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Nutrient Budget and Feasibility of Closed Cycle Shrimp Farm Systems

Financial (and Economic) Performance of Shrimp Farming Classified by Water Management

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ABSTRACT

A closed cycle shrimp (*Penaeus monodon*) farm was conducted for two consecutive crops. This system comprised of two grow-out ponds, one reservoir and one sediment pond. The reservoir was used for water storage and treatment. Average total production was 3,755 kg ha^{-1} for the first crop and 5,253 kg ha^{-1} for the second. Feed was the major source of nutrient to grow-out ponds, contributing an average 361 kg ha^{-1} of N (85.8% of TN) and 69 kg ha^{-1} of P (51.5% of TP) for the first crop compared with 485 kg ha^{-1} of N (82.3% of TN) and 92 kg ha^{-1} of P (50.8% of TP) for the second crop. Major losses were accumulation in the sediment accounting for 30% of TN and 88% of TP outputs. This system results demonstrated the feasibility of the system in culturing shrimp for at least two consecutive crops with no effect on shrimp production and water quality. The system could obtain high feeding efficiency, and low water exchange was used per production. The production was also reasonable. However, increased levels of nutrients and sediment in the reservoir may create problems in the subsequent crops. This needs to be further studied regarding the effects of the long term accumulation on the shrimp production.

INTRODUCTION

Many studies have noted the risks involved in open system shrimp farms, and the development of low water exchange systems in order to minimise the risk of problems such as polluted water and diseases, at a reasonable cost. It was noted that these systems, if managed responsibly, also had the potential to reduce the impact of the farm on the surrounding environment (Chanratchakool *et al.*, 1998).

As most farms were small-scale units (<1.6 ha), farmers did not normally want to operate low water exchange systems particularly recycle systems as they lost revenue from land used for reservoirs or water treatment ponds. However, some of exiting farms in Thailand presently have at least one reservoir in their farms. Thus, to make shrimp farms more sustainable and environmentally friendly, using existing reservoir ponds for two purposes - water storage, and treatment before reuse or release, was increasingly an option. According to Muir (1982), in areas of water shortage, water from intensive production ponds could be recycled through reservoirs, which can serve as waste treatment lagoons. However, data on such systems is scare and their operations and interactions are little understood.

The purpose of this study was therefore to obtain more information regarding water and soil quality, and nutrient (TN and TP) balances in a closed cycle system farm, over two consecutive crops. A better understanding of these parameters and their changes and relationships will be useful in improving low water exchange system design and management techniques.

MATERIALS AND METHODS

Study site

The study site was in Chonburi province in the eastern area of Thailand, located in a low salinity area. This was chosen as it was a small-scale farm, having a reservoir and not far (~2 hrs travel) from the laboratory station (Kasetsart University, Bangkok). The farm had been operating for two years. Its size was 1.6 ha water area, comprising 0.64 ha of reservoir pond, two grow-out ponds of 0.32 ha and one 0.16 ha of sediment pond. The remaining area was for dikes. The depth of the reservoir was 4 m, with 3 m water depth (19,200 m^3) and the depth of grow-out pond was 1.5 m, with 1 m water depth (3,200 m^3 per pond).

A centre drain was used to drain water to the reservoir and a spillway was used to wash out surplus water, particularly rain water. The reservoir was used for two purposes: water stocking during the culture period, and effluent water treatment. Discharged water from the grow-out ponds was kept in the reservoir and treated in order to reuse it for the next crop. De-silting and aeration were the methods used for water treatment. In the sediment pond, sediment was retained for one year and then disposed of or used for pond maintenance.

This farm normally reared two crops of shrimp a year with a culture period of around four months each. In this present study, the first crop was conducted during rainy season from 11/7/99 to 1/11/99 (i.e.120 days) and the second crop was conducted during summer season from 28/1/00-7/5/00 (i.e.124 days).

Between crop cycles, grow-out pond bottoms were allowed to dry for one month to enhance microbial decomposition of soil organic matter, and sediment from the previous crop was removed to the sludge pond. Pond bottoms were compacted before refilling water to reduce potential erosion.

Each grow-out pond was aerated by four long-armed paddle wheels on the surface of the pond water positioned in the middle of each dike and 3 m out from the bottom dike, and by a diffused -air system which distributed air from the pond bottom. A 3 HP (6.9 kW ha^{-1}) blower delivered air through one 50 mm diameter PVC pipe, positioned above the pond water surface (40 m length in each side along the dike). This was attached to 96 air stones (8 cm diameter), suspended in the water approximately 30 cm above the pond bottom.

