and the resulting need for formulated feed. SGOPs were stocked at a density of 15 post larvae

m^{-2} for *P. monodon* (mostly in the dry season) or 30 post larvae m^{-2} for *P. vannamei* (mainly in the wet season) while IRSPs were stocked with *P. monodon* with a mean density of 2 post larvae m^{-2}. SGOPs were stocked once early in the dry season (*P. monodon*) and once at the beginning of the wet season (*P. vannamei*). For the IRSPs, stocking occurred every 2-3 months during the two-year period over both the wet and dry season. Mud crabs (*Scylla paramamosain*) were also stocked in the IRSPs having an estimated density of 0.5 crab m^{-2}. Formulated feed (Tomboy, UP) was added to SGOPs while shrimp in the IRSPs consumed only natural food present in those ponds.

Paddlewheels (Motor 3HP or diesel engines) were used in the SGOPs, whereas IRSPs were not aerated. Two paddlewheels were typically installed in each SGOP so that aerators could supply enough oxygen for shrimp, especially in the rainy weather, during the night and in periods of chemical treatment (Boyd, 1998).

Pumping times for exchanging water from both SGOPs and IRSPs were recorded and the pumping times correlated with flow rates to determine the volume of water exchanges. Additionally, the water depth in the ditch and platform of IRSPs, and the water depth of SGOPs were recorded throughout the growth season. When this information was combined with the area of the farm, the volumes of water could be calculated.

2.3. Shrimp harvest

For IRSPs, trap nets with a large mesh size were used for partial harvests throughout the year to ensure that only shrimp greater than 20 g were caught and removed from the ponds. At the end of the year, the ponds were drained, and additional shrimp were harvested using trap or seine nets. Fifty shrimp were weighed at each harvest to estimate the total biomass and mean weight. In addition to the shrimp, mud crabs were occasionally harvested and biomass recorded.

At the end of culture period, SGOPs were drained, and shrimp were caught using large seine nets and subsets of animals weighed. The feed conversion ratio (FCR) was calculated as well as the survival and total biomass of shrimp. The FCR was calculated as total weight of dry feed given divided by the total weight gain. Survival was determined as the number of shrimp caught divided by the initial number of shrimp stocked in each pond, and total biomass as final total wet weight per crop.

2.4. Water sampling and analyses

Physico-chemical parameters, i.e. temperature, salinity and dissolved oxygen (DO), were measured weekly using calibrated loggers (Thermocron ibuttons, Odyssey conductivity probes). Water samples for nutrient analyses were collected monthly. This involved collecting surface water samples with a bucket of the inlet water, and each ditch in the IRSP, as well as each SGOP. Samples were taken at five different locations in IRSPs and SGOPs, and for inlet water using a 1.0 L bottle. Each bottle of water was poured into one bucket to make a composite sample from which subsamples for various analyses were taken. Known volumes of water for chlorophyll *a* analysis were filtered through glass fibre filters (Whatman GF/F with nominal pore size 0.7 µm, 2.5 cm diameter). Filters were stored in a freezer until analyzed as chlorophyll *a* degraded easily. Similar sampling method was applied for total suspended solid (TSS) parameter.

Two replicate samples were taken for total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP), which were then frozen. For ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), soluble reactive phosphate (PO_4-P), total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) analyses, a subsample was taken and filtered through a 0.45 µm membrane filter (Sartorius, 2.5 cm diameter), then frozen until analyzed.

NH_4-N was analyzed using the phenate method; NO_2-N, NO_3-N using cadmium reduction and sulphanilamide method; PO_4-P using the ascorbic acid method, and TP, TDP, TN and TDN using the persulfate method followed by colorimetric analyses (APHA, 2005). Concentrations of chlorophyll *a* were determined by acetone extraction of the glass fibre filters and spectrophotometric measurements following APHA methods (2005). TOC was determined following APHA methods (2005) using chromic acid rapid titration method. For TSS samples, filters were defrosted and dried in an oven at 60^{0}C for 24 hours (APHA, 2005).

2.5. Sediment, benthic algae, feed, fertilizer, shrimp and crab data

In the SGOPs, sediment samples were collected by taking different cores (up to 15 cm depth) from each pond and mixed in a composite sample for analysis. All sediment samples were oven-dried at 60^{0}C for 24 h, pulverized to pass through a 0.25 mm mesh screen, and analyzed for TN, TP and TC (APHA, 2005).

Benthic algae in IRSPs were collected four times per year (two in the dry season and two in the rainy season) in both ditch and platform. For the platform, a bucket was placed over benthic algae and pushed into the sediment so that the bucket was firmly held in place. The bucket was reached into, and all plant material (i.e., rice stubble, grass) within the area of the bucket were removed. For the ditch, a beam trawl was used, and it was dragged around 1.0 m down the ditch. After that, the beam trawl net was washed out to remove as much mud as possible. Benthic algae samples in both ditch and platform were placed inside plastic bags, and this procedure was repeated at four other sites on the platform and four other locations on the ditch. All samples were combined and recorded weight, and stored in the freezer until analyzed.

Nutrient (TN, TP and TC) content of benthic algae, shrimp feed, fertilizer, harvested shrimp and crab were also analyzed using the same methods as for sediment. Samples were prepared by freeze-drying and pulverizing to pass samples through a 0.85 mm screen.

It was not possible to quantify sedimentation in the IRSPs due to the confounding effect of erosion from the platforms and banks.

2.6. Calculation of nutrient budget

Nutrient (N, P and C) inputs and outputs in the IRSPs were based on shrimp, crab, water and fertilizer inputs, and harvested shrimp, crab, discharge water and benthic algae biomass outputs. Inputs and outputs were calculated as follows:

Nutrient input in shrimp = Nutrient concentration in shrimp at stocking × total shrimp stocking weights (as dry weight).

