Quantifying sustainability indicators in striped catfish *Pangasianodon hypophthalmus* downstream and upstream ponds

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ABSTRACT: To assess the potential for improving sustainability and efficiency in an important Vietnamese finfish culture, we quantified sustainability indicators for 2 downstream and 2 upstream 3 to 4 m deep ponds for striped catfish *Pangasianodon hypophthalmus* (Sauvage, 1878) production along the Mekong River, Vietnam. The resources used per kg fish produced were (downstream vs. upstream): 2.8 vs. 7.1 m^3 water, 0.04 vs. 0.14 kWh energy, 0.06 vs. 0.11 h human labour and 0.06 vs. 0.15 g antibiotics (p < 0.05). The feed conversion ratio (kg feed dry matter per kg fish wet weight) was 1.50 vs. 1.65 and feed dry matter utilization efficiency was similar (28 vs. 30%) for both types of ponds (p > 0.05). Nitrogen and phosphorus utilization efficiencies were 44 vs. 40% for nitrogen (p < 0.05) and 17.7 vs. 17.6% for phosphorus (p > 0.05). An advantage of production in deep ponds is the breakdown of organic matter through denitrification and fermentation. Based on the difference between feed input and monitored outputs and sinks, an estimated 29–37% of dry matter volatilized as CO_2 and 30–34% of nitrogen was lost as N_2. A major disadvantage of the deep pond production system is its dependency on water exchange with the Mekong River, resulting in low biosecurity, which is aggravated by the lack of availability of disease-free fingerlings. Dealing with disease caused farmers to apply suboptimal feeding rations and to lengthen the culture period. Developing (semi-)closed systems that adopt elements from recirculation technology could improve both culture performance and sustainability.

KEY WORDS: Pangasius · Striped catfish · Nutrient budget · Water quality · Waste effluent · Mass balance

INTRODUCTION

Striped catfish *Pangasianodon hypophthalmus* (Sauvage, 1878) farming in the Mekong Delta of Vietnam has developed rapidly into one of the country's major aquaculture industries (Phuong & Oanh 2010). In 2016, total catfish production reached 1.1 million tonnes produced in 5500 ha of ponds. About 600 000 tonnes of processed pangasius products have been exported to more than 150 countries (MARD 2016).

With a production of 70–800 metric tonnes (MT) ha⁻¹ yr⁻¹ (Phan et al. 2009), striped catfish culture is intensive. Water quality is maintained through water exchange. Water use is an important sustainability indicator. The Aquaculture Stewardship Council (ASC) has set the not-to-exceed standard at 5000 l kg⁻¹ striped catfish (ASC 2012). Water use values reported in the literature are either 20–50% smaller (2500–4050 l kg⁻¹ fish; Bosma et al. 2009, Phan et al. 2009) or 82% larger (9167 l kg⁻¹ fish; Anh et al. 2010). ASC indicators for nitrogen (N) and phosphorus (P) discharge are 27.5 g N and 7.2 g P kg⁻¹ fish (ASC 2012). These ASC-indicator values are substantially lower than the estimated values for N and P dis-

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charge reported in the literature: 38–46 g N kg^{-1} (Anh et al. 2010, De Silva et al. 2010) and 9.9–14.4 g P kg^{-1} fish produced (De Silva et al. 2010).

Today, the common practice is to culture striped catfish in 2–6 m deep earthen ponds close to the Mekong River (Phan et al. 2009). Striped catfish farming started upstream (US) before expanding to downstream (DS) areas. Both US and DS farmers practice tidal water exchange. DS farmers have the advantage of a larger tidal amplitude and less potential conflict with other types of land use (Bosma et al. 2009). In addition, DS farmers use less energy than US farmers, because in contrast to the latter, they do not have to pump to realize sufficient water exchange. However, higher water exchange might also result in more waste discharge. Thus, when analyzing the sustainability of current striped catfish farming technology, it is important to quantify the nutrient discharge related to water exchange. The objective of this study was to quantify the water exchange, nutrient utilization efficiency and sustainability indicators in striped catfish US and DS ponds in the Mekong Delta. To improve the sustainability of striped catfish production it is important to get insights into water and nutrient utilization over a complete culture period (ASC 2012). Many studies have already reported nutrient utilization, water use and energy use of striped catfish ponds during a full production cycle (e.g. Bosma et al. 2009, De Silva et al. 2010), but have not measured parameters at the level of detail presented in the current study. In addition, differences between DS and US ponds have not been previously reported. A comparison was made to reported nutrient and water budgets for other major aquaculture species and options to improve sustainability of striped catfish pond farming are suggested.

MATERIALS AND METHODS

Experimental ponds

Four ponds were used, 2 per farm: one farm located DS and the other located US in the Mekong Delta, Vietnam. The 2 DS ponds were located at the Phuoc Binh hamlet, Quoi Thien commune, Vung Liem district, Vĩnh Long province, 63 km apart from the 2 US ponds at the My Suong hamlet, Cao Lanh district, Dong Thap province. The ponds were newly constructed and had a surface area of 1.11 ± 0.1 ha at the DS and 1.08 ± 0.1 ha at the US farm (Table 1). Because of the high sampling frequency and the fact that the large number of parameters measured re-

quired extensive manpower and a permanent presence at each of the study ponds, there was insufficient capacity and budget to sample more than 4 ponds. The selected ponds were representative of farming practices in DS and US locations in this part of the Mekong Delta.

Pond management

The 2 DS and 2 US ponds were operated following the farm's protocol and monitored during a full production cycle. Fish were stocked at a water depth between 2.5 and 3.0 m; the water was raised to a depth of 3.4–4.2 m 1 mo after stocking. This depth was maintained until harvest. In DS ponds, tidal water exchange was practiced, whereas in US ponds a combination of tidal exchange and active pumping was used. No aeration was applied during culture. Pond management included control of water exchange, liming and sludge removal (Table 1, Fig. 1).

Fish, feed and feeding

Striped catfish *Pangasianodon hypophthalmus* fingerlings were stocked at a density of 51.0 ind. m^{-2} in DS ponds and at 51.3 ind. m^{-2} in US ponds, with a mean individual weight of 46 and 31 g, respectively. The same commercial extruded feeds were applied in all ponds (Viet Thang Company). During each of 3 distinct periods in the culture cycle (Days 1–59, 60–122, 123 to harvest), a diet with different composition and pellet size was fed (Table 2). The fish were hand-fed daily at 10:00 h. The farmers aimed to feed 2–3% body weight d^{-1}. For each distinct period, feed samples from 5 randomly selected 25 kg feed bags were pooled to determine the proximate composition (Table 2).

Sampling and measurement

Sampling

During the production cycle, pond influent (river water) and pond water were sampled biweekly (see 'Measurements and analyses' below). Water in each pond was sampled at 5 locations, after which samples were mixed into one composite sample following the procedure described by Nhan et al. (2008). The influent water was sampled next to the inlet sluice gate in the river. Water samples were collected in a PVC

Table 1. Pond characteristics and management in downstream (DS) and upstream (US) striped catfish ponds. Labour use included farm activities of feeding, water exchange, fish health monitoring, water quality monitoring, sludge removal, fish transport, feed transport, log keeping, and accounting; the labour for transport, log keeping and accounting were classified as indirect labour. Lime was applied to maintain pH and alkalinity during culture; antibiotics were applied during fish disease outbreaks but not during the 2 mo before harvest (Fig. 2). Electricity from the public grid was used. Mean ± SD (n = 2), where applicable

