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Partial nutrient budgets for semi-intensive shrimp farms in Honduras

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Abstract

Shrimp farms in Latin America typically have relatively low stocking rates and are managed without aeration. Nutrient budgets for these farms have not been well established. Intake and discharge from 21 ponds on six shrimp farms located on estuaries or embayments of the Gulf of Fonseca in Honduras were characterized during rainy and dry seasons. Mean shrimp stocking rate, yield, and feed conversion ratio (FCR) for these ponds were $8.2/m^2$, 633 kg/ha, and 2.74, respectively. Mean intake values of soluble reactive phosphate (SRP), dissolved inorganic nitrogen (DIN), total nitrogen (TN), total phosphorus (TP) and BOD_5 were significantly higher in estuaries than in embayments during both seasons. Water exchange produced a mean net discharge of TN, TP, BOD_5, chlorophyll *a*, COD, total alkalinity and salinity, and a mean net intake of DIN; mean SRP was practically equal in discharge and intake water. Each kilogram of feed nitrogen and phosphorus applied to ponds resulted in 0.21 kg of net nitrogen discharge and 0.16 kg of net phosphorus discharge by water exchange. Use of inorganic fertilizers promoted net discharge of phosphorus and nitrogen. Net nitrogen discharge by water exchange significantly increased as nitrogen input by feed increased ($P < 0.01$). Ponds gained nitrogen primarily from intake water (63%) and feed (36%), and nitrogen was lost primarily from water exchange (72%) and harvested shrimp (14%). Ponds gained phosphorus mostly from intake water (51%) and feed (47%), and phosphorus was lost primarily from water exchange (56%) and harvested shrimp (9%). About 7% of input nitrogen and almost a third (31%) of input phosphorus were not accounted for in measured losses, and presumably were fixed or metabolized in ponds. Mean conversion of feed

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nitrogen and phosphorus to shrimp flesh averaged 41% and 20%, respectively. Each kilogram of shrimp production resulted in 16.8 g of net nitrogen loss and 2.3 g of net phosphorus loss by water exchange.

Keywords: Nutrient budgets; Shrimp farms; Honduras

1. Introduction

The shrimp industry in Honduras generated over $72 million in 1995 from about 11,500 ha of ponds. Current area under production is about 14,000 ha (Rosenberry, 1998). Sustainability of the industry is economically important to the country and could depend on estuarine water quality. A 2-year baseline of water quality was established for the major shrimp-producing areas of the Gulf of Fonseca (Teichert-Coddington, 1995). Estuarine water quality was strongly influenced by freshwater influx during rainfall and proximity to the Gulf of Fonseca. Nutrient concentrations increased and indicators of water quality worsened upstream in estuaries because of poor exchange with the Gulf. During the dry season, estuarine nutrient concentrations and the likelihood of low estuarine dissolved oxygen were higher. Estuarine water quality was most likely to limit shrimp production during the dry season because assimilative capacities were lowest during this period.

Water quality in regions of shrimp production is influenced by municipal discharge, runoff from agricultural fields, organic matter from fringe mangroves, as well as shrimp farm discharge. The quality of water in ponds, in turn, depends on the quality of water which supplies the ponds. The contribution that shrimp farms make to nutrient loading of estuaries cannot be known simply by determining the nutrient content of pond discharge, because nutrient loading of ponds also occurs from supply water. The contribution that farm management makes to the nutrient loading of pond water can only be estimated by determining the difference between mass intake and discharge of nutrients. The chemical characterization and quantification of nutrients in farm effluents are prerequisites to estimating the carrying capacities of estuaries for shrimp culture.

Chemical budgets can be formulated to account for all sources of nutrient gains and losses, and they are useful to quantify environmental impacts of aquaculture and for environmental management. Chemical budgets have been formulated for experimental ponds containing channel catfish (Boyd, 1985), stripped bass (Daniels and Boyd, 1989), tilapia (Green and Boyd, 1995) and high densities of shrimp (Hopkins et al., 1993; Couch, 1998). Phosphorus and nitrogen budgets were formulated for commercial shrimp ponds in Thailand (Briggs and Funge-Smith, 1994). Chemical budgets of semi-intensively managed commercial shrimp ponds in Latin America are unknown. Therefore, the objectives of this study were to characterize commercial farm intake and discharge water, quantify nutrient exchanges during water exchange, and formulate partial nutrient budgets for nitrogen and phosphorus.

2. Materials and methods

2.1. Characterization of water

Six farms peripheral to the Gulf of Fonseca in southern Honduras were sampled during 1993–1994. Farms were supplied with water from estuaries dominated by rivers or from embayments of the Gulf of Fonseca (Teichert-Coddington, 1995). Most farms began exchanging pond water with supply water starting 2–3 weeks after stocking shrimp. Water exchange usually occurred daily, although several farms modified exchange rates based on farm-specific criteria like dissolved oxygen concentrations or pH. Pond intake and effluent water were sampled every 2 weeks during a production cycle. Intake samples were collected at the gates where water entered ponds from the supply canal, and effluent samples were collected at the discharge gates. On most occasions, samples were taken approximately halfway through an exchange event. If this was not possible, several samples were collected during an exchange event and then pooled. All samples were immediately placed on ice for transport to the laboratory. Because of distinctive seasonal yield differences (Teichert-Coddington and Rodriguez, 1995; Teichert-Coddington et al., 1994), production ponds were sampled during dry and wet seasons. A total of 21 ponds were monitored (Table 1).