Nutrient input in crab = Nutrient concentration in crab at stocking × total crab stocking weights.

Nutrient input in water = Nutrient concentration in inlet water × total amount of water supplied.

Nutrient input in fertilizer = Nutrient concentration in fertilizer × total amount of fertilizer supplied.

Nutrient output in shrimp = Nutrient concentration in harvested shrimp × total shrimp biomass.

Nutrient output in crab = Nutrient concentration in crab harvesting × total crab biomass.

Nutrient output in water = Nutrient concentration in outlet water × total amount of water released.

Nutrient output in benthic algae = N concentrations were based on chlorophyll *a* concentrations, using the ratio of chlorophyll to C of Legendre and Michaud (1999), and the benthic algae P and C were calculated from the Redfield (1958) molar ratio (C:N:P = 106:16:1).

Nutrient (N, P and C) inputs and outputs in the SGOPs were calculated using shrimp, water, feed and fertilizer inputs, and harvested shrimp, discharge water and sedimented material outputs. Inputs and outputs were calculated as follows:

Nutrient input in shrimp = Nutrient concentration in shrimp at stocking × total shrimp stocking weights (as dry weight).

Nutrient input in water = Nutrient concentration in inlet water × total amount of water supplied.

Nutrient input in feed = Nutrient concentration in feed × total amount of feed supplied.

Nutrient input in fertilizer = Nutrient concentration in fertilizer × total amount of fertilizer supplied.

Nutrient output in shrimp = Nutrient concentration in harvested shrimp × total shrimp biomass (as dry weight).

Nutrient output in water = Nutrient concentration in outlet water × total amount of water released.

Nutrient output in sedimented material (referred to as sediment) = Nutrient concentration in the sediment × total settled materials (as dry weight).

It should be noted that this research did not quantify C exchange with the atmosphere, i.e. carbon fixation and respiration processes, so these inputs and outputs were not included in the C budget.

2.7. Data analysis

Analysis of variance (ANOVA) with Duncan multiple range tests was applied to determine the significant differences in water quality parameters in the wet and dry season, using SAS software (SAS 9.4).

3. Results

3.1. Production

Mean shrimp survival ranged from 4.1 to 8.5% across the 12 IRSPs (M1-M6 and C1-C6), and shrimp yield was 113.2 ± 37.5 kg ha^{-1} (Table 1). In addition to the shrimp harvest, there was also a significant crab harvest from a number of farms (mean crab yield: 38.4 ± 17.3 kg ha^{-1}). Rice harvests were only obtained from three of the twelve IRSPs over the entire two-year study period (112-258 kg ha^{-1}, based on platform area only).

For the SGOPs (M1-M6), the survival of the shrimp varied substantially, with a mean of 77.1% (*P. vannamei*) and 59.2% (*P. monodon*) for those ponds where a harvest was achieved (there were three of the six ponds where survival was 0%). The shrimp production ranged from 3667 to 4167 kg ha^{-1}, with the mean of 3917 kg ha^{-1} for *P. vannamei*, and an average of 1551 kg ha^{-1} for *P. monodon*. Mean FCR for *P. vannamei* ponds was 1.08 while *P. monodon* was 1.44 (Table 1).

3.2. Water quality

In IRSPs, chlorophyll *a* concentration ranged from 2 to 180 µg L^{-1} and was significantly different between the beginning (first month) and the end (final month) of the culture period ($P < 0.05$) (Table 2). The concentrations of DO were consistently low (usually less than 2 mg L^{-1}), especially in the early morning. TN concentrations in the water column of IRSPs ranged from 3.03 to 3.14 mg L^{-1} in the dry season, and 0.64 to 1.16 mg L^{-1} in the wet season. TDN concentrations in IRSPs fluctuated throughout the year with no obvious changes between the wet and dry season. TOC in the IRSPs was around 13 mg L^{-1} which was less than a half that of the SGOPs (approximately 26 mg L^{-1}) (Table 2).

DO concentrations tended to be lower toward the end of the culture period in SGOPs (both *P. vannamei* and *P. monodon*). Overall, DO concentration varied from 3.4 to 7.1 mg L^{-1} for *P. vannamei*, and between 3.2 and 5.9 mg L^{-1} for *P. monodon* (Table 2). In SGOPs, the NH_4–N, NO_2–N and NO_3–N ranged from 0.08 to 1.29, 0.01 to 0.54, 0.03 to 1.66 mg L^{-1}, for *P. vannamei*, and 0.01 to 1.70, 0.01 to 0.20, 0.01 to 1.72 mg L^{-1} for *P. monodon*, respectively (Table 2). There were significant ($P < 0.05$) increase in NH_4–N, NO_2–N and NO_3–N concentrations in the pond water in the final month of culture as compared to the values for the first month of the culture period. Additionally, PO_4–P concentrations ranged from 0.01 to 0.03 mg L^{-1} for *P. vannamei,* and 0.01 to 0.19 mg L^{-1} for *P. monodon* ponds, whereas TP concentrations were between 0.1 to 0.4 mg L^{-1} for *P. vannamei* and 0.3 to 0.7 mg L^{-1} for *P. monodon* ponds. Both PO_4–P and TP concentrations also increased significantly ($P < 0.05$) from the first month to the final month of the culture period for *P. monodon* ponds, but not the case for *P. vannamei* ponds. Chlorophyll *a* concentrations increased gradually over the production period, and at the end of the culture period they were around 83 and 57 µg L^{-1} for *P. vannamei* and *P. monodon*, respectively (Table 2). The TSS concentrations in the SGOPs were just two-thirds that of IRSPs.