| Parameter	Downstream	Upstream
Pond depth (m)	3.4 ± 0.1	4.2 ± 0.1
Pond surface area (ha)	1.1 ± 0.1	1.1 ± 0.1
Pumping	2 diesel pumps (8 HP pump^{-1}); no electric pump	1 electric pumping station (30 HP), 5–8 h d^{-1} at neap tide and 1–2 h d^{-1} at spring tide
Water exchange		
Timing	Discharge at low tide, intake at high tide, no exchange during neap tide	Discharge at low tide, intake at high tide, exchange through pumping during neap tide
Daily exchange (%)	In first 3 mo: 0–10 At harvest: 10–40	In first 2 mo: 0–10 At harvest: 12–50
Time to refill (h)	8–12	6–8
Sludge removal		
Volume (m^3)	3199 ± 842	3200 ± 212
Percent dry matter	2.1 ± 0.4	2.6 ± 0.6
Frequency	3 times	Once
Labour use pond^{-1}	3 farm employees, 1 technician	3 farm employees, 1 technician
Chemical use		
Lime (kg CaCO$_3$ ha^{-1})	1000	2100
Iodine (10%)	0.5–1	0.5–1
NaCl (table salt; ppm)	10–15	10–15
Antibiotic use (g kg^{-1} feed)		
Doxycycline	2.5–5	2.5–5
Oxytetracycline	2.5–5	2.5–5
Florphenicol	2–6	2–6
Energy/fuel use		
Electricity	Light during nighttime, on farm lodges, office and operation	Water exchange; light during nighttime, on farm lodges, office and operation
Diesel	Sludge removal, (emergency) pumping	Sludge removal, emergency pumping
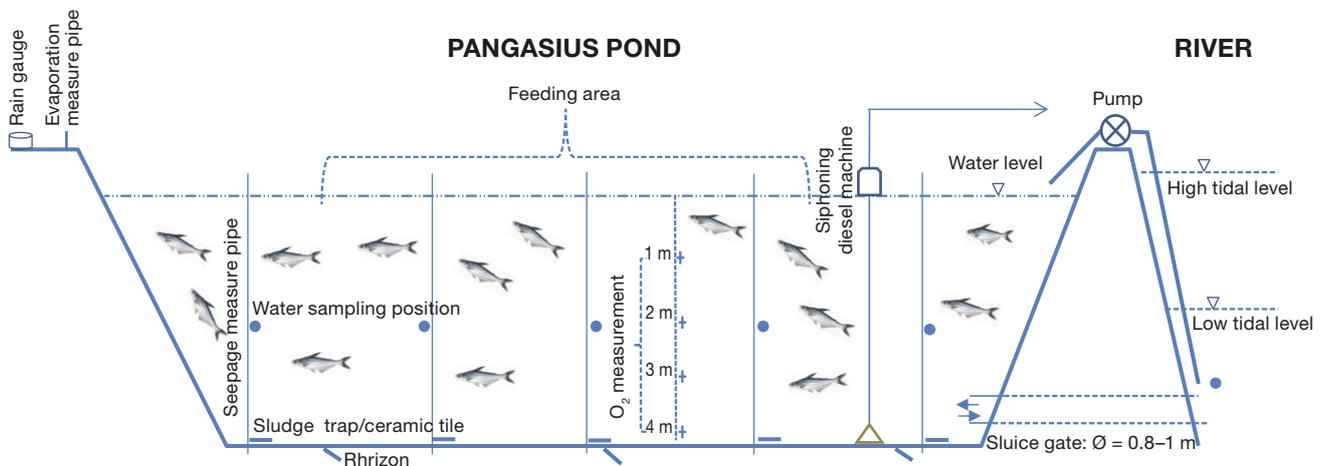
Fig. 1. Schematic view of experimental striped catfish ponds. Number of sample locations for sludge (fixed) and water column samples (random) are shown. Oxygen measurements were taken at fixed depths at random locations. Evaporation and rain volume measurements were taken on the dike. Position of the sluice gate was 0.5 m above the bottom (inner sluice valve not shown). Pumps for water exchange were positioned on top of the dam next to the river, and located in the corner away from the sluice gate. When sludge was siphoned from the bottom, 3 floating movable diesel pumps were used (see also Table 1)

Table 2. Diet composition, pellet size and amount of feed used in 3 different culture periods of the pangasius production cycle. Nutrient content was analyzed on wet weight basis (g kg^{-1} feed). COD: chemical oxygen demand; NFE: nitrogen-free extract; DS: downstream; US: upstream. COD content of the diet was calculated as described in Dalsgaard & Pedersen (2011): COD$_{feed}$ = crude protein (g kg^{-1}) × 1.77 + crude fat (g kg^{-1}) × 2.88 + NFE (g kg^{-1}) × 1.16 + fiber (g kg^{-1}) × 1.16. Energy content of the diet was calculated as 3.4 kcal g^{-1} COD according to Henken et al. (1986)

Parameter	Period 1 (Day 1–59)		Period 2 (Day 60–122)		Period 3 (Day 122–harvest)	
	DS	US	DS	US	DS	US
Pellet diameter (mm)	2.5	2.5	4.0	4.0	8.0	8.0
Total feed (10^3 kg)	17.95	8.55	79.18	26.83	389.25	353.54
Dry matter (g kg^{-1} feed)	889.1	891.9	894.0	894.0	892.0	894.0
Crude protein (g kg^{-1} feed)	303.6	300.7	282.0	280.0	262.0	263.0
Crude fat (g kg^{-1} feed)	52.0	52.0	53.0	53.0	52.0	54.0
NFE (g kg^{-1} feed)	406.3	405.9	419.0	416.0	431.0	424.0
Fiber (g kg^{-1} feed)	54.2	59.2	67.0	68.0	73.0	76.0
Ash (g kg^{-1} feed)	73.0	74.1	73.0	77.0	74.0	77.0
Total-P (g kg^{-1} feed)	13.3	13.2	13.2	13.5	14.0	13.4
COD (g kg^{-1} feed)	1221.4	1,216.9	1215.5	1209.7	1198.1	1201.0
Energy (kcal kg^{-1} feed)	4157.7	4137.5	4132.8	4112.9	4073.7	4083.5

pipe (5.8 cm inner diameter) with the length adjusted to the pond depth; the pipe was lowered vertically at each sampling site, covering the full water column. Once the pipe was in position, the bottom opening was closed by a stopper pulled in place by a rope passing through the pipe. In the river, a 3 m long pipe with the same diameter was used to sample the water column between 1.5 and 4.5 m depth (Fig. 1). Rhizon pore water samplers (Eijkelkamp Agrisearch Equipment) were installed 0.3 m deep in the sediment at 3 randomly chosen locations in each pond to collect seepage water as described by Muendo et al. (2005). The collected rhizon water samples were mixed into one composite sample. Precipitation was measured daily at DS and US locations.

Every fortnight, 50 fish pond^{-1} were caught by casting net, and batch weighed to determine the average individual weight. Of these 50 fish, 15 were randomly taken to determine proximate composition; the remaining fish were returned to the pond. At harvest, all fish were removed by a processor, of which 15 fish pond^{-1} were processed to record fillet yield and fillet coloration, and another 15 fish were analyzed for proximate composition.

At 3 randomly selected locations in each pond, a 0.6 m^2 circular sludge trap and a 0.4 m^2 ceramic tile were installed horizontally on the sediment surface. Sludge traps were emptied on a weekly basis, because they would spill over when sampled biweekly. However, the amount of sludge collected was reported on a biweekly basis. The areas with tiles were marked and sediment accumulating above each tile was left undisturbed until harvest. On the day of harvest, the accumulated sludge above the tiles was quantified and analyzed. Farmers decided when to remove sludge that accumulated at the bottom in the pond (Table 1). Sludge removal was done using a diesel powered suction pump when the sludge bed grew higher than 20 cm (checked by divers). When this happened, a sludge sample was collected and the total volume removed was recorded. Thus, the total amount and composition of the sludge removed could be determined.

Measurements and analyses

Water. Dissolved oxygen and pH were measured daily at 06:00 h at 3.5 m depth in the river next to the inlet of the sluice gate (Fig. 1). Inside each pond, water temperature (°C), dissolved oxygen (mg l^{-1}) and pH were measured by a multi-parameter meter (HI9828, Hanna Instruments). Secchi disk transparency (cm) (Almazan & Boyd 1978) was measured daily at 06:00 and 14:00 h at 5 randomly chosen locations at 1, 2, 3 and 4 m depth (Fig. 1).

The collected water samples in river and ponds, including rain and seepage water, were analyzed according to APHA (1999) for chemical oxygen demand (COD; dichromate reflux, 0.45 μm filter pore size), 5 d biological oxygen demand (BOD$_5$), total organic carbon (TOC; high temperature combustion method), total carbon (TC; high temperature combustion method), carbon dioxide (CO$_2$; free CO$_2$ reacts with sodium hydroxide to form sodium bicarbonate), total alkalinity (titration with sulfuric acid and methyl orange indicator), total Kjeldahl nitrogen (Kj-N; Kjeldahl method), total ammonia nitrogen (TAN; colorimetric method,

and un-ionized ammonia by calculation), nitrite nitrogen (NO_2-N; colorimetric method with diazotized sulfanilamide), nitrate nitrogen (NO_3-N; cadmium reduction to nitrite and measurement of nitrite), hydrogen sulfide (H_2S; photometric method), total suspended solid (TSS; dried to constant weight at 103 to 105°C), chlorophyll *a* (chl *a*; spectrophotometer method), orthophosphate (PO_4-P; ammonium molybdate and potassium antimonyl tartrate method) and total phosphorus (TP; photometric method on sample digested by ammonium persulfate and sulfuric acid to convert all phosphorus to orthophosphate). For rainfall, the amount of rain water was measured daily by a 20 cm diameter Snowdon rain gauge (Mill 1907) installed next to the ponds on each farm (Fig. 1). Evaporation water was calculated for each pond through provided data from the nearest weather station.

Fish, feed and sludge. Whole fish, feed and sludge were analyzed for dry matter (DM), total Kj-N and TP. Each sample of fish, feed and sludge was minced and homogenized. All treatment samples for TP measurements were digested by ammonium persulfate and sulfuric acid to convert all phosphorus to orthophosphate. The DM was determined gravimetrically after drying at 105°C for 24 h (AOAC 2000). Total Kj-N was analyzed by the Kjeldahl method (AOAC 2000). The crude protein in feed was calculated from total Kj-N multiplied by 6.25. For TP in whole fish, feed and sludge were analyzed spectrophotometrically following Kitson & Mellon (1944). Dead fish collected during culture were weighed and counted, and the associated nutrient content was calculated based on the biweekly measured proximate composition.

The 15 fish collected from each pond at the end of the culture period were filleted manually by a professional expert from a processing company, and fillet percentage and color grade were determined according to Sang et al. (2012). The grade of fillet coloration was defined as white (score 1), pink (score 2) or yellow (score 3).