The volume of water exchange was based on farm records. Precipitation was measured with a computerized tipping bucket rain gauge (Texas Electronics, Dallas, TX) located on one of the farms. Attempts to determine evaporation at the farm site were frustrated by swarms of bees and flocks of birds that came to drink freshwater from the pan. Therefore, evaporation was estimated from historical 11-year mean monthly rates that had been determined at a Honduran Government weather station in Sn. Bernardo near the study area (Enriquez, Dept. de Hidrologia, Ministerio de Recursos Naturales, unpublished data). Pond water budgets were calculated from water exchange volumes, evaporation, and precipitation for periods between samples. Water exchange was accomplished by first draining ponds and then refilling. The effluent water volume was calculated from farm exchange records and the nominal pond water area and volume determined during pond construction. The intake volume was calculated by increasing the effluent volume by an amount equivalent to evaporation, and decreasing it by an amount equivalent to rainfall. Ponds were drained to harvest shrimp. Nets were placed

Table 1
Characteristics of ponds in southern Honduras sampled during the study

Farm	Location	Number of ponds	Mean pond area (ha)	Mean duration of culture (days)	Mean density (number/m^2)	Mean water exchange (% day^{-1})
A	Estuary	9	27	97	6.9	5.4
B	Embayment	2	8	95	10.1	4.3
C	Estuary	2	24	104	7.3	2.6
D	Embayment	1	8.5	162	25	3.7
E	Embayment	3	6	114	9.6	8.5
F	Estuary	4	22	114	9.1	3.5
Mean		–	20.6	106	8.9	4.8

around the water discharge structure to capture and remove shrimp that exited with the water. Total nutrient discharge at harvest was calculated from weighted averages of samples collected at 100%, 50%, 25%, 10% and 0% of pond volume during a draining event.

Water was analyzed for total settleable solids (TSS) (American Public Health Association (APHA) et al., 1992), nitrate nitrogen by cadmium column reduction to nitrite (Parsons et al., 1992), nitrite nitrogen (Parsons et al., 1992), total ammonia nitrogen (TAN) (Parsons et al., 1992), soluble reactive phosphate (SRP) (Grasshoff et al., 1983), chlorophyll *a* (Parsons et al., 1992), total alkalinity by titration to 4.5 pH endpoint (American Public Health Association (APHA) et al., 1992), salinity, and 2-day biochemical oxygen demand (BOD). BOD was determined at room temperature averaging 27°C after diluting raw samples by two to four times with water of a similar salinity. Saline water was prepared with distilled water and laboratory grade NaCl, $MgSO_3$ and $NaHCO_3$ (Strickland and Parsons, 1972). Bottles were wrapped in aluminum foil and placed in an insulated box to moderate temperature fluctuations. BOD control values were determined in bottles containing the artificial saline water. BOD_5 was estimated by linear regression on BOD_2. The regression was developed from an unpublished study in the same estuaries supplying the shrimp ponds. The equation was: $BOD_5 = -0.064 + 2.145(BOD_2)$; $R^2 = 0.94$. Total nitrogen (TN) and total phosphorus (TP) were determined by nitrate and phosphate analysis, respectively, after simultaneous persulfate oxidation of unfiltered water samples (Grasshoff et al., 1983).

2.2. Nutrient exchanges and chemical budgets

Mass exchanges of nutrients were calculated for water exchange events, and partial budgets for nitrogen and phosphorus were calculated for ponds that had complete record sets. Occasionally, there were several days of heavy rainfall when some ponds discharged indeterminate quantities of water. Data from these ponds were excluded from analyses. Rainfall during the dry season was zero or less than evaporation. Records of feed, fertilizer, water exchange, stocking rates, and harvest weights were obtained from the producers. Complete data sets were available for five ponds during the rainy season and nine ponds during the dry season. Concentrations of P and N were determined by analysis of intake, effluent and drainage water in each pond. Nutrient input by rainfall was not taken into account, but this effect on the nutrient budget was probably unimportant (Briggs and Funge-Smith, 1994), particularly since rainfall was minimal in most cases. The general balance equation is:

$$S_{in} + F_{in} + Fert_{in} + PV_{in} + WE_{in} = S_{out} + PV_{out} + WE_{out} \pm UN,$$

where S = shrimp; F = feed; Fert = fertilizer; PV = pond volume; WE = water exchange; and UN = unaccounted nutrient. No attempt was made to quantify nutrients in pond sediments.

Feed from various farms was analyzed for nitrogen and phosphorus composition. Manufacturer's analyses of feed were used when independent analyses were not available. Nitrogen and phosphorus composition of shrimp was determined by elemental analyses (Boyd and Teichert-Coddington, 1995). The mean percentages of nitrogen and phosphorus in *Penaeus vannamei* dry matter were 11.2% and 1.25%, respectively.

2.3. Data analysis

The results of intake water characterization were grouped according to water supply source and season. Mean differences among groups were declared significant by non-coincidence of 95% confidence intervals. Nutrient exchanges and chemical budgets were expressed in terms of kilogram per hectare over 100 days (kg/ha − 100 days). Gains and losses were calculated by subtracting discharge quantities from intake quantities. A negative result indicated a net loss. Regression and correlation analyses were used to reveal relationships between selected variables, and one-factor ANOVA was used to determine significant differences between fertilized and unfertilized ponds. Data were analyzed using StatView v4.0 (Abacus Concepts, Berkeley, CA, USA).