A 3 HP (6.9 kW ha^{-1}) electric motor was used to power three of the paddle wheel aerators with 9 paddle wheels per unit (6 blades, 90 cm diameter and 0.30 cm width) and a 6 HP (6.9 kW ha^{-1}) diesel engine was set up on the bank between the two ponds to power the other paddle wheel aerators (12 paddle wheels per unit) in each pond. This system also acted as an emergency aerator. In addition, a 3 HP (4.7 HP ha^{-1} or 3.5 kW ha^{-1}) electric motor was used for a long-armed paddle wheel aerator positioned in the middle of the reservoir.

Water quality analyses

Water samples were collected fortnightly at 10.00 -12.00 h using a water sampler at 50 cm. under surface water at two stations; one at the centre of the pond and the other 3 m.

from the pond dike. Water filled in the reservoir before starting the second crop was also measured. At harvest, water samples were collected at 100%, 50%, 25 and 10% of pond volume for analysis. Water quality parameters including pH, DO, salinity, temperature and secchi disk visibility were measured in the field, while alkalinity, TAN, NO_2-N, NO_3-N, TN, TP, PO_4^{3-}, SS, BOD and Chl-a were analyzed in the laboratory. Water salinity was measured by Salino refractometer (Atago, Model. S-28). pH was measured by pH meter (Hach Model). Transparency was measured by Secchi disk. Dissolved Oxygen (DO) was measured using a Polarographic DO meter and probe (Yellow Spring Instrument Co., Model 51B). Laboratory parameters, Alkalinity, Biological Oxygen Demand (BOD_5^{20}), Total solids, Dissolved solids, Suspended solids, Chlorophyll a and Soluble reactive phosphorus (Orthophosphates) were analysed using the standard methods (APHA, 1989). Total ammonia-nitrogen was measured by the Indophenol method and Nitrite-nitrogen were measured by diazotization (Grasshoff, 1974). Nitrate-nitrogen and Total phosphorus were analysed by the methods in Strickland and Parson (1972).

Bottom soil analyses

Bottom soil samples were collected monthly using a core sampler 10 cm diameter underwater extracting the top 10 cm from the centre and the feeding areas of each pond. After harvest, the wet volume of sediment accumulated in the culture pond over each crop cycle was estimated by measuring its depth with a ruler every 5 m along two diagonal (corner to corner) transects. In the reservoir, the top 10 cm cores of ten random locations were collected underwater and then measured depth from the surface. Soil quality parameters including OM, OC, pH, TAN, BOD, PO_4^{3-}, TP and TN were analyzed in the laboratory. Soil samples were collected approximately 1 kg and kept in plastic bags for carrying back to the laboratory. BOD520 was analysed along the Standard method (APHA, 1989) and Musig and Yutharutnukul (1991). Bottom soil texture was analysed by Hydrometer method (Kilmer and Alexander, 1949; Day, 1965). Organic matter and organic carbon were analysed by Wet oxidation (Jackson, 1958; Walkely and Black, 1934). pH was measured by pH meter (dilution of soil : water = 1 : 1). Ammonium-nitrogen was measured by mixing approximately 0.5 g of soil with 200 ml-distilled water and then supernatant was analysed by Koroleff's indophenol blue method (Grasshoff, 1974). Total nitrogen and available phosphorus were analysed by the Kjeldahl method of Murphy and Rilly, respectively (Authanan *et al.*, 1989).

Feeding rates for all ponds were based on standard feed suppliers tables (Chanrathchakool *et al.*, 1998) and adjusted daily for consumption rate using feeding trays (6 trays ha^{-1}). The total amount of feed applied to each pond was recorded by the manager. Following each culture cycle, shrimp were harvested by complete drainage of the ponds and weighed to determine gross yield.

RESULTS

Shrimp production

Table 1, shows that despite the crop having the same stocking density of 43.75 PL m^{-2}, survival rates in the second crop were 72.4% compared with 43.5% for the first crop, where FCRs were consequently a little higher than that for the second crop. Whilst average harvest size of the second crop was 60.6 shrimp kg^{-1} (16.6 g $shrimp^{-1}$), that for the first crop was larger at 51 shrimp kg^{-1} (19.7 g $shrimp^{-1}$). Average total production was 3,755 kg ha^{-1} for the first crop lower than 5,253 kg ha^{-1} for the second.