Calculations and statistics

Parameter units and calculation formulas are summarized in Table A1 in the Appendix. Water use consists only of pond-associated water use, not feed-associated water use (Verdegem et al. 2006, Verdegem & Bosma 2009). Sludge includes the removed and accumulated fractions. Differences in water quality parameters, fish performance parameters, nutrient inputs or outputs, resource utilization parameters (consumption or use of fingerlings, water, diesel oil, electricity, labour, chemicals [lime, NaCl, $CuSO_4$ and iodine]), antibiotics, nutrients retained in fish (DM, P, N) and nutrient discharge (DM, P, N) between DS and US ponds were analyzed by 1-way ANOVA, followed by Tukey test in case of significant differences ($p < 0.05$). All statistical comparisons were first done using individual weight at stocking as the co-variable. The latter was retained in the analysis when significant ($p < 0.05$). Daily and biweekly measurements were averaged over the culture period before ANOVA. Daily and biweekly measurements were used to make water and nutrient mass balances (Table A1).

RESULTS

Water quality

Mean values per water quality parameter for the entire production cycle are summarized in Table 3.

Pond influent (river water)

No significant differences ($p > 0.05$) were observed in pond influent between DS and US locations for pH, TAN, ammonia nitrogen (NH_3-N), NO_2-N, NO_3-N, PO_4-P, TP, alkalinity, CO_2, TC, TOC, TSS, chl *a*, COD or BOD_5 (Table 3). Significant differences ($p < 0.05$) were observed in pond influent water between DS and US ponds for oxygen (4.9 vs. 4.7 mg l^{-1}), total Kj-N (3.2 vs. 6.2 mg l^{-1}) and salinity (0.4 vs. 0.06 ppt).

Pond water

No significant differences ($p > 0.05$) were observed in pond water between DS and US ponds for morning pH and for Kj-N, TAN, NO_3-N, H_2S, PO_4-P, CO_2, TC, TOC, chl *a*, COD or BOD_5. However, pond morning and afternoon water temperature, NO_2-N, TP, alkalinity, TSS and salinity in DS ponds were significantly higher than in US ponds. The afternoon pH, morning oxygen concentrations at 1, 2, 3 and 4 m, afternoon oxygen concentrations at 1, 2 and 3 m, morning and afternoon water transparency, and NH_3-N were lower in DS than in US ponds.

Pond influent (river water) versus pond water

There were no significant differences between DS pond influent (river water) and corresponding pond

Table 3. Water quality in pond influent (from river) and in downstream (DS) and upstream (US) striped catfish ponds, averaged (mean ± SD and min.–max. values) over a full production cycle and location. Chemical parameter abbreviations: Kj-N: total Kjeldahl nitrogen; TAN: total ammonia nitrogen; NH_3-N: ammonia nitrogen; NO_2-N: nitrite nitrogen; NO_3-N: nitrate nitrogen; H_2S: hydrogen sulfide; PO_4-P: orthophosphate as phosphorus; TP: total phosphorus; TC: total carbon; TOC: total organic carbon; TSS: total suspended solids; COD: chemical oxygen demand; BOD_5: 5 d biological oxygen demand. Mean values with different superscript letters in the same row are significantly different ($p < 0.05$)

Parameter	DS influent Mean ± SD	DS influent Min.–max.	DS pond Mean ± SD	DS pond Min.–max.	US influent Mean ± SD	US influent Min.–max.	US pond Mean ± SD	US pond Min.–max.	p-value
Temperature (°C)									
Morning	–	–	30.4[a] ± 1.1	28.0–33.0	–	–	29.5[b] ± 1.6	27.0–33.0	0.001
Afternoon	–	–	31.6[a] ± 1.3	29.0–35.0	–	–	30.9[b] ± 1.2	28.0–33.0	0.001
pH									
Morning	6.4[ab] ± 0.2	6–7	6.3[c] ± 0.3	6.0–7.0	6.4[a] ± 0.2	5.7–7.0	6.2[c] ± 0.4	5.6–7.2	0.012
Afternoon			6.6[b] ± 0.4	6.0–7.9			6.7[a] ± 0.6	5.7–7.0	0.001
Oxygen (mg l^{-1})									
Morning									
1 m			1.5[b] ± 0.7	0.7–3.8			1.9[a] ± 0.6	0.6–3.6	0.001
2 m			1.2[d] ± 0.6	0.5–3.4			1.6[c] ± 0.5	0.6–3.5	0.001
3 m			0.8[b] ± 0.4	0.2–2.7			1.4[c] ± 0.4	0.5–3.4	0.001
3.5 m	4.9[a] ± 0.9	2–6.8			4.7[b] ± 1	2.0–6.8			0.001
4 m			0.5[b] ± 0.1	0.3–0.7			1.1[a] ± 0.4	0.5–3.2	0.001
Afternoon									
1 m			1.9[b] ± 0.1	1.6–10.6			2.2[a] ± 0.1	1.9–9.0	0.001
2 m			1.5[b] ± 0.1	1.0–8.7			1.8[a] ± 0.1	1.2–8.7	0.008
3 m			1.0[b] ± 0.1	0.8–7.2			1.3[a] ± 0.1	1.2–18.6	0.001
4 m			–	–			0.8 ± 0.1	0.5–3.0	–
Transparency (cm)									
Morning			24.6[b] ± 6.8	14.0–47.0			30.2[a] ± 4.4	20.0–50.0	0.001
Afternoon			24.2[b] ± 5.0	15.0–48.0			28.2[a] ± 4.5	20.0–42.0	0.001
Chemical parameters (mg l^{-1}, except otherwise noted)									
Kj-N	3.2[bc] ± 1.8	0.5–7.3	9.9[a] ± 8.9	3.0–45.7	6.2[ab] ± 3.9	2.0–16.7	7.1[ab] ± 3.7	1.6–22.8	0.001
TAN	0.19[cd] ± 1.8	0.01–0.7	1.4[a] ± 1.3	0.3–5.6	0.2[c] ± 0.4	0.01–1.9	1.2[ab] ± 1.1	0.03–5.5	0.001
NH_3-N	0.0[bd]	0.0–0.001	0.01[b] ± 0.0	0.0–0.02	0.01[abc] ± 0.02	0.0–0.7	0.02[a] ± 0.0	0.0–0.1	0.001
NO_2-N	0.02[bd] ± 0.02	0–0.7	0.3[a] ± 0.3	0.0–1.4	0.03[bf] ± 0.06	0.0–0.2	0.1[b] ± 0.1	0.0–1.04	0.001
NO_3-N	0.5[a] ± 0.3	0.1–1	0.4[a] ± 0.3	0.3–1.0	0.3[a] ± 0.2	0.1–1.0	0.4[a] ± 0.3	0.02–0.5	0.300
H_2S	–	–	0.2[a] ± 0.1	0.01–0.5	–	–	0.1[a] ± 0.2	0.0–0.8	0.615
PO_4-P	0.04[a] ± 0.02	0.01–0.1	0.4[a] ± 0.5	0.0–1.7	0.4[a] ± 1.7	0.0–7.5	0.4[a] ± 0.5	0.01–1.5	0.400
TP	0.5[cd] ± 0.3	0.2–1.0	2.4[a] ± 1.2	0.4–5.9	0.7[c] ± 0.3	0.2–1.6	1.5[b] ± 1.0	0.2–5.1	0.001
Alkalinity	50.7[bc] ± 8.6	40.3–65.3	61.6[a] ± 9.8	48.9–83.2	43.0[cd] ± 9.2	28.9–60.3	51.1[b] ± 8.7	40.2–67.3	0.001
CO_2	34.3[a] ± 12.8	17.8–65.7	42.4[a] ± 28.1	7.4–106.9	28.2[a] ± 14.2	4.4–59.5	30.9[a] ± 19.3	1.2–68.3	0.057
TC	13.7[d] ± 5.5	5.6–27.3	28.9[b] ± 16.3	10.2–103.2	14.8[cd] ± 4.6	5.6–27.3	30.4[ab] ± 24.1	7.0–129.4	0.001
TOC	2.3[bd] ± 2.2	0.5–9.4	8.4[a] ± 11.5	1.03–64.9	3.2[abc] ± 2.3	0.8–9.4	6.3[ab] ± 5.4	1.3–29.9	0.015
TSS	182.9[ab] ± 47.7	139.7–335.1	80.8[c] ± 33.6	31.8–155.8	221.3[a] ± 51.2	122.4–306.8	49.3[d] ± 21.5	17.5–122	0.001
COD	6.0[c] ± 1.5	3.5–9.7	19.4[a] ± 5.7	11.5–29.4	6.9[cd] ± 1.4	4.3–8.8	19.4[ab] ± 5.1	7.9–29.0	0.001
BOD_5	5.4[c] ± 0.9	4.2–7.2	15.4[a] ± 5.0	9.1–23.7	4.9[cd] ± 1.1	3.2–6.8	15.0[ab] ± 4.2	7.0–24.0	0.615
Chlorophyll a (µg l^{-1})	6.0[c] ± 3.2	2.1–11.6	114.3[a] ± 73.5	23.3–267.8	5.7[cd] ± 2.3	1.9–10.2	100.0[ab] ± 45.9	27.9–189.8	0.001
Salinity (ppt)	0.4[a] ± 0.3	0.1–1.2	0.4[a] ± 0.3	0.1–1.2	0.06[b] ± 0.02	0.04–0.08	0.06[b] ± 0.02	0.04–0.08	0.002

water for NH_3-N, NO_3-N, PO_4-P, CO_2 and salinity, and between US pond influent water and corresponding pond water for Kj-N, NH_3-N, NO_2-N, NO_3-N, PO_4-P, CO_2, TOC and salinity. Mean concentrations in pond influent were always lower than in the pond water for TAN, TP, alkalinity, TC, chl a, COD and BOD_5, and higher for pH, oxygen and TSS ($p < 0.05$). At DS locations, concentrations in influent were lower than in corresponding ponds for Kj-N, TAN, NO_2-N, TP, alkalinity, TC, TOC, chl a, COD and BOD_5. The same was observed in US ponds for TAN,

TP, alkalinity, TC, chl a, COD and BOD_5 ($p < 0.05$). Concentrations in DS and US pond influent were similar to concentrations observed in DS and US ponds for NO_3-N, PO_4-P and CO_2, respectively.