3. Results

3.1. Water characterization

3.1.1. Water intake

Mean intake concentrations of SRP, nitrate and nitrite, TAN, TN, TP and BOD_5 were significantly higher in estuaries than in embayments during both seasons (Fig. 1; Table 2). Concentrations of chlorophyll *a* and COD were significantly higher in estuaries than in embayments during the dry season, but not during the wet season.

Mean intake salinity and total alkalinity were significantly lower on estuarine farms because of freshwater input from rivers. There were times during the dry season, however, when the salinity of estuaries became higher than in embayments, because evaporation exceeded freshwater input and dilution by the Gulf of Fonseca.

3.1.2. Nutrient exchange

Pond characteristics, production results, and nutrient exchanges of 14 sampled ponds are given in Table 3. The possibility of differences due to source of water supply was not explored, because only two of the 14 ponds were located on embayments.

Water exchange produced a mean net loss of TN, TP, BOD_5, chlorophyll *a*, COD, total alkalinity and salinity (Table 4), and a mean net gain of dissolved inorganic nitrogen (DIN) including nitrate, nitrite, and TAN. Mean SRP was practically equal in discharge and intake water.

Fertilizers were applied to five ponds, and their effect on nutrient exchange was notable compared with nine unfertilized ponds. A mean ($\pm$S.E.M.) net loss of 2.0 ± 1.35 kg/ha − 100 days SRP was recorded in fertilized ponds, whereas a mean net gain of 0.84 ± 0.89 kg/ha − 100 days SRP was recorded in unfertilized ponds. The difference was significant ($P < 0.10$). There was a net gain of DIN in both fertilized and unfertilized ponds. However, the gain tended to be less in fertilized ponds, probably because the demand for nitrogen in fertilized ponds was partially met by applications of

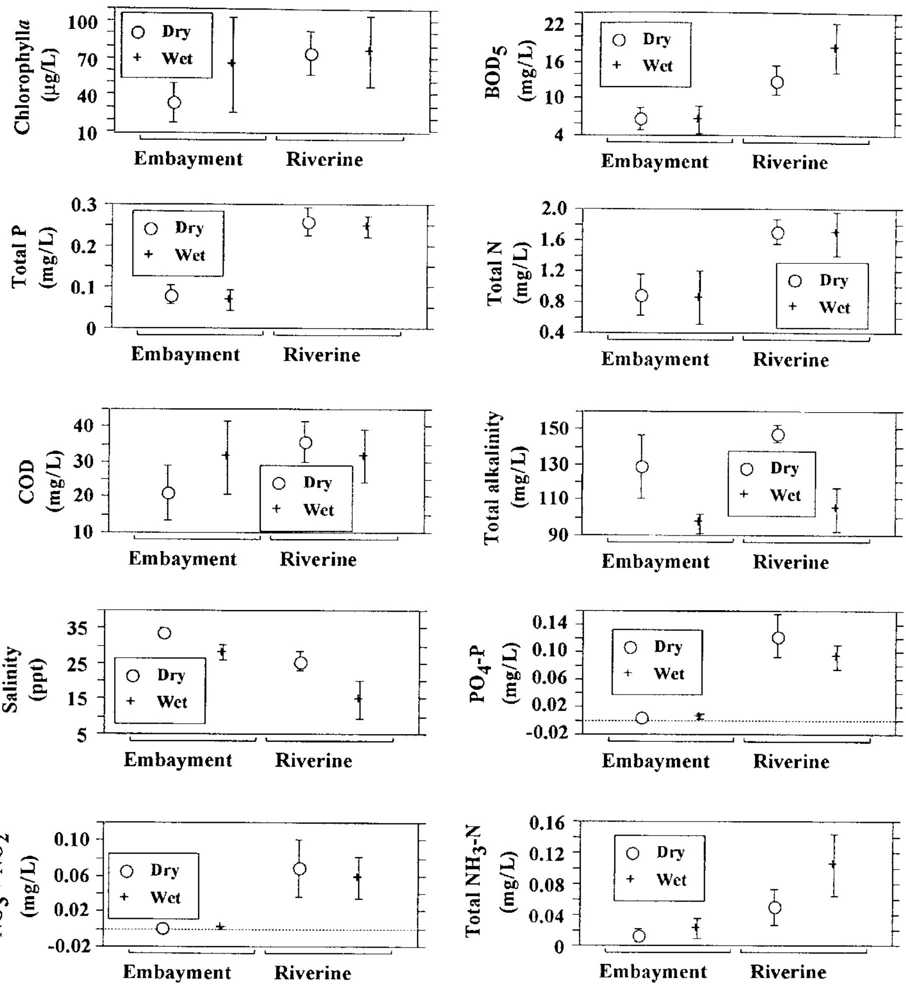

Fig. 1. Characterization intake water (mean ± 95% CI) for shrimp farms located on the Gulf of Fonseca in southern Honduras.

mineral fertilizers. Mean (±S.E.M.) net DIN gain was 2.2 ± 0.80 kg/ha – 100 days in fertilized ponds compared with 5.5 ± 1.94 kg/ha – 100 days in unfertilized ponds. The means were not significantly different ($P > 0.10$).