Table 1 Grow-out ponds and reservoir data for two crops

Parameter	First crop				Second crop			
	Pond I	Pond II	Average	Reservoir	Pond I	Pond II	Average	Reservoir
Pond size (ha)	0.32	0.32	0.32	0.64	0.32	0.32	0.32	0.64
Pond water depth (m)	1.0	1.0	1.0	3.0	1.0	1.0	1.0	3.0
Water stock (m^3)	3,200	3,200	3,200	19,200	3,200	3,200	3,200	19,200
Water stocked (m^3 ha^{-1})	10,000	10,000	10,000	30,000	10,000	10,000	10,000	30,000
Stocking density (shrimp m^{-2})	43.75	43.75	43.75		43.75	43.75	43.75	
Survival (%)	41.6	45.4	43.5		63.5	81.2	72.4	
Harvest size (shrimp kg^{-1})	53	49	51		60	61	60.6	
Mean weight (g)	18.9	20.5	19.7		16.7	16.5	16.6	
Production (kg ha^{-1} $cycle^{-1}$)	3,441	4,069	3,755		4,652	5,854	5,253	
Food fed (kg $ha^{-1}cycle^{-1}$)	5,162	6,104	5,633		6,885	8,254	7,570	
FCR	1.5	1.5	1.5		1.48	1.41	1.45	
Culture period (days)	118	120	119		123	124	123.5	

Water budget

Water balances of the system in two culture crops of grow-out and reservoir ponds are summarized in Table 2. Total water budget of each grow-out pond was 25,116 m3$ha^{-1}crop^{-1}$ for the first crop and 30,681 m3$ha^{-1}crop^{-1}$ for the second crop. Water requirements for the second crop were higher than for the first crop due to higher evaporation rates, greater water exchange to control water quality and phytoplankton, and the longer culture period. However, the water budget per kg production was 7,299 m^3 t^{-1} for grow-out pond I and 6,172 m^3 t^{-1} for pond II in the first crop, and 6,595 and 5,241 m^3 t^{-1} of production in the second crop. Water exchange was achieved approximately every 3 days for the first crop and every 2 days in the second during the third and forth culture months. Average water inflow (i.e., water exchange and replacement) in the first crop was 12.7 mm day^{-1} compared with 16.7 mm day^{-1} for the second crop.

Table 2 Water budget for shrimp grow-out and reservoir ponds in two consecutive crops

First crop

Pond	In (m^3 ha^{-1} $crop^{-1}$)						Out (m^3 ha^{-1} $crop^{-1}$)							
	Initial fill	Replacement	Inflow	Rainfall	Drainage	Total	Outflow	Fill pond	Evaporation	Seepage	Drainage	Replacement	Water left	Total
1	10,000	5,116	10,000			25,116	10,000		3,688	1,428	10,000			25,116
2	10,000	5,116	10,000			25,116	10,000		3,688	1,428	10,000			25,116
Reservoir	30,000		10,000	6,188	10,000	56,188	10,000	10,000	3,689	1,428		5,116	25,955	56,188

Second crop

Pond	In (m^3 ha^{-1} $crop^{-1}$)						Out (m^3 ha^{-1} $crop^{-1}$)							
	Initial fill	Replacement	Inflow	Rainfall	Drainage	Total	Outflow	Fill pond	Evaporation	Seepage	Drainage	Replacement	Water left	Total
1	10,000	5,681	15,000			30,681	15,000		4,200	1,481	10,000			30,681
2	10,000	5,681	15,000			30,681	15,000		4,200	1,481	10,000			30,681
Reservoir	30,000		15,000		10,000	55,000	15,000	10,000	4,198	1,477		5,681	18,644	55,000

Water quality in the grow-out ponds and reservoir

It was found that concentrations of all water quality parameters were higher in the second crop (Table 3). These was due to more feed being applied, associated with higher survival rates of the second crop, from which the remaining nutrients (i.e. uneaten feed and nutrients left from the previous crop, discussed later) could stimulate the development of high levels of phytoplankton production (high Chl a), particularly in the summer season with high both solar radiation and temperature. Fluctuations of pH and dissolved oxygen concentration commonly occur in ponds with high phytoplankton production (Boyd, 1998). To deal with those problems, the farmer applied more chemicals particularly $CaCO_3$ and used high aeration application rates (high DO levels in the second crop) to maintain water quality at acceptable levels. By comparison, the first crop in the rainy season had less phytoplankton (less Chl a).