Growth performance

Fish behaviour during feeding was monitored and feeding was stopped when fish began to show a decrease in appetite. In DS ponds, this resulted in real-

ized feeding rates of 1.0 ± 0.4, 2.3 ± 0.5 and 2.5 ± 0.2% body weight d^{-1}, respectively, during culture days 1–59, 60–122, and 123 until harvest. In US ponds, realized feeding rates were 1.1 ± 0.2, 0.8 ± 0.1 and 1.7 ± 0.8% body weight d^{-1}, respectively, during culture days 1–59, 60–122, and 123 until harvest.

In all ponds, fish were harvested when >700 g average individual weight, which is considered the minimum market size. The total harvested biomass was 353 ± 43 MT in DS ponds and 247 ± 21 MT in US ponds. Total feed load was higher in DS ponds when compared with US ponds (p < 0.05). Specific growth rate was similar between DS and US ponds (p > 0.05). In addition, survival, feed conversion ratio (FCR), fillet dress out percentage and fillet coloration were similar between US and DS ponds (p > 0.05) (Table 4).

Nutrient mass balances in striped catfish ponds

Dry matter mass balance

Feed DM input was 434 MT in DS and 341 MT in US ponds, of which 30 and 28% was retained as fish biomass in DS and US ponds, respectively (p > 0.05) (Table 5). Uneaten feed was likely minimal, as the provision of food was stopped at signs of low appetite during feeding. However, feed waste collectors were not deployed during or after feeding, so this is an assumption in the calculations, and we assume any feed not retained in fish biomass was therefore metabolic waste. Feeding to satiation resulted in large fluctuations in feeding between consecutive feeding days (Fig. 2). At the pond level, DM input was the sum of DM in metabolic waste and in influent water (Table 5). Mekong water provided 33% of the DM input in DS ponds and 56% in US ponds, which was significantly different (p < 0.05). The largest fraction of DM input was removed by pumping out sludge, which was similar between DS and US ponds (46 and 58%, respectively; p > 0.05). Unaccounted DM was also similar between DS and US ponds (37 and 29%, respectively; p > 0.05).

Table 4. Fish performance and feeding in downstream (DS) and upstream (US) striped catfish ponds. Values are means ± SD (n = 2). BW: body weight; MT: metric tonnes; WW: wet weight. (*): parameters with a significant (p < 0.05, not shown) co-variable effect of individual weight at stocking. Period 1: Day 1–59; Period 2: Day 60–122; Period 3: Day 123–harvest

Parameter	DS pond	US pond	p-value
Final BW (g ind.$^{-1}$)	791.00 ± 14.1	875.00 ± 63.6	0.210
Initial number of fish (×10^3)	600.00 ± 183.8	553.50 ± 1.4	0.755
Initial biomass* (MT)	27.40 ± 7.9	15.70 ± 0.4	0.171
Final biomass (MT)	352.80 ± 43.1	247.10 ± 21.4	0.090
Yield (kg fish m^{-2})	31.80 ± 3.9	22.90 ± 2.0	0.117
Yield (kg fish m^{-3})	9.30 ± 0.4	5.50 ± 1.2	0.054
Total feed (MT, WW)	486.40 ± 15.0	381.00 ± 28.8	0.044
Survival* (%)	76.40 ± 13.0	51.00 ± 0.6	0.110
Specific growth rate (% BW d^{-1})	1.24 ± 0.0	1.21 ± 0.4	0.746
Period 1 (% BW d^{-1})	0.82 ± 0.2	0.95 ± 0.2	0.575
Period 2 (% BW d^{-1})	1.19 ± 0.6	1.34 ± 0.2	0.764
Period 3 (% BW d^{-1})	1.45 ± 0.1	1.24 ± 0.1	0.191
Feed conversion ratio	1.50 ± 0.1	1.65 ± 0.0	0.211
Fillet percentage (%)	35.50 ± 1.2	35.20 ± 1.7	0.465
Fillet colour grade (1–3)	1.47 ± 0.6	1.20 ± 0.5	0.071

Table 5. Dry matter (DM) mass balance in downstream (DS) and upstream (US) striped catfish ponds per production cycle. DM in feed not retained in live or dead fish is considered to become metabolic waste. Values (in 10^3 kg) are means ± SD (n = 2)

Mass balance component	DS pond Mean ± SD	%	US pond Mean ± SD	%	p-value
Fish level					
Feed	434.0 ± 13.4	100.0	340.6 ± 25.8	100.0	0.045
Live fish	123.7 ± 14.0	28.5	88.1 ± 8.6	25.9	0.092
Dead fish	4.7 ± 2.1	1.1	6.2 ± 0.9	1.8	0.415
Metabolic waste	305.6 ± 2.8	70.4	246.3 ± 17.1	72.3	0.040
Pond level					
DM input					
Metabolic waste	305.6 ± 2.8	67.3	246.3 ± 17.1	44.1	0.040
Influent	148.3 ± 13.1	32.7	311.6 ± 11.1	55.9	0.006
Total	453.9 ± 10.4	100.0	557.9 ± 28.2	100.0	0.039
DM output					
Effluent	74.5 ± 5.9	16.4	68.7 ± 0.5	12.3	0.295
Sludge	209.5 ± 35.7	46.2	325.6 ± 22.6	58.4	0.060
Unaccounted	169.9 ± 31.3	37.4	163.6 ± 5.1	29.3	0.806

P mass balance

More P was administrated with the feed in DS ponds than in US ponds (p < 0.05) (Table 6). On average, 18% of feed-P was retained in fish biomass, including dead fish, in both DS and US ponds. The remaining 82% became metabolic waste. Of the combined P input through metabolic waste and river influent water, 34% in DS ponds and 38% in US ponds was discharged with effluent water. In the P mass balance,
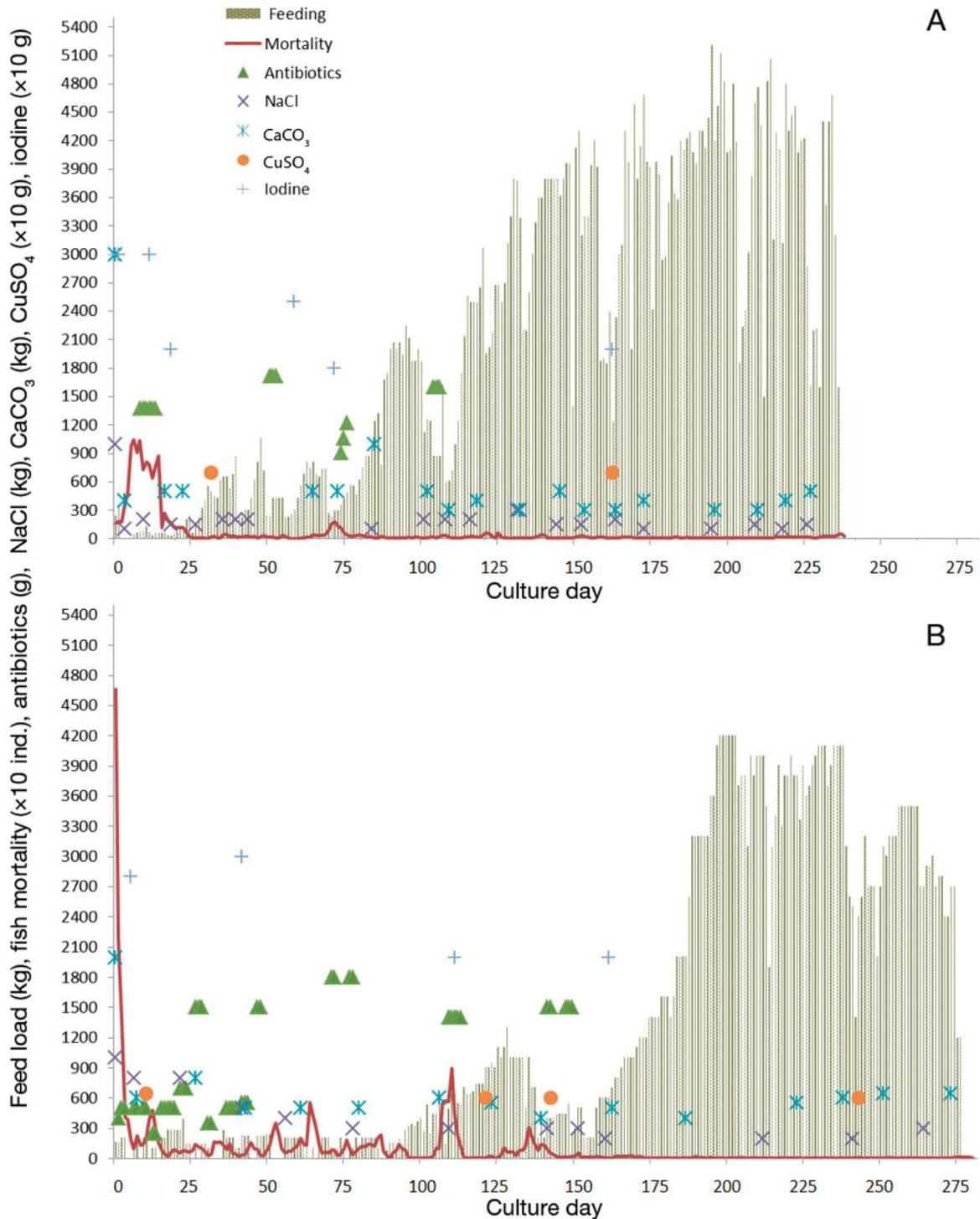
Fig. 2. Daily feed load, fish mortality, and antibiotic and chemical use during the culture period in (A) downstream (DS) and (B) upstream (US) ponds