Mean net discharge of major nutrients from ponds by water exchange was 10.7 kg/ha – 100 days for nitrogen and 1.46 kg/ha – 100 days for phosphorus (Table 4). Each kilogram of shrimp production resulted in 16.8 g of net nitrogen loss and 2.3 g of net phosphorus loss by water exchange. Each kilogram of feed nitrogen applied to ponds resulted in 0.21 kg of net nitrogen loss (21% of feed nitrogen) by water exchange (Table 5). Each kilogram of feed phosphorus resulted in 0.16 kg of net phosphorus loss (16% of feed phosphorus) (Table 6).

Table 2
Characterization of intake water during rainy and dry seasons from 21 ponds on six farms located on estuaries or embayments of the Gulf of Fonseca in southern Honduras

Variable	Embayment				Estuary				Grand mean ± S.E.M.
	Dry	Rainy	Mean ± S.E.M.	*n*	Dry	Rainy	Mean ± S.E.M.	*n*	
Total alkalinity (mg/l)	129	97	112 ± 5.0	41	147	104	131 ± 3.6	76	124.3 ± 3.0
TN (mg/l)	0.88	0.85	0.87 ± 0.105	40	1.71	1.68	1.70 ± 0.068	79	1.42 ± 0.068
Total ammonia N (mg/l)	0.013	0.022	0.018 ± 0.004	40	0.05	0.011	0.071 ± 0.011	78	0.053 ± 0.007
Nitrate + nitrite N (mg/l)	0.002	0.001	0.002 ± 0.0005	41	0.069	0.058	0.065 ± 0.011	80	0.043 ± 0.008
TP (mg/l)	0.08	0.07	0.07 ± 0.008	40	0.26	0.25	0.25 ± 0.011	80	0.19 ± 0.011
SRP (mg PO_4 P/l)	0.004	0.006	0.005 ± 0.001	41	0.124	0.093	0.112 ± 0.010	79	0.76 ± 0.008
BOD_5 (mg/l)	6.7	6.5	6.6 ± 0.58	30	13.0	18.2	15.6 ± 0.97	60	11.5 ± 0.80
COD (mg/l)	21	31	26 ± 3.2	40	36	32	34 ± 2.3	76	32 ± 1.9
Chlorophyll *a* (μg/l)	33	64	49 ± 10.2	40	74	75	75 ± 7.7	75	66 ± 6.2
Salinity (ppt)	34	28	31 ± 0.8	41	26	15	21 ± 1.4	79	25 ± 1.1

Net nitrogen and phosphorus loss by water exchange during 100 days were subjected to stepwise regression on mean daily water exchange rates, stocking density, feed

Table 3
Characteristics of ponds for which nutrient exchanges and partial nitrogen and phosphorus budgets were determined

Pond	Season	Water supply[a]	Area (ha)	Duration (days)	Water exchange (% day^{-1})	Stocking (number/ha)	Fertilization	Feed			Yield (kg/ha)	FCR
								Input (kg/ha)	% N	% P		
2–11	Dry	Est	31	103	4.2	60,000	No	1180	3.21	0.79	213	5.55
2–17	Dry	Est	24	100	7.7	81,000	No	1409	3.06	0.84	580	2.43
2–5	Dry	Est	25	118	6.1	60,000	No	1725	3.21	0.79	404	4.27
3–17	Dry	Est	24	96	4.5	60,000	No	897	2.98	0.87	343	2.62
1–11	Wet	Est	31	90	5.4	60,000	No	1100	3.03	0.85	900	1.22
E3	Dry	Emb	8.0	95	4.3	102,000	No	1416	2.56	0.85	462	3.07
E4	Dry	Emb	7.8	94	4.3	100,000	No	1452	2.56	0.85	469	3.09
A2	Dry	Est	24.9	110	2.6	70,500	No	1218	3.4	0.85	1001	1.22
11	Wet	Est	4.4	104	8.5	104,500	Yes	1987	4.34	0.85	617	3.22
26	Wet	Est	7.0	124	8.5	87,000	Yes	1524	4.92	0.85	771	1.98
13	Wet	Est	21.4	123	3.5	112,000	Yes	1626	4.7	0.85	1231	1.32
5	Wet	Est	23	100	3.5	101,600	Yes	1135	4.7	0.85	1187	0.96
2	Dry	Est	17	104	3.5	73,000	No	1462	4.7	0.85	462	3.17
3	Dry	Est	27.3	129	3.5	79,000	Yes	929	4.7	0.85	219	4.24
Mean			19.7	106.4	5.0	82,186		1361	3.7	0.84	633	2.74

[a]Estuary type: Est = estuary; Emb = embayment.

Table 4
Mass nutrient exchange (nutrient gain less nutrient loss) with water exchange during 100 days of shrimp culture, and per weight of shrimp yield in southern Honduras

	kg/ha – 100 days					Nutrient exchange[a] (g/kg shrimp)
	Mean	Standard deviation	Number of ponds	Minimum	Maximum	
Total alkalinity	462.3	622.8	14	−604	1702	730.3
TN	−10.7	15.62	14	−51	10.4	−16.84
Total ammonia nitrogen	2.04	2.528	14	−0.1	8.7	3.216
Nitrate + nitrite nitrogen	2.27	2.928	14	−0.1	9.1	3.581
Nitrite nitrogen	0.475	0.569	14	−0.1	1.8	0.750
TP	−1.46	2.62	14	−7.4	1.5	−2.31
SRP	−0.171	3.035	14	−6.6	4.3	−0.270
Chlorophyll *a*	−1.032	1.829	14	−5.50	1.70	−1.630
COD	−593.0	840.6	14	−2934	300	−936.9
BOD_5	−102.9	182.60	12	−558	153	−162.5