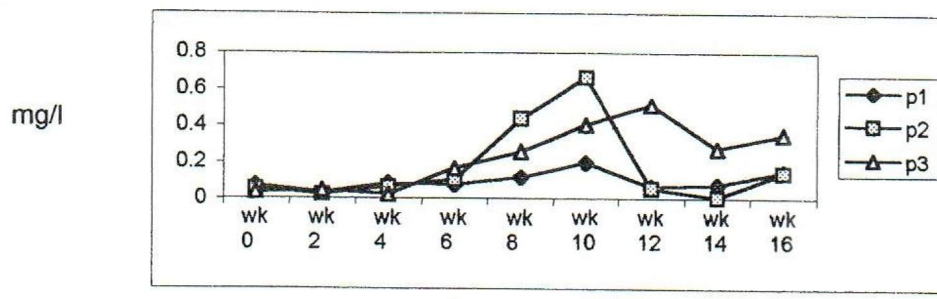
During the culture periods, levels of TAN in the grow-out ponds increased with rearing time, and in both crops were highest at the beginning of the third month of culture (Fig. 1). Pond II, in particular, with a higher production in both crops, generated higher TAN levels. Later in the production period, when the pond waters were exchanged by flow through from the reservoir, TAN levels decreased, while reservoir levels increased. Overall NO_2-N and NO_3-N concentrations in the grow-out ponds and the reservoir pond fluctuated for both crops and increased in the final month, but were found to be at very low concentrations in all ponds.

Table 3 Water quality (Mean + S.D.) in two consecutive shrimp crops

Parameter	Crop 1			Crop 2		
	Pond 1	Pond 2	Reservoir	Pond 1	Pond 2	Reservoir
Temperature (C°)	29.5+1.2	29.2+1.4	30.0+1.6	30.7+1.5	30.7+1.6	30.8+1.9
DO (mg L^{-1})	7.7+1.4	7.5+1.5	7.2+0.9	8.9+0.9	8.8+1.0	7.2+1.4
PH	8.3±0.5	8.4±0.3	7.9±0.3	8.6±0.5	8.6±0.4	8.0±0.3
Alkalinity (mg L^{-1})	119.1+15.8	128.8+13.2	114.6+6.4	146.7+11.3	152.7+12.3	131.8+17.9
TAN (mg L^{-1})	0.12±0.05	0.13±0.23	0.11±0.18	0.13±0.08	0.13±0.20	0.12±0.26
NO_2-N (mg L^{-1})	0.010±0.03	0.012±0.10	0.007±0.02	0.025±0.01	0.029±0.03	0.023±0.01
NO_3-N (mg L^{-1})	0.004+0.02	0.005+0.001	0.003+0.01	0.006+0.001	0.008+0.002	0.006+0.002
TN (mg L^{-1})	2.85±0.24	2.90±0.38	2.38±0.38	3.90±0.35	3.98±0.33	3.42±0.60
PO_4^{3-} (mg L^{-1})	0.012+0.01	0.013+0.02	0.011+0.01	0.015+0.002	0.018+0.01	0.013+0.002
TP (mg L^{-1})	0.146+0.06	0.150+0.08	0.090+0.02	0.148+0.05	0.152+0.06	0.11+0.03
Secchi depth (cm)	29.8+10.7	26.4+11.8	33.1+8.4	29.0+13.4	27.9+12.3	27.8+11.3
SS (mg L^{-1})	45+20	49+32	33+11	50+22	56+21	34+10
Chl a (mg L^{-1})	61.42±32.23	75.47±59.9	49.57±13.88	84.95±43.14	83.11±62.94	50.10±17.37
BOD (mg L^{-1})	12.48±5.3	12.99±5.3	8.00±2.0	12.54±5.0	13.46±6.0	8.20±2.1
Salinity (ppt)	3.8±1.3	3.2±1.2	1.9±0.7	6.1±2.3	6.01±2.1	6.10±3.6

S.D.= Standard deviation

Figure 1 Total ammonia in closed recycle system



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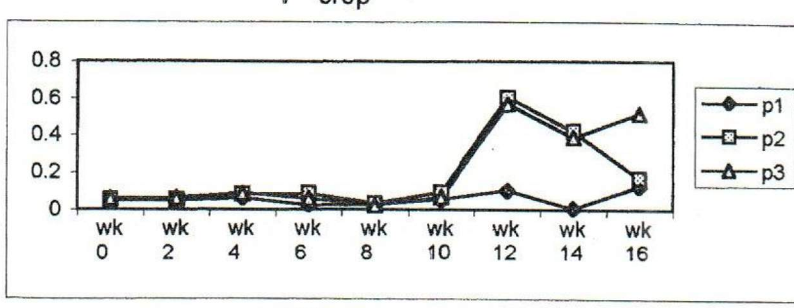