0.8 and 2.1% remained unaccounted in DS and US ponds, respectively, at the end of the production cycle. The largest fraction of P was removed with sludge pumped out of the pond (65% of metabolic waste in DS and 59% in US ponds; $p > 0.05$).

N mass balance

More N was administrated with the feed in DS ponds than in US ponds ($p < 0.05$) (Table 7). The percentage of feed-N retained in fish, including dead

Table 6. Phosphorus (P) mass balance in downstream (DS) and upstream (US) striped catfish ponds per production cycle. For details on fish level components, see Table 5. Values (in 10^3 kg) are means ± SD (n = 2)

Mass balance component	DS pond Mean ± SD	%	US pond Mean ± SD	%	p-value
Fish level					
Feed	6.73 ± 0.20	100.0	5.11 ± 0.38	100.0	0.034
Live fish	1.09 ± 0.11	16.2	0.77 ± 0.88	15.1	0.082
Dead fish	0.10 ± 0.03	1.5	0.13 ± 0.06	2.5	0.261
Metabolic waste	5.54 ± 0.07	82.5	4.20 ± 0.30	82.2	0.025
Pond level					
P input					
Metabolic waste	5.54 ± 0.07	92.3	4.20 ± 0.30	81.9	0.025
Influent	0.46 ± 0.01	7.7	0.93 ± 0.16	18.1	0.055
Total	6.00 ± 0.07	100.0	5.13 ± 0.46	100.0	0.119
P output					
Effluent	2.05 ± 0.27	34.2	1.96 ± 0.20	38.2	0.746
Sludge	3.90 ± 0.18	65.0	3.05 ± 0.30	59.2	0.075
Unaccounted	0.05 ± 0.01	0.8	0.11 ± 0.04	2.1	0.152

Table 7. Nitrogen (N) mass balance in downstream (DS) and upstream (US) striped catfish ponds per production cycle. For details on fish level components, see Table 5. Values (in 10^3 kg) are means ± SD (n = 2)

Mass balance component	DS pond Mean ± SD	%	US pond Mean ± SD	%	p-value
Fish level					
Feed	20.78 ± 0.69	100.0	16.13 ± 1.22	100.0	0.043
Live fish	8.22 ± 0.84	39.6	5.88 ± 0.58	36.5	0.082
Dead fish	0.96 ± 0.67	4.6	0.50 ± 0.02	3.1	0.441
Metabolic waste	11.60 ± 0.52	55.8	9.76 ± 0.67	60.4	0.092
Pond level					
N input					
Metabolic waste	11.60 ± 0.52	77.0	9.76 ± 0.67	57.3	0.092
Influent	3.47 ± 0.35	23.0	7.27 ± 0.55	42.7	0.014
Total	15.07 ± 0.87	100.0	17.03 ± 0.12	100.0	0.088
N output					
Effluent	8.51 ± 1.17	56.5	10.0 ± 0.15	58.7	0.215
Sludge	1.42 ± 0.91	9.4	1.89 ± 0.22	11.1	0.557
Unaccounted	5.139 ± 1.12	34.1	5.15 ± 0.21	30.2	0.991

fish, was similar in DS and US ponds, fluctuating between 39 and 44 % (p > 0.05). The remaining 56–60 % of feed-N became metabolic waste. Of the combined N input through metabolic waste and influent water, 57–59 % was discharged with effluent water, 9–11 % pumped out with sludge, and 30–34 % remained unaccounted. These results were similar for DS and US ponds (p > 0.05). Assuming the unaccounted N volatilized, then in DS ponds 44 % of the metabolic waste volatilized while in US ponds 53 % volatilized. As a consequence, 56 and 47 % of the metabolic

waste was discharged to the Mekong River from DS and US ponds, respectively.

Pond management

Pond sustainability indicators are presented in Table 8. Use of water, electricity, labour, lime, salt and antibiotics kg^{-1} fish produced were 61, 71, 45, 66, 49 and 60 % lower, respectively, in DS than in US ponds (p < 0.05). However, diesel oil use and sludge removal frequency kg^{-1} fish produced were, respectively, 113 and 200 % higher in DS ponds than in US ponds (p < 0.05). No differences between DS and US ponds were observed for $CuSO_4$ or iodine use (p > 0.05). The period of no antibiotic use before harvest was 133 d in DS ponds and 126 d in US ponds (Fig. 2).

DISCUSSION

Pond performance

None of the measured water quality parameters in the DS or US pond influent exceeded the limits set by the Vietnamese Ministry of Agriculture and Rural Development for striped catfish pond farming (MARD 2003). The FCR over the full production cycle was on average 1.5 in DS ponds and 1.7 in US ponds, in agreement with earlier reported FCRs for striped catfish farming in the Mekong Delta (Bosma et al. 2009, Phan et al. 2009). Observed differences in survival between DS and US ponds were possibly due to differences in management and water regimes at the 2 locations. In all ponds, the fraction of input-P remaining unexplained over the complete production cycle was less than –2 %, which is lower than reported by Adhikari et al. (2014) and Thakur & Lin (2003). A higher fraction of DM and N remained unexplained in the mass balance, because contrary to P, not all possible sinks were measured. It is assumed that the unaccounted fractions of DM and N in the mass balances were mainly volatilized as CO_2 and N_2, respectively (Boyd 1985, Lin et al. 1997, Funge-

Table 8. Sustainability indicator expressed per kg feed (based on wet weight) consumed and per kg fish produced for downstream (DS) and upstream (US) striped catfish ponds. Values are means ± SD (n = 2); DM: dry matter

Parameter	Unit	DS pond		US pond		p-value
		Mean ± SD	Min.–max.	Mean ± SD	Min.–max.	
Resource use						
Fingerlings use	No. kg^{-1} fish	1.70 ± 0.30	1.50–1.90	2.20 ± 0.20	2.10–2.40	0.161
Water use	m^3 kg^{-1} feed	1.90 ± 0.10	1.80–1.90	4.30 ± 0.10	4.30–4.40	0.001
	m^3 kg^{-1} fish	2.80 ± 0.10	2.70–2.90	7.10 ± 0.0	7.12–7.14	0.001
Diesel oil use	ml kg^{-1} feed	1.10 ± 0.10	1.10–1.20	0.50 ± 0.01	0.40–0.60	0.013
	ml kg^{-1} fish	1.60 ± 0.30	1.40–1.80	0.75 ± 0.03	0.70–0.80	0.048
Electricity use	kWh kg^{-1} feed	0.02 ± 0.01	0.02–0.03	0.09 ± 0.01	0.08–1.00	0.007
	kWh kg^{-1} fish	0.04 ± 0.01	0.03–0.04	0.14 ± 0.01	0.10–0.15	0.004
Labour use	h kg^{-1} feed	0.05 ± 0.00	0.046–0.05	0.07 ± 0.01	0.06–0.07	0.030
	h kg^{-1} fish	0.06 ± 0.00	0.050–0.07	0.11 ± 0.01	0.10–0.12	0.035
Chemical use						
Lime (CaCO$_3$)	g kg^{-1} feed	8.50 ± 0.30	8.30–8.70	25.40 ± 2.70	23.50–27.30	0.013
	g kg^{-1} fish	14.40 ± 3.60	11.80–16.90	41.90 ± 5.10	38.30–45.50	0.025
Salt (NaCl)	g kg^{-1} feed	7.10 ± 0.60	6.60–7.40	12.00 ± 0.90	11.40–12.60	0.023
	g kg^{-1} fish	10.60 ± 1.70	9.40–11.80	20.90 ± 0.30	20.70–21.10	0.014
CuSO$_4$	g kg^{-1} feed	0.03 ± 0.02	0.01–0.04	0.04 ± 0.01	0.03–0.06	0.235
	g kg^{-1} fish	0.04 ± 0.02	0.02–0.05	0.09 ± 0.01	0.06–0.11	0.226
Iodine	g kg^{-1} feed	0.16 ± 0.06	0.12–0.20	0.20 ± 0.12	0.20–0.21	0.173
	g kg^{-1} fish	0.30 ± 0.08	0.17–0.33	0.40 ± 0.01	0.04–0.43	0.165
Antibiotic use	g kg^{-1} feed	0.04 ± 0.01	0.03–0.05	0.09 ± 0.01	0.08–0.97	0.020
	g kg^{-1} fish	0.06 ± 0.01	0.05–0.07	0.15 ± 0.01	0.14–0.16	0.020
Nutrient use efficiency						
DM retained	%	29.5 ± 2.8	27.5–31.5	27.7 ± 0.5	27.3–28.0	0.451
N retained	%	44.2 ± 0.7	43.7–44.6	39.5 ± 0.4	39.2–39.8	0.014
P retained	%	17.7 ± 1.4	16.7–18.7	17.6 ± 0.4	17.3–17.9	0.973
Nutrient discharge						
DM discharge	g kg^{-1} fish	414.7 ± 42.0	384.6–444.9	356.5 ± 19.3	342.8–370.2	0.221
	g kg^{-1} feed	278.2 ± 49.9	242.9–313.6	216.5 ± 14.9	205.9–227.1	0.236
N discharge	g kg^{-1} fish	19.8 ± 2.0	17.2–22.9	20.1 ± 4.0	18.4–21.2	0.943
	g kg^{-1} feed	13.3 ± 1.7	12.1–14.5	12.0 ± 1.4	11.1–13.0	0.493
P discharge	g kg^{-1} fish	17.0 ± 1.6	15.8–18.1	17.7 ± 0.2	17.6–17.8	0.579
	g kg^{-1} feed	11.3 ± 0.2	11.2–11.4	10.7 ± 0.1	10.7–10.8	0.054