[a]Nutrient gain less nutrient loss.

conversion ratio (FCR), and nitrogen or phosphorus gain by feeding and fertilization. Net nitrogen loss significantly increased as nitrogen input by feed increased ($R = 0.63$; $P = 0.016$). No other correlations were significant for nitrogen. Net phosphorus loss by water exchange was most highly correlated with increasing phosphorus gain from application of fertilizer phosphorus (partial correlation = −0.87). Residual variation in phosphorus loss after accounting for fertilizer phosphorus was significantly correlated with increasing gain from feed phosphorus (partial correlation = −0.52). Inputs of fertilizer and feed phosphorus together explained 82.5% of the variation in phosphorus loss by water exchange ($R = 0.91$; $P < 0.0001$).

3.1.3. Pond drainage

Concentrations of some water quality variables in effluents changed during pond drainage. Fig. 2 reveals that mean TP, TN, DIN, SRP and TSS concentrations increased markedly during draining of the final 10% of pond volume. Total suspended solids were particularly concentrated at the end of drainage (mean = 12 ml/l) compared with the start of drainage (mean = 0.16 ml/l). Despite an increase in many nutrients and settleable solids with a decrease in pond volume, mean BOD remained constant from start to finish during pond drainage.

3.2. Partial chemical budgets

3.2.1. Nitrogen

Nitrogen gain to ponds occurred primarily from intake water (63%), then feed (36%), while fertilizer (1.1%) and shrimp (0.4%) accounted for the remainder (Table 5; Fig. 3). Nitrogen loss from ponds occurred primarily from discharge of water; daily water exchange (72%) and pond drainage (8%) accounted for 80% of TN loss (Fig. 3).

Table 5
Partial nitrogen budget, feed nitrogen conversion efficiency, and nitrogen discharge by water exchange per unit of nitrogen input in feed

Pond	Nitrogen gain (kg/ha – 100 days)					Nitrogen loss (kg/ha – 100 days)				Balance (gain–loss)	Feed N conversion (%)	N discharge/feed N
	Water	Fertilizer	Feed[a]	Shrimp	Total	Water	Shrimp	Pond[b] drainage	Total			
2–11	71.5	0.0	33.8	0.33	105.7	83.6	5.9	16.7	106.2	–0.5	17.4	–0.36
2–17	122.5	0.0	39.7	0.46	162.6	112.1	16.6	8.5	137.2	25.5	41.8	0.26
2–5	79.9	0.0	43.2	0.29	123.4	78.8	9.8	13.9	102.5	20.9	22.6	0.03
3–17	98.1	0.0	25.6	0.36	124.1	98.8	10.2	14.9	123.9	0.2	39.8	–0.03
1–11	63.7	0.0	34.1	0.38	98.1	61.8	28.6	7.5	97.9	0.3	83.9	0.06
E3	54.6	0.0	35.1	0.61	90.3	73.4	13.9	6.7	94.0	–3.7	39.5	–0.54
E4	43.0	0.0	36.4	0.61	80.0	69.1	14.3	18.7	102.1	–22.1	39.2	–0.72
A2	56.7	0.0	34.6	0.37	91.7	57.9	26.0	6.3	90.2	1.5	75.0	–0.03
11	78.5	5.0	76.3	0.57	160.3	129.4	16.9	8.8	155.1	5.2	22.2	–0.67
26	100.1	6.8	55.6	0.40	163.0	125.1	17.8	10.4	153.3	9.7	31.9	–0.45
13	71.2	2.2	57.2	0.52	131.0	79.9	28.6	5.4	113.9	17.2	50.0	–0.15
5	71.6	0.0	49.1	0.58	121.3	81.7	33.9	4.2	119.8	1.4	69.1	–0.21
2	77.4	1.2	60.8	0.40	139.8	85.6	12.7	6.6	104.9	34.9	20.9	–0.13
3	89.6	2.9	31.1	0.35	124.0	90.4	4.9	7.7	103.0	21.0	15.6	–0.03
Mean	77.0	1.3	43.8	0.45	122.5	87.7	17.1	9.7	114.6	7.96	40.6	–0.21

[a]Feed dry matter = 92%.
[b]Pond drainage = total nutrient discharge during drainage less nutrient input from initial pond filling.

Table 6
Partial phosphorus budget, feed phosphorus conversion efficiency, and phosphorus discharge by water exchange per unit of phosphorus input in feed