2 nd crop

Orthophosphate concentrations in both crops increased during the first one or two months of culture and then decreased (Fig. 2), while BOD, SS and Chl a significantly increased and secchi disk visibility decreased as the culture period progressed (Fig. 3, Fig. 4, Fig. 5 and Fig. 6). Dissolved oxygen concentrations and pH levels did not greatly change during culture period since the farmer maintained these parameter levels through the use of aeration and lime applications. As it was summer season in the second crop, pond water salinity in the first crop declined during culture period progressed, while it increased in the second crop in the summer season.

Figure 2 Orthophosphate in closed recycle system

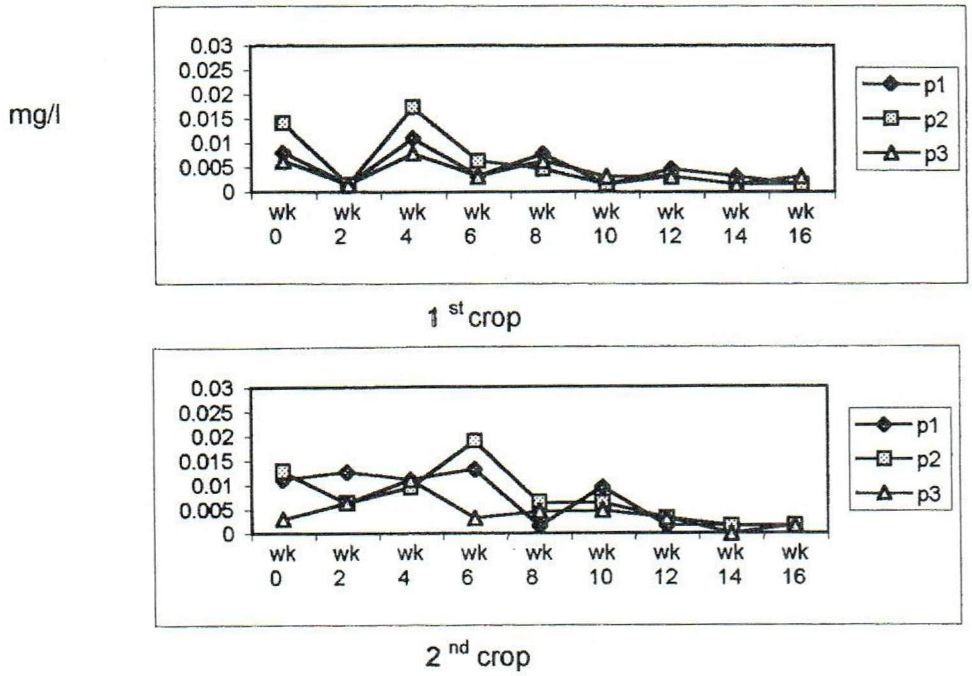
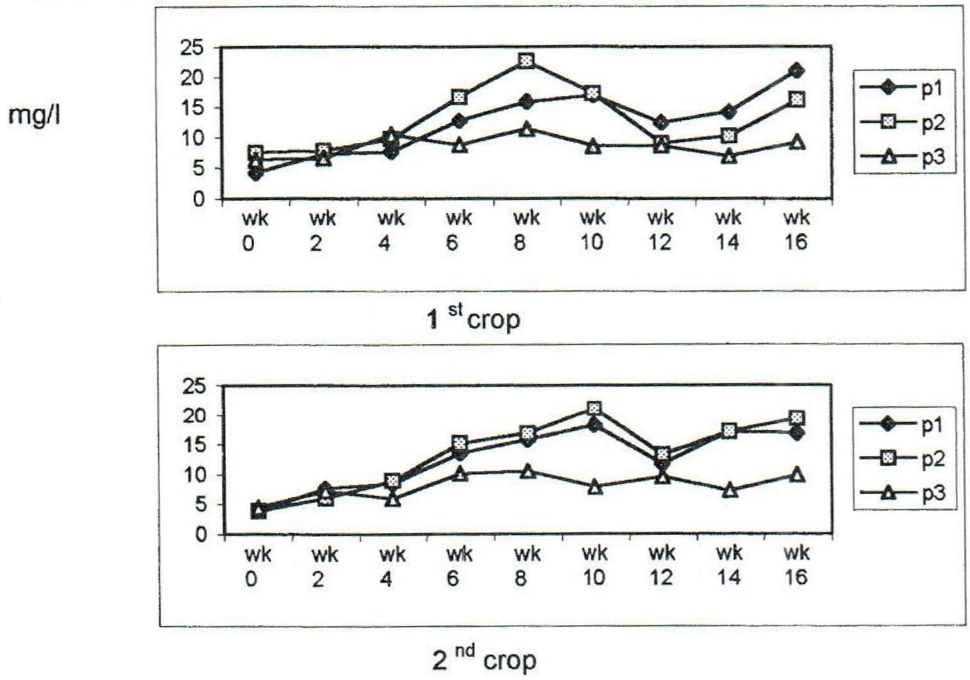
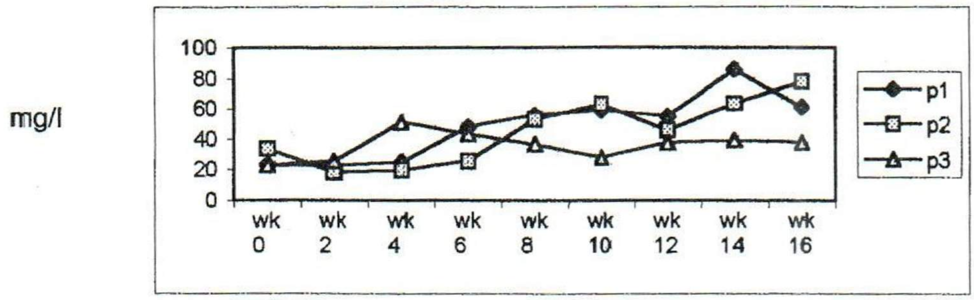