Smith & Briggs 1998, Gross et al. 2000, Adhikari et al. 2014), and that other fractions in the mass balances were quantified with the same accuracy as for P.

Water exchange and water quality

Water exchange was one of the main factors influencing pond water quality. Water use in US ponds was 7.1 m^3 kg^{-1} fish, which was 2.5 times higher than the 2.8 m^3 kg^{-1} fish exchanged in DS ponds. Higher daily water exchange with the Mekong River in US ponds concurred with significantly lower pond concentrations for NO$_2$-N, TP, alkalinity and CO$_2$ compared to DS ponds. The observed difference in Kj-N concentration of 3.2 mg l^{-1} in influent in DS ponds compared to 6.2 mg l^{-1} in US pond influent resulted in 16% additional protein load kg^{-1} feed in US ponds. Considering Kj-N concentrations in influent water, an estimated 58 g additional protein (13%) kg^{-1} feed entered DS ponds and 161 g (58%) kg^{-1} feed entered US ponds. This might — depending on settling properties, in-pond water retention time and degradability — impact oxygen availability for fish and microbial respiration. If completely decomposed and not accounting for oxidation of nitrogen, 1 g protein consumes 1.77 g oxygen (Dalsgaard & Pedersen 2011), which indicates an additional oxygen demand of 102 and 285 g O$_2$ kg^{-1} feed in DS and US ponds, respectively. If only 10% of this protein were degraded in the pond it means 35 and 59% more oxygen demand in DS and US ponds, respectively, would be required than the amount supplied by the influent water. Hence, the exchange water significantly increased pond oxygen demand.

The low difference in oxygen concentration of 4.9 mg l^{-1} in influent water to DS ponds versus 4.7 mg l^{-1} to US ponds had a negligible effect on striped catfish growth performance. During the production cycle, growth performance remained favourable, even with dissolved oxygen dropping below 2 mg O$_2$ l^{-1} at 1 m depth within 2 mo after stocking. This is possible because striped catfish are facultative air-breathers (Lefevre et al. 2011b), and therefore dissolved oxygen in the water is less important for maintaining growth. To indicate this, we assumed a conservative oxygen consumption of 200 g O$_2$ kg^{-1} feed intake by striped catfish (Table 9), similar to the air-breathing African catfish *Clarias gariepinus* (Eding & Weerd 1999). This conforms with a feed-based oxygen consumption of 37.4 g O$_2$ m^{-2} d^{-1}, concurring with an average feed load of 187 g feed m^{-2} d^{-1} in both DS and US ponds. For the pond culture conditions in the current study, the oxygen supply was estimated to be 0.96 g O$_2$ m^{-2} d^{-1} through water exchange, 21.5 g O$_2$ m^{-2} d^{-1} through primary production and 3 g O$_2$ m^{-2} d^{-1} through the water surface oxygen exchange. Oxygen consumption in the water column was estimated at 10.47 g O$_2$ m^{-2} d^{-1} and 12.42 g O$_2$ m^{-2} d^{-1} in the sediment. This leads to an oxygen deficit of 34.8 g O$_2$ m^{-2} d^{-1}, equaling 93% (34.8 / 37.4 × 100) of the oxygen requirement of striped catfish in the pond (Table 9). This in part explains why the fish remained close to the surface, even in deep ponds (Lefevre et al. 2011a). Striped catfish prefer, under non-fed conditions, to consume oxygen from the water column provided there is sufficient oxygen (Lefevre et al. 2011b). However, under fed conditions, results show that striped catfish in the Mekong Delta are produced under dissolved oxygen deficient conditions. This observation means that striped catfish can be produced under low water exchange conditions, because only 7% of the oxygen demand kg^{-1} feed (=14 g O$_2$ kg^{-1} feed) was provided by dissolved oxygen resources. Assuming surface aeration is negligible, at 30°C a flow rate of 7 to 8 m^3 kg^{-1} feed d^{-1} should be sufficient to cover the water oxygen demand of striped catfish (influent concentration 7.2 mg O$_2$ l^{-1} [95% saturated], effluent 4.5 mg O$_2$ l^{-1}). A higher flow rate of 12 m^3 kg^{-1} feed was reported for African catfish by Eding & Kamstra (2002) to control oxygen and ammonia and assuming the fish consumed 300 g O$_2$ kg^{-1} feed.

The average H$_2$S concentration was 0.1–0.2 mg l^{-1}, and was similar in DS and US ponds, with peak concentrations reaching 0.5–0.8 mg l^{-1} (Table 3). Considering the NO$_3$-N concentrations in the ponds were low (0.3–0.5 mg l^{-1}), diffusion of NO$_3$-N into the flocculent bottom layer was too low to prevent H$_2$S formation under oxygen depleted conditions. The large water volume and daily exchange in the ponds helped to keep H$_2$S concentrations low. The sludge removal frequency (3 times in DS ponds, 1 time in US ponds) was sufficient to maintain favourable water quality, as in our study no correlation was found between fish growth or fish mortality and H$_2$S concentration ($p > 0.05$). Nevertheless, the H$_2$S concentration increased during culture (H$_2$S [mg l^{-1}] = 0.0016 × culture day − 0.0192; $r^2 = 0.5649$, $p < 0.05$)

Table 9. Estimated oxygen mass balance of an average downstream pond, based on average water quality, feed input and fish biomass considering the complete production cycle. BOD$_5$: 5 d biological oxygen demand; DM: dry matter; DO: dissolved oxygen

Parameter	g O$_2$ m^{-2} d^{-1}		% of fish respiration		Reference
	Input	Sink	Input	Sink	
Fish respiration (200 g O$_2$ kg^{-1} feed; average feed load 187 g feed m^{-2} d^{-1})		37.40		100.0	Eding & Weerd (1999)
Water exchange[a] (0.36 m^3 m^{-2}, 3.7 g O$_2$ m^{-3} d^{-1})	1.32		3.52		Present study
Water column respiration (based on BOD$_5$ measurement)		10.47		28.0	Present study
Gross photosynthesis (assuming 3% chl *a* in algae DM; 3.47 g O$_2$ g^{-1} C fixed)	21.51		57.05		Desortová (1981), Drapcho & Brune (2000)
Surface gas exchange (2 m s^{-1} wind speed at 30°C)	3.00		8.00		Boyd & Tucker (1998)
Sediment oxygen demand (based on BOD$_5$ measurement)		12.42		33.20	Present study
DO deficit		34.46		92.15	Present study

[a]Water entering and leaving downstream ponds contains 4.9 (influent) and 1.2 g O$_2$ m^{-3} (effluent = pond water at 2 m depth), respectively (Table 3): 4.9 − 1.2 = 3.7 g O$_2$ m^{-3}

and was similar between DS and US locations (p > 0.05). Furthermore, the observed H_2S concentrations always remained below threshold concentrations reported to affect fish growth and fillet meat quality (Linh 2012). H_2S concentrations were measured bi-weekly, and occasionally reached a peak value of 0.8 mg l^{-1}. Linh (2012) reported a 10% lethal concentration (LC_{10}) for striped catfish of 0.83 mg l^{-1} over a 60 d observation period. Daily monitoring of H_2S concentrations and investigating possible chronic effects of low H_2S on striped catfish survival over the full production cycle requires further research.

The NO_2-N concentration was never higher than 1 mg l^{-1}, which is much lower than reported safe levels for striped catfish (Huong et al. 2011). Salinity of influent water to DS ponds (0.4 ppt; range: 0.1–1.2) was higher than in US ponds (0.06 ppt; range: 0.04–0.08). These parameters did not influence survival or fish yield, which were similar between DS and US ponds (p = 0.11 and 0.12, respectively).