3.3. Nutrient budgets

In IRSPs, water intake was the main nutrient and carbon input (92% N, 57% P, 95% C) while fertilizer addition accounted for 8% N, 43% P and 5% C. Shrimp survival was only around 4.1-8.5% across the two years, hence shrimp only occupied 6% N, 5% P and 10% C of total output (Table 3, Fig. 3). Water discharge accounted for the highest output (75% N, 41% P, 57% C), followed by unaccounted (11% N, 50% P, 25% C) (Table 3, Fig. 3).

In *P. vannamei* ponds (SGOPs), formulated feed was the primary nutrient (N, P and C) input, i.e. 82, 75 and 85%, of the total input respectively. Intake water was 8, 6 and 10% N, P and C in that order. N, P and C inputs in the form of fertilizer were 10, 19 and 5%, respectively. Shrimp biomass tended to be the dominant output as it accounted for around 35% of total nutrient outputs. Approximately 10, 13 and 29% of N, P and C output, respectively, were unaccounted for (Table 4, Fig. 4).

For the *P. monodon* ponds (SGOPs), the feed was also the major input of nutrient (75% N, 55% P and 77% C), followed by fertilizer (14% N, 40% P and 8% C). Shrimp harvest was approximately 26% of the total output. A major portion of the nutrient inputs were deposited on the floor of the ponds (i.e., sediment) as well as discharged over the season in the discharge water (40% N, 57% P, 41% C and 24% N, 9% P, 17% C, respectively, of total nutrient retention in the culture system) (Table 4, Fig. 5).

4. Discussion

This study is the first to determine nutrient budgets in the IRSPs, and showed, for the first time, that SGOPs were more efficient than IRSPs. In the SGOPs, the feed was more efficiently converted to shrimp biomass. In contrast, in IRSPs, nutrients and C in water intake was largely discharged, especially in the case of N. Hence, most of the nutrients did not get assimilated in the ponds. One key reason for this poor assimilation was low shrimp survival (6.3 ± 2.2%), thus the nutrient (especially N and P) in this system did not convert to shrimp biomass. This, combined with the low rice harvest (mostly no rice crop over the two-year period of the sampling at the 12 farms due to high salinity affecting rice production), supports the conclusion that SGOPs were a more efficient system than IRSPs in our study.

In SGOPs, the nutrient budgets, and more particularly the N budgets of *P. vannamei* ponds were higher than that of *P. monodon* ponds. This was because of two reasons: firstly, *P. vannamei* ponds had much higher stocking densities (30 post larvae m^{-2} compared to 15 post larvae m^{-2} of *P. monodon*); and, secondly that the higher stocking densities in *P. vannamei* ponds required higher feed inputs compared to *P. monodon* ponds. The results from our *P. vannamei* ponds were similar to those from *P. vannamei* ponds studied by Xia et al. (2004). They found inputs of 315 kg N ha^{-1} and 56 kg P ha^{-1} with a stocking density of 50 post larvae m^{-2}. In addition, Sahu et al. (2012) had similar N, P and C in their *P. monodon* harvests on semi-intensive ponds compared to our study (107-293 kg N ha^{-1} $crop^{-1}$, 23-57 kg P ha^{-1} $crop^{-1}$, 763-1831 kg C ha^{-1} $crop^{-1}$ at the stocking density of 10-22 post larvae m^{-2}). The FCRs in our study were low compared with other studies suggesting the feed utilization efficiency was high (Jackson et al., 2003; Sahu et al., 2012).

Moreover, in the comparison between *P. vannamei* and *P. monodon* ponds, the results demonstrated that *P. vannamei* was more efficient than *P. monodon* since *P. vannamei* reached harvest size faster (2.7 ± 0.4 months for *P. vannamei* as opposed to 4.2 ± 0.5 months for *P. monodon*), had higher survival, higher production, and a better FCR. Some SGOPs had no harvest in this research due to a disease outbreak (mainly Early Mortality Syndrome - EMS) on both *P. vannamei* and *P. monodon* ponds. EMS has become the most severe disease affecting shrimp in the Mekong Delta since 2010 (FAO, 2013). Occurrences of EMS usually happen in the first 30 days after shrimp stocking, and mortality can be higher than 70% (Lightner et al., 2013). Therefore, a faster time to harvest reduces the risks of loss, which, in turn, results in more production and income for farmers.

Incorporation of nutrients into benthic algae was quite low in this study which proposes that natural feed may be limiting. Hence the management of benthic algae in the IRSPs could be critical (Burford and Williams, 2001; Burford et al., 2004; Tho et al., 2013). However, at times, large amounts of nutrients were stored in macrophytes (aquatic plants) and benthic algae on the platform, but this biomass was found to vary considerably over time and between farms. It was unclear what drove this variability, but the change in salinity and temperature might reduce the biomass (Dien et al., 2016). Traditional pond management practices often include fertilization to promote primary productivity, but this practice is questionable since nutrient levels in the ponds were high compared with other studies (Alongi et al., 2000). This is because incoming water from the canals contained high loads of N and P from sewage and other nutrient waste inputs.

Additionally, fertilizer may be of limited value in ponds where formulated feed is added. Studies in Choluteca, Honduras, indicated that inorganic fertilization of ponds with feed added was of dubious value during the wet season, and did not increase shrimp yield during the dry season when ambient conditions hinder shrimp growth (Teichert-Coddington et al., 2000). In SGOPs, fertilizer can have a considerable effect on effluent discharge concentrations of soluble N, P and C (Wahab et al., 2003; Xia et al., 2004). Studies also suggest that farm managers should minimize the use of fertilizers unless site-specific studies demonstrate that fertilization increases yields (Barua et al., 2011; Burford et al., 2004; Rouf et al., 2012). Our study also suggests that fertilizer addition may be an unnecessary expense.