Pond	Phosphorus gain (kg/ha – 100 days)					Phosphorus loss (kg/ha – 100 days)				Balance (gain–loss)	Feed P conversion (%)	P discharge/ feed P
	Water	Fertilizer	Feed[a]	Shrimp	Total	Water	Shrimp	Pond[b] drain	Total			
2–11	10.3	0.0	8.3	0.02	18.6	11.0	0.68	1.9	13.5	5.1	8	−0.08
2–17	19.4	0.0	10.9	0.03	30.3	17.9	1.85	2.0	21.7	8.6	17	0.14
2–5	13.0	0.0	10.6	0.02	23.6	12.6	1.29	0.9	14.8	8.8	12	0.04
3–17	12.6	0.0	7.5	0.02	20.1	12.5	1.09	1.8	15.4	4.7	15	0.01
1–11	12.6	0.0	9.6	0.02	22.2	11.4	3.19	0.1	14.7	7.5	33	0.13
E3	4.9	0.0	11.7	0.03	16.6	6.7	1.55	0.4	8.2	8.3	13	−0.15
E4	3.5	0.0	12.1	0.03	15.6	5.4	1.59	1.3	6.9	8.7	13	−0.15
A2	7.2	0.0	8.7	0.02	15.9	5.8	3.19	0.7	9.0	6.9	37	0.16
11	8.3	1.6	14.9	0.03	24.9	13.1	1.89	0.9	15.0	9.9	13	−0.32
26	6.7	0.8	9.6	0.02	17.2	8.8	1.98	1.3	10.8	6.4	21	−0.22
13	10.9	0.3	10.3	0.03	21.5	12.0	3.19	0.0	15.2	6.4	31	−0.11
2	12.0	0.0	8.9	0.03	20.9	12.6	3.79	0.0	16.4	4.5	43	−0.07
3	14.3	1.3	11.0	0.02	26.6	19.1	1.42	1.1	20.5	6.1	13	−0.44
5	14.9	3.2	5.6	0.02	23.8	21.2	0.54	1.6	21.8	2.0	10	−1.12
Mean	10.8	0.5	10.0	0.0	21.3	12.1	1.9	1.0	14.6	6.7	20	−0.16

[a]Feed dry matter = 92%.
[b]Pond drainage = total nutrient discharge during drainage less nutrient input from initial pond filling.

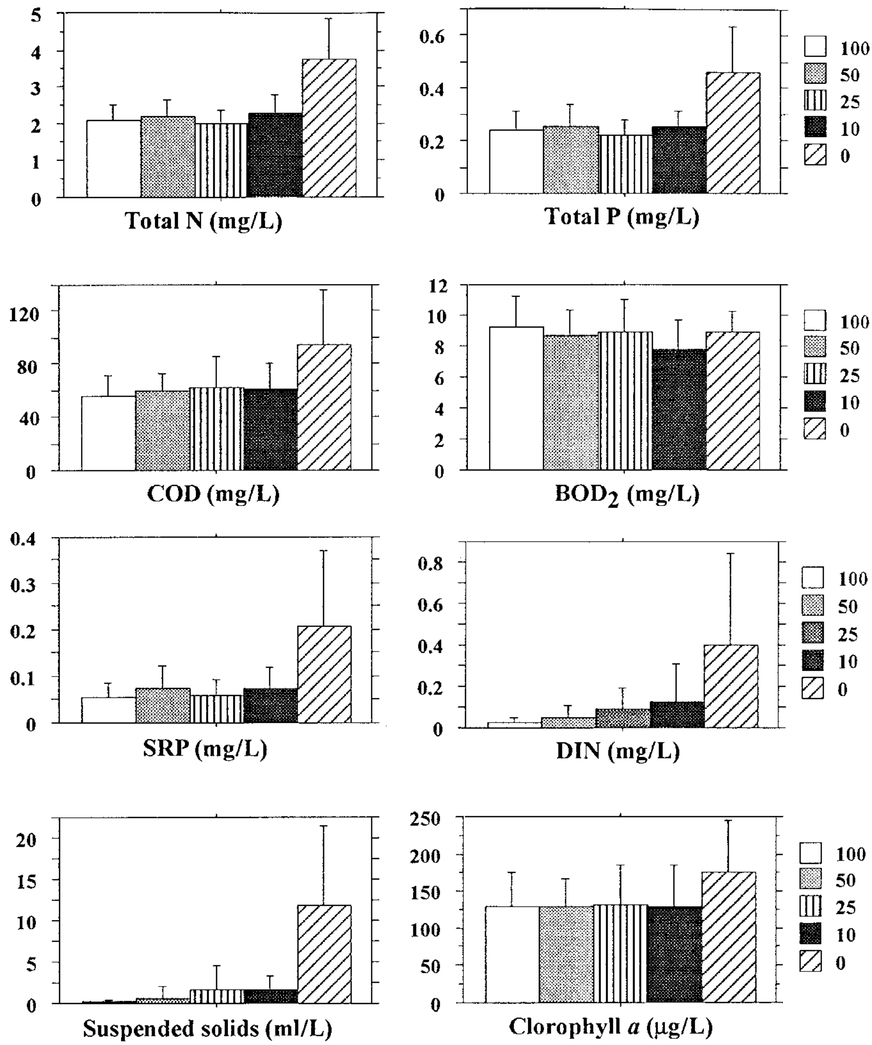

Fig. 2. Mean effluent concentrations of nutrients at 0%, 10%, 25%, 50%, or 100% of pond volume during pond draining.

Removal of shrimp at harvest accounted for another 14% of nitrogen loss. TN gain was greater than total recorded nitrogen loss; unrecorded nitrogen averaged 6.5%.

Conversion ratios of feed to shrimp on a wet weight basis (FCR) ranged from 0.96 to 5.55 and averaged 2.74. The FCR was significantly greater during the dry season ($P < 0.05$), averaging 3.30 compared with 1.74 for the rainy season. The conversion efficiency of feed nitrogen to nitrogen in shrimp flesh ranged from 16% to 84% and averaged 40.6%. Therefore, at least 59% of feed nitrogen was wasted to the pond environment.