Figure 3 BOD in closed recycle system



p1 = pond 1; p2 = pond 2; p3 = reservoir; wk = week

Figure 4 Suspended solids in closed recycle system



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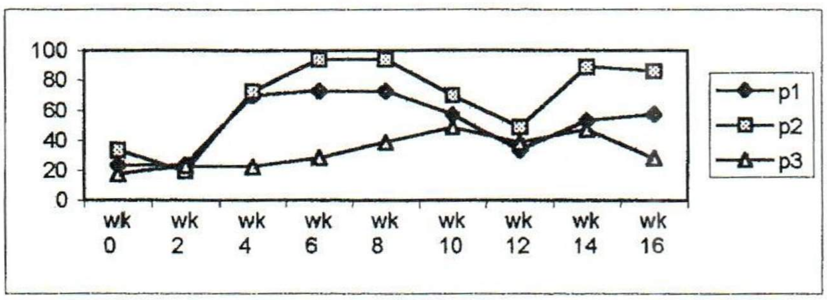

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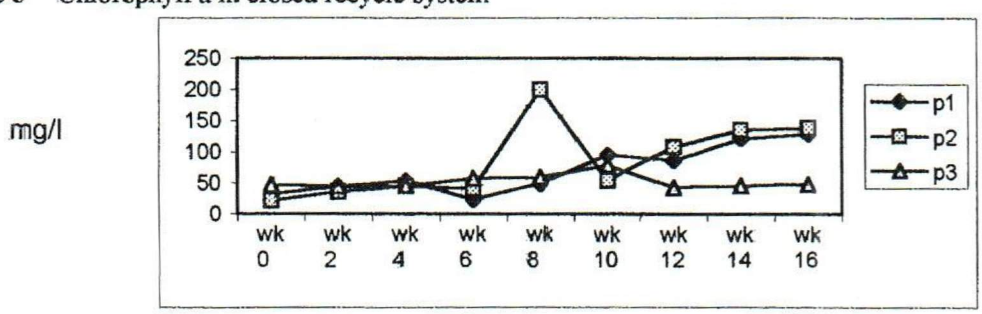
Figure 5 Chlorophyll a in closed recycle system