Nutrient and C in water discharge from IRSPs was lower than SGOPs, thus IRSPs have a lower environmental impact than SGOPs (Chowdhury et al., 2011). However, in this study, this was counteracted by poor production likely due to chronically low DO concentration affecting growth and mortality, in particular between the evening and the early morning period (Leigh et al., 2017). This issue could be considered the main reason for the low shrimp survival because safe DO concentrations for shrimp health should be more than 3.0 mg L^{-1} (MNRE, 2008). DO concentration decreases with increased depth of water, and also when temperature and salinity decline. Shrimp survival in IRSPs was also likely to be affected by food availability (Burford and Lorenzen, 2004; Burford et al., 2004; Islam, 2003). Furthermore, the high salinity in IRSPs resulted in the failure of the rice-crop. High salinity is considered the primary risk factor for rice (Leigh et al., 2017; Nhan et al., 2011). Hence, unless these risk factors are addressed, IRSPs cannot be made more sustainable.

It is advised that pond preparation of IRSPs was vital to enhancing water quality, especially for increasing DO concentrations during the culture period. To overcome the oxygen deficiency in the IRSPs, some solutions might include: water exchange through the renewal of pond water with high-quality water either by sluice-gate or pumping; aeration by using paddle wheels; and, use of probiotics that are bio-friendly agents and contain such as *Lactobacillus* and *Bacillus* spp. (Thakur and Lin, 2003). However, it may not be feasible to apply these methods to increase DO concentrations in the IRSPs because of the large area: around 2.0-3.0 ha (Table 1). Hence, a more economical way may be to focus on pond preparation to remove sludge from the bottom layer of the ditch (Thuy and Ford, 2010). Subsequently, a mechanism is needed so that water quality can be monitored and maintained properly during the culture period.

Denitrification and ammonia volatilization are two potential losses of N that were not measured in our study and are not often measured directly in aquaculture systems. In most studies, these factors are estimated indirectly as the difference between the N inputs and outputs (Briggs and Funge-Smith, 1994; Martin et al., 1998; Miranda et al., 2009; Paez-Osuna et al., 1999; Sun and Boyd, 2013; Xia et al., 2004). The study showed that in the grow-out pond, around 10% N was estimated as lost via these processes in both *P. vannamei* and *P. monodon* ponds. The unaccounted for component varies widely between studies. Most of the studies estimated less than 15 % of N as unaccounted (Briggs and Funge-Smith, 1994; Martin et al., 1998). However, much higher losses from 27 to 66% have also been reported (Hopkins et al., 1993; Martin et al., 1998; Paez-Osuna et al., 1999). Burford and Longmore (2001) did one of few studies to measure fluxes and infer denitrification in shrimp ponds and found < 2% of available N was denitrified. They attributed this to low availability of nitrate substrate, in turn, due to low nitrification of ammonia nitrogen. Therefore, further research should be conducted to quantify “unaccounted” regarding nutrient outputs, especially focusing on N outputs to thoroughly understand the N dynamics in both SGOPs and IRSPs.

5. Conclusions

This study showed that the main nutrient input (92% N, 57% P and 95% C) in the IRSPs came from intake water, and water discharge accounted for the highest output (75% N, 41% P, and 57% C). Shrimp survival in IRSPs was low over the two years (4.1-8.5%), which resulted in the low nutrient output in the harvested shrimp (6% N, 5% P and 10% C). In contrast, the SGOPs had much higher survival (77.1% for *P. vannamei* and 59.2% for *P. monodon*) in the three of the six farms where the crop survived through to harvest. In these ponds, formulated feed was the highest nutrient input (*P. vannamei*: 82% N, 75% P and 85% C; *P. monodon*: 75% N, 55% P and 77% C) with approximately a third of the nutrients being in shrimp harvest. These results showed that nutrients in the IRSPs were used less efficiently than in SGOPs, thus mechanisms to improve shrimp survival and production are urgently needed.

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Figure captions

Figure 1. Map of 12 farms and the adjacent canal in Ca Mau province, Vietnam.

Figure 2. Design of an integrated rice-shrimp pond (left) and an intensive shrimp grow-out pond (right) with a settling pond on the same farm.

Figure 3. The nutrient (% N, % P and % C) budgets in integrated rice-shrimp ponds.

Figure 4. The nutrient (% N, % P and % C) budgets in shrimp *P. vannamei* ponds.

Figure 5. The nutrient (% N, % P and % C) budgets in shrimp *P. monodon* ponds.

Tables

Table 1. Production (mean ± SD) and related data for integrated rice-shrimp ponds and shrimp grow-out ponds.

Ponds	Pond area (m^2)	Survival (%)	Culture period (months)	Shrimp yield (kg ha^{-1})	Crab yield (kg ha^{-1})	FCR
Rice-shrimp	24,500 ± 9,439	6.3 ± 2.2	24 (semi-continuous harvesting)	113.2 ± 37.5	38.4 ± 17.3	-
Grow-out:						
P. vannamei	3000 ± 245	77.1 ± 10.4	2.7 ± 0.4	3917 ± 250	-	1.08 ± 0.02
P. monodon	3000 ± 376	59.2 ± 5.3	4.2 ± 0.5	1551 ± 312	-	1.44 ± 0.17

Table 2. Water quality parameters (range and mean values) in integrated rice-shrimp ponds during 2014–2015, *P. vannamei* ponds across the three months of grow-out, and *P. monodon* ponds across the five months of grow-out. All units were presented at mg L^{-1}, except Chlorophyll *a* (µg L^{-1}).