Water quality maintenance for fish growth

The FCR over the full production cycle was on average 1.5 in DS ponds and 1.7 in US ponds, which corresponds with earlier reported FCRs for striped catfish farming in the Mekong Delta (Bosma et al. 2009, Phan et al. 2009). The fact that the specific growth rate (SGR) increased in DS ponds during the production cycle (Table 4) is contradictory to normal culture conditions for other fish species, including striped catfish. Temperature remained close to optimal during the culture period, and cannot explain the increase in SGR during culture. Fish mortality due to disease was high during period 1 (Days 1–59), and when disease occurred, feeding was reduced or even suspended. Ponds were not fed 15 and 17% of culture days in DS and US ponds, respectively (Fig. 2A,B). The larger feed input deficiency in US ponds concurred with a culture period of 277 d compared to 234 d in DS ponds. A 43 d longer culture period in US ponds required more labour and energy, delayed income from fish sales and increased emissions of chemicals and drugs. In US ponds, the longer culture period concurred with reduced feeding during disease treatment, either by application of antibiotics or $CuSO_4$ (Fig. 2A,B). Improving biosecurity, stocking disease-free fingerlings, controlling pathogens (including parasites) in the exchange water (Phan et al. 2009) and reducing transmission by possible hosts (Bondad-Reantaso et al. 2005) would contri-

bute to better growth and feed utilization. Disease control in striped catfish pond culture remains a challenge, considering it is an open system connected to the Mekong River.

Striped catfish farmers prefer 1 ha ponds that are 2 to 6 m deep, located along channels and rivers accessible by ships to supply feed and transport harvested fish to the processing plant (Phan et al. 2009). The culture cycle starts with 2–3 m water depth during the first month, which is subsequently raised to the maximum pond depth and maintained until the end of the production cycle. In deep ponds, water movement above the bottom is minimal, resulting in negligible resuspension of settled sludge. Fish-driven resuspension is also negligible as the fish stay close to the surface. The farmer checks the height of the sludge layer above the sediment, and removes it when it becomes too high. Water exchange pipes are situated at ±2 m depth, allowing the exchange of large volumes of surface water with minimum disturbance to the deep-water layers in the pond (especially the flocculent layer) to avoid fish gill damage. The decision to culture striped catfish in 4–6 m deep ponds developed as an adaptation to the semi-tidal conditions in the Mekong Delta with two 3 h tidal water exchange periods daily, allowing use of the first period to discharge and the second period to take in water. As a consequence, between tides, the pond water volume is lower than when the pond is full. By using deep ponds, the risks of resuspension and a high suspended solid concentration in the water column is reduced during the period of low water levels. When too much sludge accumulates at the bottom, it is pumped to sedimentation ponds or to the river. This is to avoid conditions in the flocculent layer switching from a situation favouring denitrification to one favouring anaerobic fermentation. Through denitrification, a large fraction of the waste is volatilized *in situ*, keeping discharge kg^{-1} fish produced low (Phu & Tinh 2012).

Assuming that 2.86 g of COD is used to remove 1 g NO_3-N by denitrification, and that oxidation of 1 g organic matter (OM) requires 1.42 g oxygen (Henze et al. 1997), on average 14 698 and 14 818 kg of OM (30 to 39 g COD or 21 to 27 g OM kg^{-1} feed) was removed from the DS and US ponds, respectively (Tables 5 & 7). When averaging the whole pond area, 1.72 and 1.98 g NO_3-N m^{-2} d^{-1} was removed daily in US and DS ponds, respectively. This corresponds to 4.95 and 5.66 g COD removal m^{-2} d^{-1}, and 0.11 and 0.13 equivalents of alkalinity production m^{-2} d^{-1} (14 g NO_3-N removal = 0.91 alkalinity equivalents; Henze et al. 1997) in US and DS ponds, respectively.

The alkalinity production compensated for a daily application of 9.1 and 10.8 g NaHCO$_3$ m^{-2} d^{-1} (1 alkalinity equivalent = 83 g NaHCO$_3$) in US and DS ponds, respectively.

Sustainability indicators

Fingerling use

The mortality (calculated as the difference between the number of fingerlings stocked and fish harvested) of striped catfish in this study was higher than reported for channel catfish production in ponds, trout in raceways and tilapia in recirculation systems (Table 10). As discussed in the previous section, reducing disease-related mortality is important. Because mortality occurs mainly during the first 2 mo of the production cycle and fingerlings are cheap, farmers do not consider lowering mortality a priority. However, when considering the drop in the number of feeding days, the high variation in feed input (Fig. 2) and the longer culture period (see previous section), then the lack of disease-free fingerlings and the higher than necessary feed conversion ratio turns out to be costly to the industry. Developing culture methods to produce fingerlings using alternative methods, such as in closed recirculation systems, could be instrumental in producing disease-free and high quality fingerlings. This needs to coincide with avoiding contamination during transport to the grow-out ponds.

Water use

Water use per kg production in aquaculture varies over a broad range, from 0.15 to more than 100 m^3 kg^{-1} fish produced (Verdegem & Bosma 2009). In this study, water use kg^{-1} striped catfish production was 20–77 times lower than for trout production in raceways, and 3–14 times smaller than for intensive shrimp ponds (Table 10). Water use in semi-intensive channel catfish ponds was similar to striped catfish production in the Mekong Delta. The water use is further reduced in recirculating aquaculture systems (RAS), where it was 12–30 times lower than for striped catfish pond culture (Table 10) (Verreth & Oberdieck 2009).

Energy use

On-farm energy use to produce 1 kg of striped catfish was 6–113 times lower than the other cultures listed in Table 10. This shows that culturing an air-breathing species in ponds with tidal water exchange requires considerably less on-farm energy input than any other type of fish culture (Boyd & Tucker 1998, Boyd & Gross 2000, d'Orbcastel et al. 2009a, Verreth & Oberdieck 2009).

N utilization efficiency

The N utilization efficiency of the feed was higher for striped catfish than for channel catfish, shrimp, tilapia and trout culture (Table 10). Better N utilization efficiencies were obtained by switching to RAS and using high quality feed (Table 10). N-discharge per kg fish produced from striped catfish ponds was 1.6–6.8 times lower than for other cultures listed in Table 10. These differences in discharge when compared to other species are much higher than for N utilization efficiency. A unique feature of the 4–6 m deep striped catfish ponds is the occurrence of denitrification at the bottom, which significantly reduced N discharge (see 'Water quality maintenance for fish growth' above).

Table 10. Key sustainability indicators of different culture species. RAS: recirculating aquaculture system; FT: flow-through system. Superscript letters indicate source: (a) this study, (b) Gross et al. (1998), (c) Boyd (2005), (d) Boyd et al. (2000), (e) Gross et al. (2000), (f) Verreth & Oberdieck (2009), (g) d'Orbcastel et al. (2009b), (h) Foy & Rosell (1991), (i) Warrer-Hansen (1982), Sumari (1982) and Solbe (1982), (j) Thakur & Lin (2003), (k) Yoo & Boyd (1994), (l) Boyd & Tucker (1998), (m) Hall et al. (1992) with commercial feed

Species	Culture system	Mortality (%)	Water use (m^3 kg^{-1} fish)	Energy use (kWh kg^{-1} fish)	Labour use (h kg^{-1} fish)	N retained (% of input)	P retained (% of input)	N discharge (g kg^{-1} fish)	P discharge (g kg^{-1} fish)
Striped catfish	Pond	23.6–49[a]	2.8–7.1[a]	0.04–0.14[a]	0.06–0.11[a]	43.7–44.3[a]	17.6–17.7[a]	19.8–20.1[a]	17.0–17.7[a]
Channel catfish	Pond	6[b]	3.7[c]	0.9[d]	–	18.3–34.8[e]	20.4[e]	29.1[b]	10.6–15.4[b]
Tilapia	RAS	0.5[f]	0.24[f]	1.8[f]	0.013[f]	32[f]	43[f]	45.9[f]	8.3[f]
Trout	FT	0.1[g]	148–215[h]	1–1.7[g]	–	18.9[h]	13.2[h]	73.3–124.2[h,i]	11.0–25.6[h,i]
Intensive shrimp	Pond	22–50[j]	20–40[k]	4.5[l]	–	22.8–30.7[j]	10.5–12.8[j]	36.5–102[j]	11.6–18[j]
Salmon	Cages	–	–	–	–	28.2–30.0[m]	17.7–19.6[m]	80.0–84.7[m]	16.7–18.9[m]

At present, the industry discharges water effluent directly to the river and sludge to a sedimentation pond or to the river. If all sludge were treated before discharge, then striped catfish farming would actually remove OM from the river. This would not be the case for N and P, because the majority of these nutrients are discharged with the water effluent and sludge. In a lab scale experiment, Anh & Mai (2009) reduced the TSS load in the effluent by nearly 20% by passing it through a stabilization pond operated with a retention time of 1 h.

P utilization efficiency

The P utilization efficiency of the feed in striped catfish ponds was better than for shrimp or trout. However, the opposite was true for channel catfish and tilapia in RAS. The use of plant ingredients in striped catfish feeds possibly lowered the P available for fish growth (Gatlin et al. 2007, Cao et al. 2008, Kumar et al. 2012, Hung et al. 2015). Nevertheless, P discharge per kg striped catfish produced was similar to the intensive culture of trout, channel catfish and shrimp, and higher than for tilapia in RAS (Table 10). In semi-extensive polyculture ponds, a larger fraction of P accumulated in the sediment (Nhan et al. 2006, 2008). In the deep striped catfish ponds, 58–60% of the metabolic waste of P accumulated in the system or was taken out during sludge removal. If this P could be trapped in sedimentation ponds (Anh et al. 2010), then transforming this into fertilizer would become an option (Phung et al. 2009, Da et al. 2015). In addition, reducing the P content in the feed and improving P availability, as was done in trout feeds (Ketola & Richmond 1994), could also contribute to a further reduction of P discharge.