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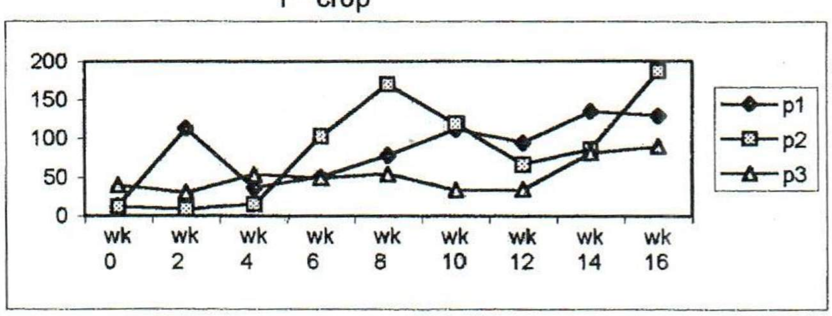
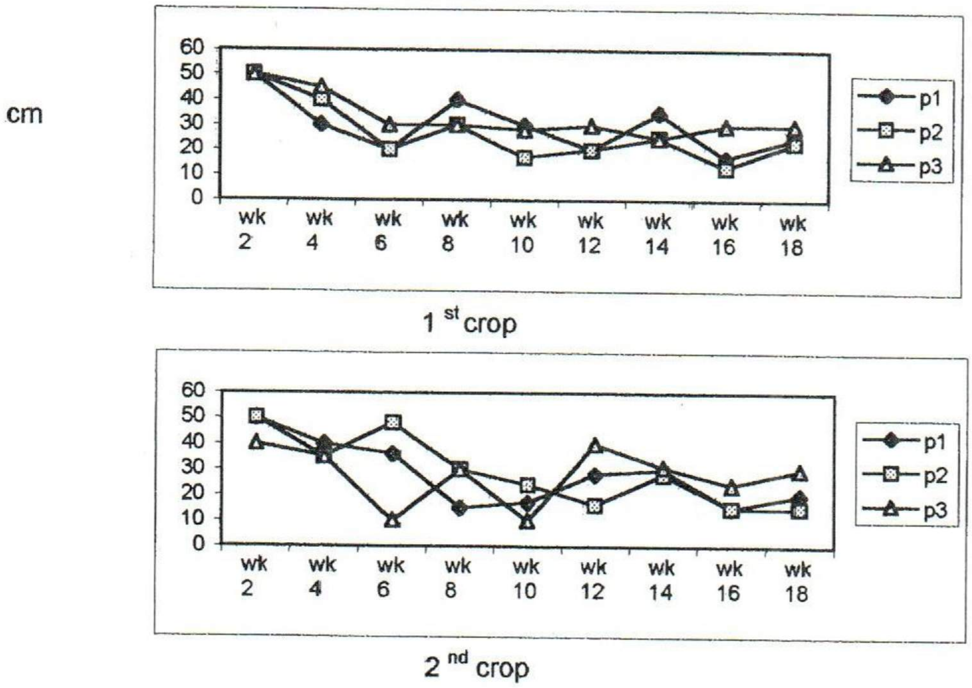


2 nd crop

p1 = pond 1; p2 = pond 2; p3 = reservoir; wk = week

Figure 6 Secchi disc visibility in closed recycle system



p1 = pond 1; p2 = pond 2; p3 = reservoir; wk = week

Only means of alkalinity and salinity levels in the second crop were higher than in the first crop, similar to the results in the grow-out ponds. These were due to the release of water into the reservoir from the culture ponds, which had a greater level of lime application and lack of rainfall in the second crop. Other parameter trends were also the same as in the culture ponds.

In comparing water quality parameters between grow-out ponds and the reservoir, all water quality parameters in the reservoir were lower. pH levels in the grow-out ponds were higher than in the reservoir pond in both crops and average dissolved oxygen and alkalinity levels in grow-out ponds in the second crop were also higher than in the reservoir. This was probably due to greater levels of lime ($CaCO_3$) application and higher aeration rate in the grow-out ponds, particularly in the second crop. Average salinity in the grow-out ponds of the first crop was higher than in the reservoir as during the wet season, rainwater would dilute salinity in the reservoir, while spillways were used in the grow-out ponds to maintain pond water salinity, and no rainfall occurred in the second crop.

Bottom soil quality in the grow-out ponds and reservoir

The pond bottom soil in the study area was sandy clay loam. Table 4 shows that bottom soil quality parameters of the grow-out ponds in the same crop or between crops are not different, though they were slightly higher in pond II than pond I and in the second crop than in the first crop. These were mainly due to greater feed being applied in pond II, at 6,104 kg

Table 4 Bottom soil quality (Mean ± S.D.) of grow-out and reservoir ponds in two consecutive shrimp crops