Parameter	**Integrated rice-shrimp ponds**			***P. vannamei* ponds**			***P. monodon* ponds**		
	Beginning (Month 1)	Middle (Month 12)	At the end (Month 24)	Beginning (Month 1)	Middle (Month 2)	At the end (Month 3)	Beginning (Month 1)	Middle (Month 3)	At the end (Month 5)
NH_4–N (mg L^{-1})	0.03-0.19 (0.10)	0.01-0.21 (0.07)	0.08-0.86 (0.20)	0.08-0.20 (0.13)	0.14-0.41 (0.28)	0.53-1.29 (0.91)	0.23-0.76 (0.53)	0.01-0.38 (0.26)	0.94-1.70 (1.36)
NO_2–N (mg L^{-1})	0.00-0.04 (0.01)	0.04-0.06 (0.05)	0.01-0.37 (0.08)	0.01-0.02 (0.02)	0.01-0.08 (0.06)	0.07-0.54 (0.34)	0.01-0.06 (0.03)	0.01-0.14 (0.06)	0.01-0.20 (0.08)
NO_3–N (mg L^{-1})	0.10-0.37 (0.26)	0.03-0.11 (0.06)	0.01-0.14 (0.06)	0.10-1.66 (0.64)	0.03-0.08 (0.06)	0.11-0.36 (0.24)	0.23-0.35 (0.29)	0.01-0.39 (0.24)	0.95-1.72 (0.23)
TN (mg L^{-1})	0.7-3.7 (1.8)	0.6-1.2 (0.8)	0.9-1.4 (1.2)	0.2-2.0 (1.1)	0.6-1.9 (1.2)	1.7-1.8 (1.8)	1.0-2.9 (1.7)	3.7-4.6 (4.1)	2.5-5.8 (4.4)
PO_4–P (mg L^{-1})	0.01-0.07 (0.03)	0.01-0.19 (0.03)	0.01-0.16 (0.05)	0.01-0.03 (0.02)	0.01-0.02 (0.02)	0.01-0.02 (0.01)	0.01-0.10 (0.06)	0.15-0.16 (0.16)	0.17-0.19 (0.18)
TP (mg L^{-1})	0.1-0.4 (0.3)	0.0-0.2 (0.1)	0.1-0.2 (0.1)	0.1-0.2 (0.2)	0.1-0.4 (0.3)	0.1-0.3 (0.2)	0.3-0.5 (0.4)	0.4-0.6 (0.5)	0.3-0.7 (0. 4)
TOC (mg L^{-1})	9.8-22.2 (18.1)	3.9-6.1 (5.0)	15.0-21.4 (19.6)	15.9-21.2 (17.8)	19.2-32.6 (26.8)	9.7-18.3 (14.0)	12.4-23.0 (18.4)	16.2-27.1 (20.0)	21.5-28.1 (23.7)
DO (mg L^{-1})	0.7-2.7 (1.6)	0.9-3.5 (2.1)	1.3-4.2 (2.9)	4.0-7.1 (5.7)	3.7-6.2 (4.8)	3.4-6.1 (4.5)	3.4-5.7 (4.4)	3.4-5.9 (4.5)	3.2-5.6 (4.3)
Chlorophyll *a* (µg L^{-1})	1.8-104.4 (23.9)	5.4-59.4 (30.2)	8.4-179.7 (90.5)	22.7-66.8 (60.7)	8.9-112.4 (67.6)	67.5-97.8 (82.6)	0.6-7.4 (3.9)	4.8-58.4 (25.8)	14.3-74.3 (57.4)
TSS (mg L^{-1})	25-247 (129)	37-87 (53)	76-147 (130)	44-88 (69)	45-142 (96)	90-122 (111)	39-54 (45)	37-71 (57)	80-106 (91)

Table 3. The nutrient budget for integrated rice-shrimp ponds (kg ha^{-1} and % of total inputs and outputs).

Nutrient	**Inputs**					**Outputs**					
	Shrimp	Crab	Water	Fertilizer	**Total**	Shrimp	Crab	Water	Benthic algae	Unaccounted	**Total**
N (kg ha^{-1})	0.01	<0.01	41.27	3.67	**44.95**	2.59	1.07	33.79	2.48	5.02	**44.95**
N (%)	0.02	<0.01	91.82	8.16	**100.00**	5.76	2.38	75.18	5.52	11.16	**100.00**
P (kg ha^{-1})	0.02	<0.01	4.96	3.74	**8.72**	0.43	0.24	3.58	0.15	4.32	**8.72**
P (%)	0.22	<0.01	56.89	42.89	**100.00**	4.93	2.75	41.06	1.72	49.54	**100.00**
C (kg ha^{-1})	0.03	<0.01	402.15	19.27	**421.45**	43.15	17.72	240.10	13.25	107.23	**421.45**
C (%)	0.01	<0.01	95.42	4.57	**100.00**	10.24	4.20	56.97	3.14	25.44	**100.00**

Table 4. The nutrient budgets for shrimp grow-out ponds (kg ha^{-1} and % of total inputs and outputs).

Nutrient	**Inputs**					**Outputs**				
	Shrimp	Water	Feed	Fertilizer	**Total**	Shrimp	Sedimentation	Water	Unaccounted	**Total**
P. vannamei ponds:										
N (kg ha^{-1})	0.2	25.2	245.7	30.0	**301.1**	104.5	113.3	54.5	28.8	**301.1**
N (%)	0.1	8.4	81.6	9.9	**100.0**	34.7	37.6	18.1	9.6	**100.0**
P (kg ha^{-1})	<0.1	3.2	39.4	9.9	**52.5**	12.5	29.7	3.4	6.9	**52.5**
P (%)	<0.1	6.0	75.1	18.9	**100.0**	23.8	56.5	6.4	13.3	**100.0**
C (kg ha^{-1})	3.4	154.4	1352.2	75.0	**1585.0**	366.7	540.0	224.0	354.3	**1585.0**
C (%)	0.2	9.8	85.3	4.7	**100.0**	23.1	34.1	14.1	28.7	**100.0**
P. monodon ponds:										
N (kg ha^{-1})	0.1	20.6	142.9	26.1	**189.7**	50.4	76.0	45.6	17.7	**189.7**
N (%)	<0.1	10.9	75.3	13.8	**100.0**	26.5	40.1	24.0	9.4	**100.0**
P (kg ha^{-1})	<0.1	2.3	26.1	19.1	**47.5**	6.0	27.1	4.4	10.0	**47.5**
P (%)	<0.1	4.9	54.9	40.2	**100.0**	12.7	57.0	9.2	21.1	**100.0**
C (kg ha^{-1})	0.9	178.5	942.1	95.0	**1216.5**	176.7	492.8	205.8	341.2	**1216.5**
C (%)	0.1	14.7	77.4	7.8	**100.0**	14.5	40.5	16.9	28.1	**100.0**