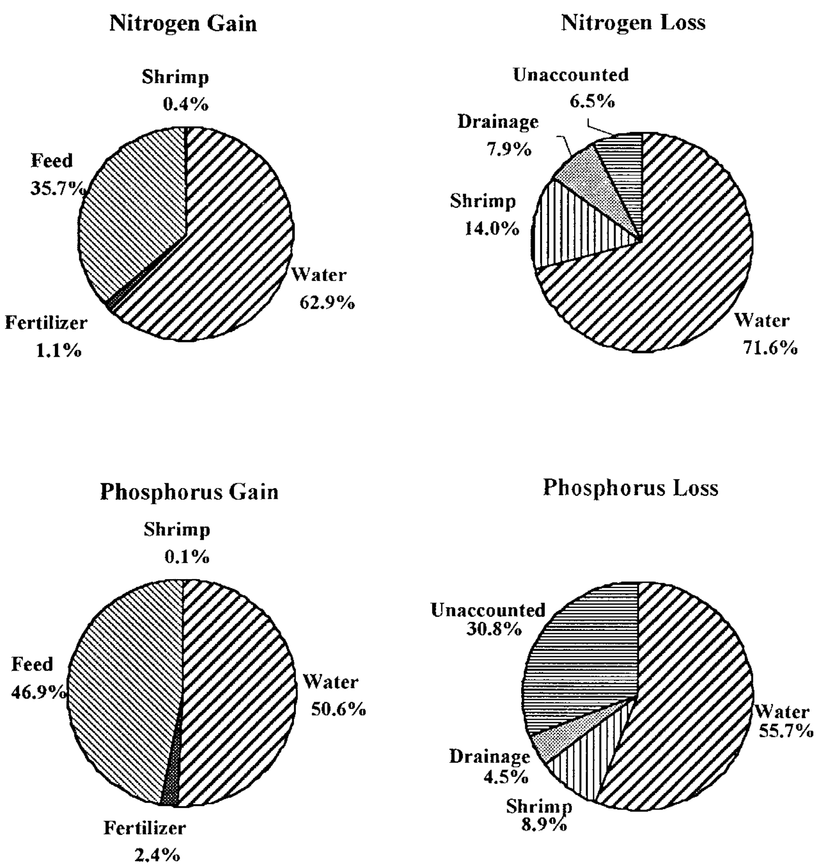

Fig. 3. Mean partial nitrogen and phosphorus budgets for shrimp production ponds in southern Honduras.

3.2.2. Phosphorus

Phosphorus gain to ponds occurred mostly from water (51%) and feed (47%), while fertilizer (2.4%) and shrimp (0.1%) accounted for the remainder (Table 6; Fig. 3). Phosphorus loss from ponds occurred primarily by discharge of water: daily water exchange (56%) and pond drainage (4.5%) accounted for about 60% of TP loss (Fig. 3). Harvested shrimp accounted for 9% of phosphorus loss. Almost a third (31%) of input phosphorus was not observed in the sum of recorded phosphorus losses.

The conversion efficiency of feed phosphorus to phosphorus in shrimp flesh ranged from 8.4% to 43% and averaged 20%. Efficiencies were significantly higher during the rainy compared to the dry season ($P < 0.05$).

4. Discussion

Partial chemical budgets indicated that commercial ponds in Honduras stocked with 7–10 shrimp/m^2 retained and/or metabolized 6.5% of the nitrogen and 31% of the phosphorus gained through feeds, fertilizer, and water. This calculation is based on nitrogen and phosphorus gains that could not be accounted for in losses through harvested shrimp and water, including daily exchange and drainage. Unrecorded nitrogen may have been adsorbed on soils, or lost through denitrification, ammonia volatilization and seepage (Boyd, 1985). Phosphorus is highly fixed on pond soil particles (Boyd, 1990) and accumulates in pond sediments over time (Munsiri et al., 1995, 1996). In comparison to the Honduras data, intensively managed commercial shrimp ponds in Thailand stocked at rates of 52–95 shrimp/m^2 retained 31% of nitrogen and 84% of phosphorus input (Briggs and Funge-Smith, 1994). Experimental ponds in Alabama stocked with 15–45 shrimp/m^2, on average, retained 39% of input nitrogen and 63% of input phosphorus (Couch, 1998). The retention and/or metabolism of nutrients in ponds apparently increases proportionate to gain by feed.

If the primary source of nutrition for shrimp was feed, then about 41% of feed nitrogen and 20% of feed phosphorus were converted to shrimp flesh. In Thailand, shrimp converted 24% of feed nitrogen and 13% of feed phosphorus to flesh (Briggs and Funge-Smith, 1994). On average, 37% of feed nitrogen and 16% of feed phosphorus were converted to shrimp flesh in Alabama ponds (Couch, 1998). Feed nitrogen conversion was relatively low in Thailand partly because survival of shrimp was low, averaging 46%. In Honduras, feed nitrogen conversion was relatively high for two reasons. Feed protein was relatively low, ranging from 20% to 27%, and low stocking rates allowed shrimp to have greater relative access to natural pond biota. Anderson et al. (1987) determined that pond biota contributed from 53% to 77% of carbon to growth of *P. vannamei* in fed ponds.