CONCLUSIONS AND RECOMMENDATIONS

When considering the sustainability indicators of energy use, labour use and N and P retention and discharge, striped catfish production in deep ponds in the Mekong Delta performed well in comparison to other aquaculture species and systems (Table 10). By developing the 2–6 m deep pond culture systems, striped catfish farmers made maximum use of the unique topography and water regime in the Mekong Delta, allowing them to keep on-farm energy and labour inputs low, while realizing nutrient efficiencies that compare well to other major aquaculture species. This in part explains the success of striped catfish farming. Nevertheless, further improvements remain possible in both US and DS ponds. Most resource utilization indicators in US ponds were higher than the DS ponds, except for fingerling use. In addition, most nutrient utilization efficiency and nutrient discharge indicators were similar in both DS and US ponds. For improving sustainability, striped catfish culture in earthen ponds can be integrated with algae ponds or helophytic filters to treat influent and effluent water. This way, striped catfish farming uses more land, which is a scarce commodity in the Mekong Delta. Another option is to utilize RAS technology, which would allow farmers to fully control waste streams resulting from culture (d'Orbcastel et al. 2009a). An additional advantage of culturing in RAS would be the reduction in water exchange with the Mekong River, which would minimize horizontal transmission of pollutants, parasites or diseases originating from other farms along the Mekong River and adjacent lands. A major challenge for developing striped catfish culture in RAS is to keep production costs sufficiently low to compete with pond culture in the Mekong Delta.

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Appendix

Table A1. Units and formulas. $C_{X.\text{parameter name}}$: nutrient (dry matter [DM], N or P) concentration in whole final fish body (%), whole initial fish body (%), inflow water (g m^{-3}), outflow water (g m^{-3}), feed (%), seepage water (g m^{-3}), in sludge removal frequency during culture cycle (g m^{-3}), remained DM of sludge in pond at harvest day (%). $E_{\text{electricity}}$: total electricity consumption per culture cycle (kWh). FW: weight of complete skinless fillet after removing fat and red muscle following standard process for export market (g); FC: cumulative feed (kg); L_{time}: total time use of labour during whole culture cycle (hours). $M_{\text{tot.chemical}}$: total amount of chemical (as lime, NaCl, CuSO$_4$ or iodine) during whole culture cycle (g); $M_{\text{tot.antibiotic}}$: total antibiotic use during whole culture cycle (g); $M_{\text{tot.sludge}}$: total remaining DM of sludge in pond at harvest day (kg). n_{white}: number of white fillet fish; n_{pink}: number of pink fillet fish (no.); n_{yellow}: number of yellow fillet fish (no.); n: number of fish samples (no.). $V_{\text{tot.inflow}}$: total amount of inflow water during culture cycle (m^3); V_{oil}: total volume of diesel oil utilization during whole culture cycle (l); $V_{\text{tot.outflow}}$: total volume of outflow water (m^3); $V_{\text{tot.seepage}}$: total volume of seepage water (m^3); $V_{\text{tot.sludge removal frequency}}$: total volume of sludge removal frequency during culture cycle (m^3). $W_{\text{Final sample}}$: fish biomass of sample at harvest (kg); $W_{\text{tot.Initial}}$: total initial fish biomass at stocking day by weight (kg); $W_{\text{tot.Final}}$: total fish biomass at harvest day by weight (kg); $W_{\text{Initial sample}}$: initial fish biomass of sample (kg). $X_{\text{fish retained}}$: DM, N or P retained in fish (g); $X_{\text{discharge}}$: DM, N or P discharge (kg)

Parameter	Unit	Formula
Fish performance		
Initial individual body weight (W_{Initial})	g	$W_{\text{Initial}} = W_{\text{Initial sample}} / n$
Final individual body weight (W_{Final})	g	$W_{\text{Final}} = W_{\text{Final sample}} / n$
Total fish stocked in pond ($N_{\text{tot.Initial}}$)	No.	$N_{\text{tot.Initial}} = 1000 \times W_{\text{tot.Initial}} / W_{\text{Initial}}$
Total fish harvested from pond ($N_{\text{tot.Final}}$)	No.	$N_{\text{tot.Final}} = 1000 \times W_{\text{tot.Final}} / W_{\text{Final}}$
Survival (S)	%	$S = 100 \times (N_{\text{tot.Final}} / N_{\text{tot.Initial}})$
Specific growth rate (SGR)	% BW d^{-1}	$\text{SGR} = 100 \times (\ln W_{\text{Final}} - \ln W_{\text{Initial}}) / \text{Day}$
Total biomass gain (G_{tot})	kg	$G_{\text{tot}} = W_{\text{tot.Final}} - W_{\text{tot.Initial}}$
Feed conversion ratio (FCR)	kg kg^{-1}	$\text{FCR} = \text{FC} / G_{\text{tot}}$
Biomass of fish mortality ($G_{\text{fish.mortality}}$)	kg	Daily accumulation
Fillet yield (FY)	%	$\text{FY} = 100 \times (\text{FW} / W_{\text{Final}})$
Fillet colour grade (FIG)		$\text{FIG} = (1 \times n_{\text{white}} + 2 \times n_{\text{pink}} + 3 \times n_{\text{yellow}}) / n$
Nutrient mass balances		
At fish level		
Nutrients in feed (X_{feed})	kg	$X_{\text{feed}} = (C_{X.\text{feed}} / 100) \times \text{FC}$
Nutrients in fish retained ($X_{\text{fish retained}}$)	kg	$X_{\text{fish retained}} = (C_{X.\text{Final fish}} \times W_{\text{tot.Final}}) - (C_{X.\text{ Initial fish}} \times W_{\text{tot.Initial}})$
Nutrients in fish mortality ($X_{\text{mortality}}$)	kg	$X_{\text{mortality}} = C_{X.\text{fish.mortality}} \times G_{\text{fish.mortality}}$
Metabolic waste production (X_{MW})	kg	$X_{\text{MW}} = X_{\text{feed}} - X_{\text{fish retained}} - X_{\text{mortality}}$
At pond level		
Nutrient input ($X_{\text{input pond}}$)	kg	$X_{\text{input pond}} = X_{\text{MW}} + X_{\text{influent}}$
Nutrient influent water (X_{influent})	kg	$X_{\text{influent}} = (C_{X.\text{inflow}} \times V_{\text{tot.inflow}}) / 1000$
Nutrient output ($X_{\text{output pond}}$)	kg	$X_{\text{output pond}} = X_{\text{effluent}} + X_{\text{sludge}} + X_{\text{unaccounted}}$
Nutrient in effluent (X_{effluent})	kg	$X_{\text{effluent}} = [(C_{X.\text{outflow}} \times V_{\text{tot.outflow}}) + (C_{X.\text{seepage}} \times V_{\text{tot.seepage}})] / 1000$
Nutrient in sludge (X_{sludge})	kg	$X_{\text{sludge}} = [C_{X.\text{sludge removal frequency}} \times V_{\text{tot.sludge removal frequency}}] / 1000 + (C_{X.\text{remained sludge}} \times M_{\text{tot.sludge}}) / 100$
Nutrient unaccounted ($X_{\text{unaccounted}}$)	kg	$X_{\text{unaccounted}} = X_{\text{inputs}} - (X_{\text{effluent}} + X_{\text{sludge}})$
Sustainability indicators[a]		
Resource utilization efficiency		
Fingerling use (FU)	# kg fish^{-1}	$\text{FU} = (N_{\text{tot Initial}} - N_{\text{tot Final}}) / G_{\text{tot}}$
Water use (WU)	m^3 kg^{-1} fish	$\text{WU} = V_{\text{tot.inflow}} / G_{\text{tot}}$
Diesel use (DU)	ml kg^{-1} fish	$\text{DU} = V_{\text{oil}} / G_{\text{tot}}$
Energy use (EU)	kWh kg^{-1} fish	$\text{EU} = E_{\text{electricity}} / G_{\text{tot}}$
Labour use (LU)	h kg^{-1} fish	$\text{LU} = L_{\text{time}} / G_{\text{tot}}$
Chemical use (CU)	g kg^{-1} fish	$\text{CU} = M_{\text{tot.chemical}} / G_{\text{tot}}$
Antibiotic use (AU)	g kg^{-1} fish	$\text{AU} = M_{\text{tot.antibiotic}} / G_{\text{tot}}$
Nutrient utilization efficiency		
XR (X = DM or P or N)	g kg^{-1} fish	$\text{XR} = 1000 \times X_{\text{fish retained}} / G_{\text{tot}}$
Nutrient discharge (XD):	g kg^{-1} fish	$\text{XD} = 1000 \times X_{\text{discharge}} / G_{\text{tot}}$ $X_{\text{discharge}} = X_{\text{effluent}} + X_{\text{sludge}} - X_{\text{influent}}$

[a]Sustainability indicators were also expressed per kg feed by dividing by FC instead of G_{tot}