Figures

Figure 1

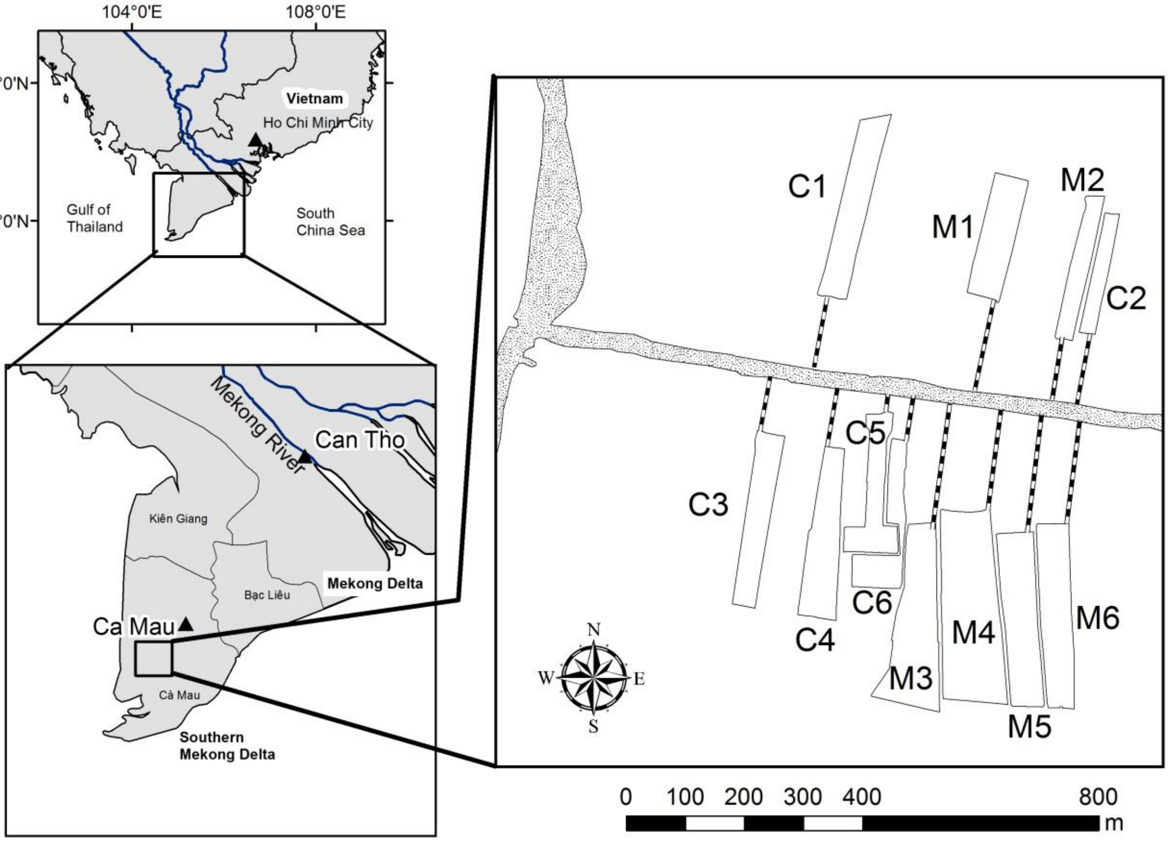
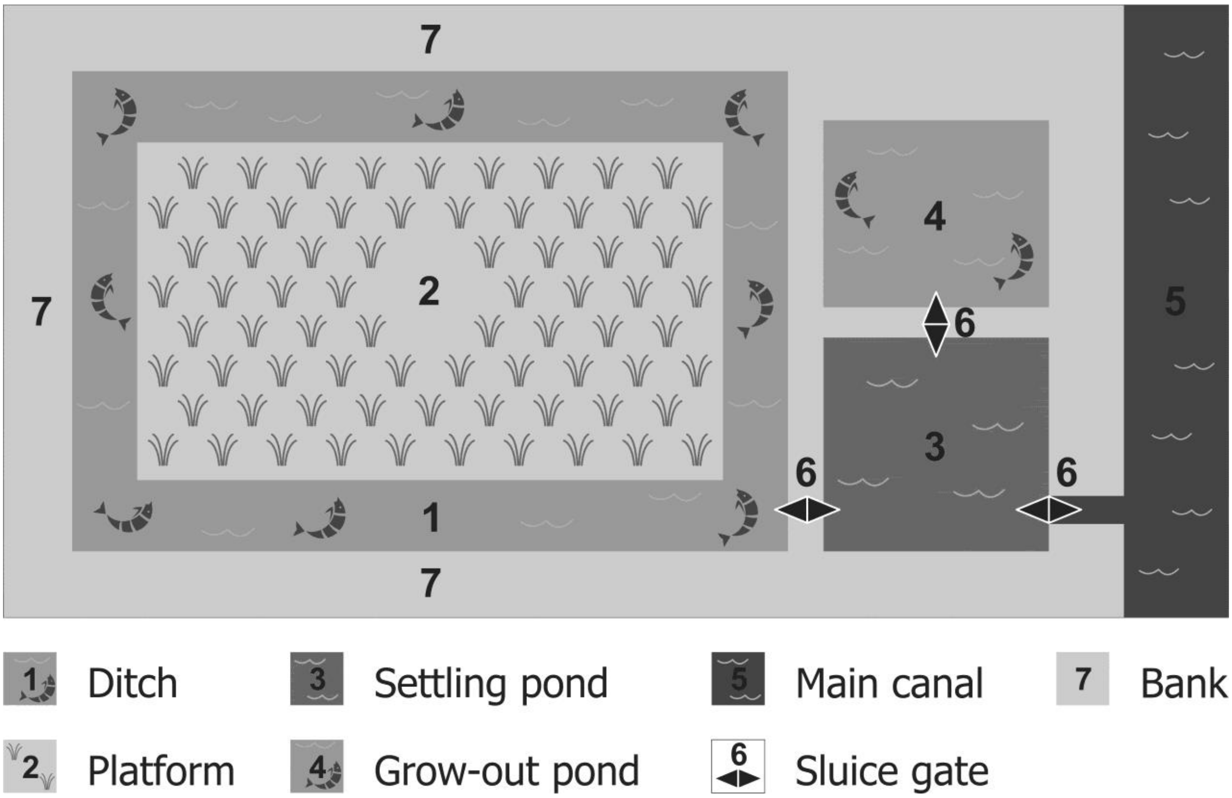