Water exchange accounted for the majority of nitrogen and phosphorus (51–63%) gained by ponds in this study. In contrast, feed was the major source of nitrogen (76–92%) and phosphorus (51–89%) in more densely stocked shrimp ponds in Thailand and Alabama. Feed normally is the single greatest source of nitrogen to fed ponds. Feed accounted for 92.3% of nitrogen gain in channel catfish ponds (Boyd, 1985) and 88% of nitrogen gain in striped bass ponds (Daniels and Boyd, 1989). In Honduras, shrimp stocking and feeding rates were low relative to other reported studies, so nitrogen gain to ponds from feed also was relatively low. In addition, nitrogen and phosphorus concentrations in the intake water were high relative to other reported studies. Mean TN ranged from 0.87 to 1.42 mg/l and mean TP ranged from 0.07 to 0.19 mg/l. Mean concentrations in Thailand and Alabama intake water ranged from 0.63 to 0.77 mg/l for TN, and from 0.07 to 0.14 mg/l for TP.

Water exchange resulted in a net discharge of organic matter as indicated by net discharge values for chlorophyll *a*, COD, BOD, TN, and TP (Table 4). Organic matter was produced in the ponds by photosynthesis and added to ponds as feed. Algal production absorbed intake inorganic nitrogen and phosphorus, resulting in a mean net gain of DIN and a balance between intake and discharge of SRP. In unfertilized ponds, more SRP was gained by ponds than lost. Fertilizers only accounted for 1–2% of total nutrient input to ponds, so the majority of net nitrogen and phosphorus loss from ponds were derived from feed. In this case, from 16% to 21% of the nitrogen and phosphorus applied in feed was discharged during daily water exchange. The mean shrimp yield for all ponds was 633 kg/ha. For each kilogram of shrimp yield, 16.8 g of N and 2.3 g of P were discharged as net loss to the environment.

Mean yield of intensive shrimp ponds in Thailand was 6355 kg/ha. In these ponds, 21 g of N and 0.7 g of P were discharged with water exchange for each kilogram of shrimp production. About five pond volumes of water were exchanged during each production cycle in both Thailand and Honduras. Therefore, 10-fold more water per kilogram of shrimp production was exchanged in Honduras than in Thailand. High water exchange rates are used in Honduras to combat projected episodes of low DO, because ponds are not equipped with aerators. If water exchange rates were decreased, then the pond nutrient balance should be biased towards increasing nutrient accumulation and metabolism in the ponds (Boyd, 1997). Hopkins et al. (1993) demonstrated that a 10-fold decrease in water exchange from 25% to 2.5% day^{-1} in ponds stocked with 44 shrimp/m^2 resulted in a twofold decrease in nitrogen discharge by water exchange.

Discharge during pond draining to harvest shrimp only accounted for 5–8% of total TN and TP loss from ponds during a culture period (Fig. 3). However, if this loss of nutrients derived from feed inputs, then about 25% of feed nitrogen (Table 5) and 11% of feed phosphorus (Table 6) was lost from ponds during pond harvest. Most producers flow water into ponds towards the end of draining to maintain acceptable dissolved oxygen concentrations and to help wash shrimp into harvest basins. The turbulence caused by incoming water and the movement of concentrated shrimp increases suspended solids and concentrations of TN and TP at the end of harvest (Fig. 2) (Schwartz and Boyd, 1994; Teichert-Coddington et al., 1999). There was high variation among ponds for TSS and nutrients because of water control during draining. Volume and rate of water flow into ponds varied among ponds depending on factors such as pond size, pond conformation and slope towards the drain, and rate of harvest. Most of the suspended solids are mineral particles that rapidly settle out of suspension (Boyd et al., 1998), so net nutrient loss at harvest could be reduced by minimizing turbulence at harvest and by diverting effluent water through settling basins (Boyd, 1997; Teichert-Coddington et al., 1999).

FCR in the current study ranged from 0.96 to 5.55 for a mean of 2.74 (Table 3). The highest mean FCR occurred during the dry season because of excessive feeding. Shrimp production is predictably lower during the dry season (Scura, 1995; Teichert-Coddington and Rodriguez, 1995), primarily because of lower temperatures (Teichert-Coddington et al., 1994). Producers sometimes try to overcome low dry season growth with higher feeding rates or higher protein feeds. Nitrogen discharge with water exchange increased as gain from feed nitrogen increased. Techniques to determine actual feed consumption, such as use of feeding trays (Clifford, 1992), may improve feeding efficiency. Most improvements to FCR could be made during the dry season when climatic and environmental conditions limit shrimp growth regardless of nutrient input (Teichert-Coddington et al., 1994). Some farms are already implementing management to minimize feeding during the dry season and others simply cease operations for a month or two at the height of the dry season.

Traditional pond management practices often include fertilization to promote primary productivity. This practice is questionable in fed ponds where primary nutrients for phytoplankton growth already are being supplied as metabolic by-products of feeds (Boyd, 1995). Studies in Choluteca, Honduras, indicated that inorganic fertilization of fed ponds was of uncertain value during the wet season, and did not increase shrimp yield during the dry season (Green and Teichert-Coddington, 1990; Rodriguez and Teichert-Coddington, 1995) when ambient conditions hinder shrimp growth (Teichert-Coddington et al., 1994). In the current study, inorganic fertilization had a notable effect on effluent concentrations of soluble nitrogen and phosphorus. Shrimp farms should minimize the use of fertilizers unless site specific studies demonstrate that fertilization increases yields.

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