Figure 2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5 Main canal
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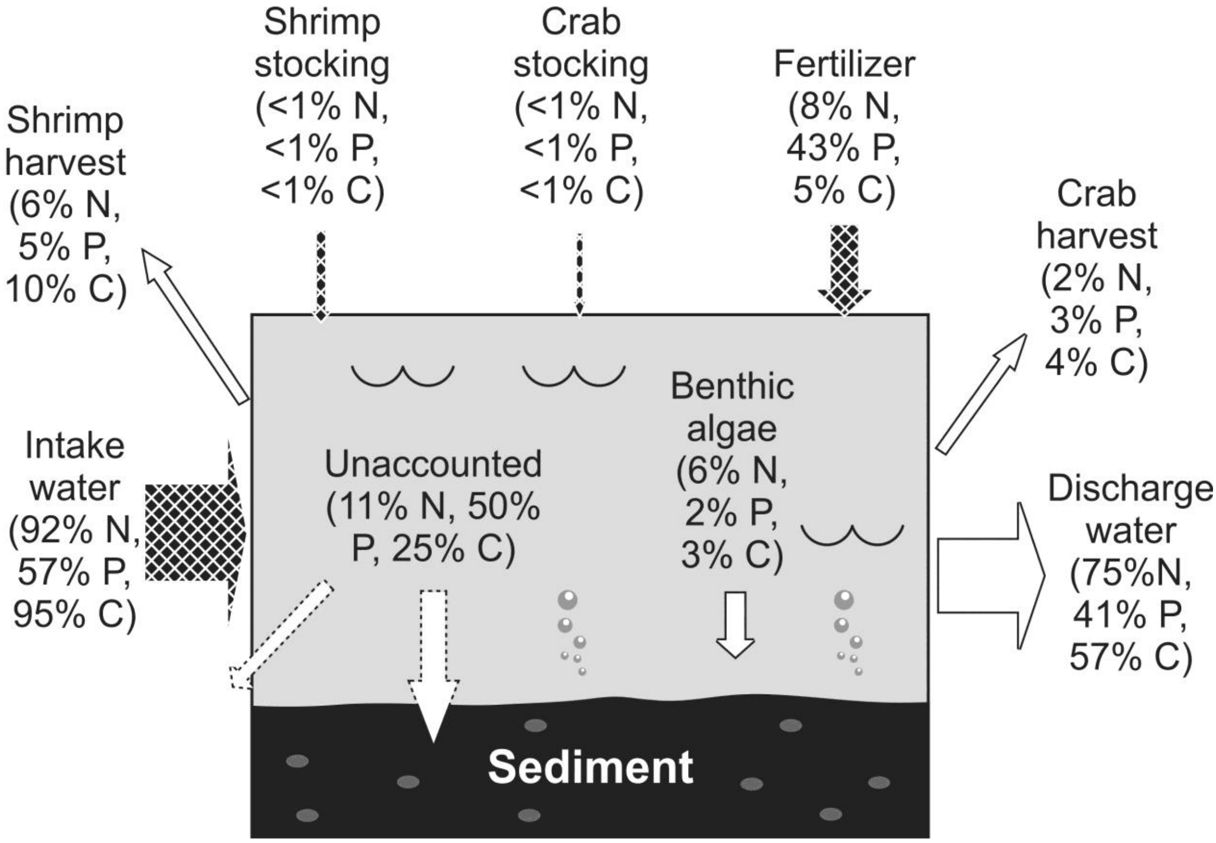
4 Grow-out pond
6 Sluice gate

580 Figure 3



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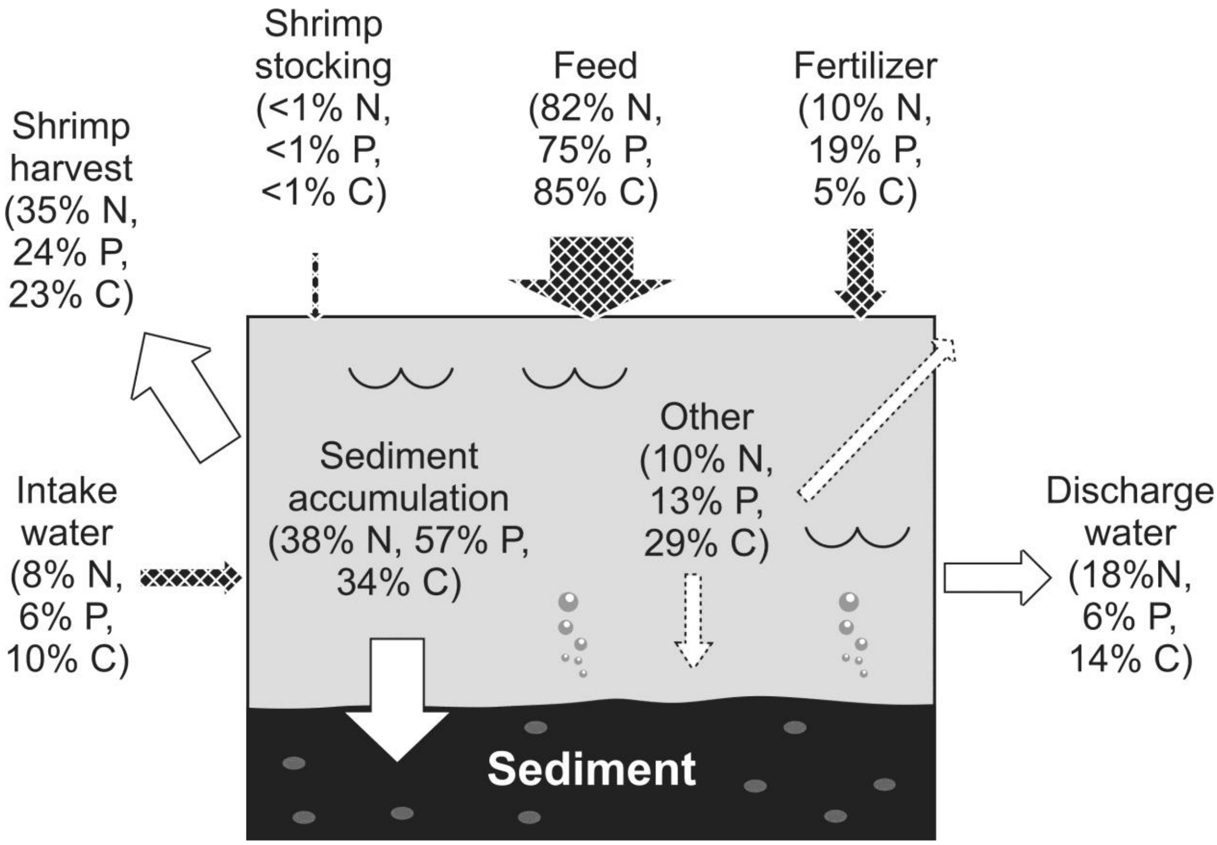

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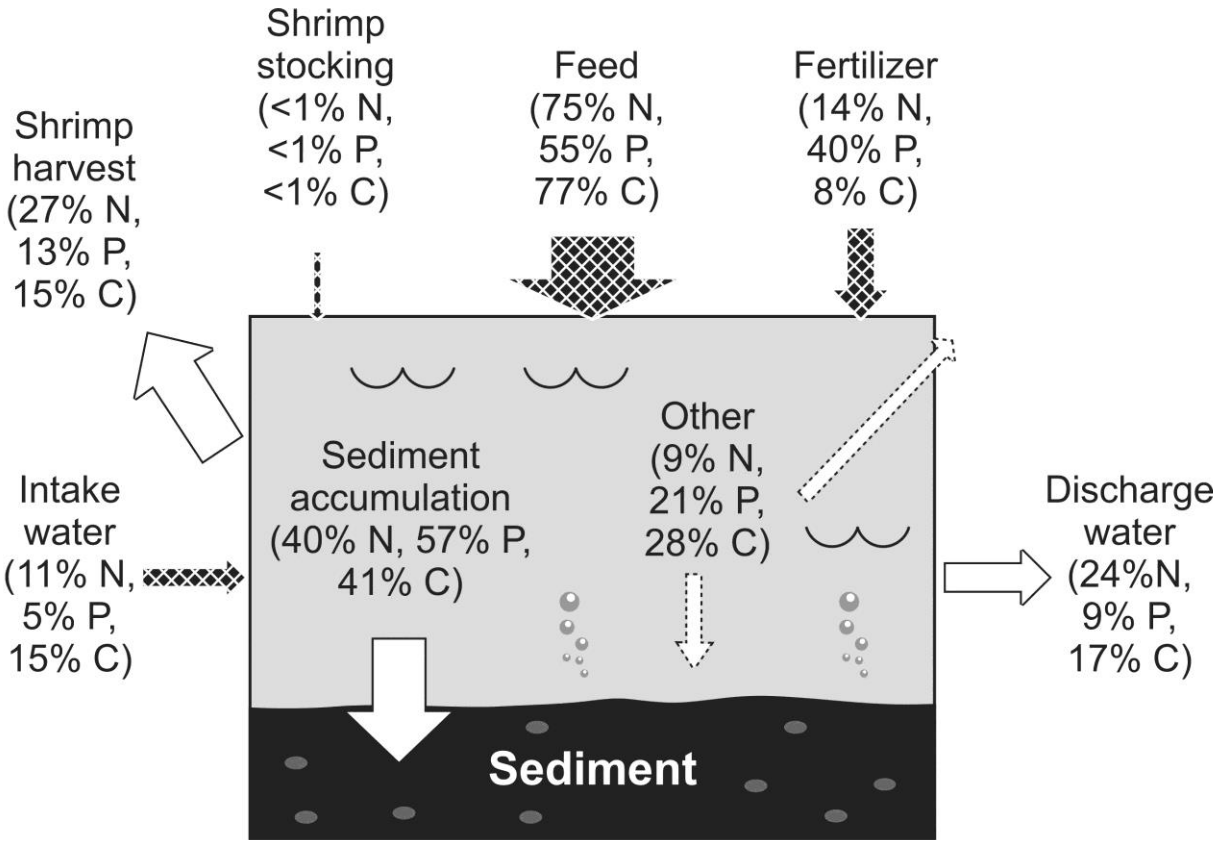
586 Figure 5



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