Parameter	Crop 1			Crop 2		
	Pond 1	Pond 2	Reservoir	Pond 1	Pond 2	Reservoir
OM (%)	1.40+1.28	1.64+1.57	0.74+0.40	1.5+1.43	1.74+1.53	1.30+1.15
OC (%)	0.81+0.74	0.95+0.94	0.43+0.23	0.87+0.79	1.01+1.00	0.75+0.66
pH	7.22+0.14	7.34+0.12	7.19+0.16	7.52+0.29	7.61+0.19	7.41+0.32
TAN (mg/g)	0.20+0.19	0.18+0.17	0.08+0.04	0.31+0.23	0.39+0.38	0.16+0.07
BOD (mg/g)	3.00+2.58	3.36+3.80	2.09+2.13	3.53+2.81	4.45+3.48	3.52+1.66
PO_4^{3-} (mg/kg)	74.56+8.74	76.88+3.48	57.26+2.40	87.47+7.36	81.77+7.37	67.01+6.27
TP (%)	0.069+0.04	0.071+0.02	0.05+0.019	0.071+0.03	0.072+0.021	0.055+0.022
TN (%)	0.071+0.03	0.073+0.04	0.05+0.02	0.074+0.019	0.078+0.033	0.056+0.03

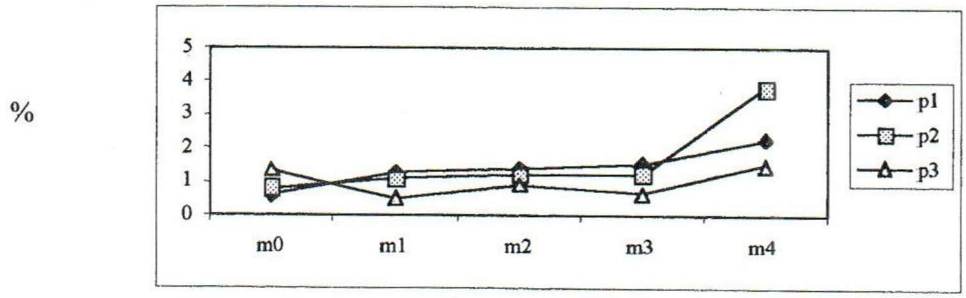
S.D. = Standard deviation

ha-1 compared with 5,162 kg ha^{-1} for the first crop and 8,254 kg ha^{-1} compared with 6,885 kg ha^{-1} for the second crop. These averaged 7,570 kg ha^{-1} for the second crop, which was greater than 5,633 kg ha^{-1} for the first.

Bottom soil quality parameters of the reservoir in two culture crops were higher in the second crop than in the first.

Most parameters in the grow-out ponds and the reservoir pond fluctuated for both crops and increased in the final month with greater feed being applied and high waste accumulation. There were high variations in bottom soil quality parameters particularly OM, OC, TAN and BOD levels (Fig. 7, Fig. 8, Fig. 9 and Fig. 10) though pH levels were rather stable because of lime application.

Figure 7 Organic matter in closed recycle system



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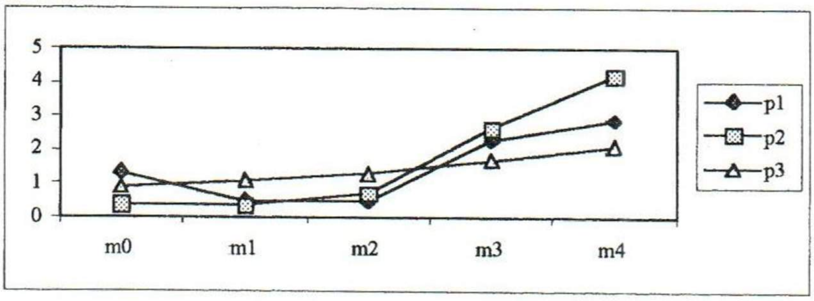
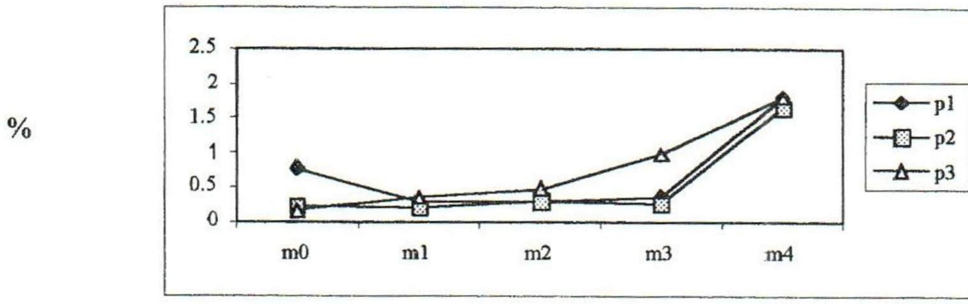


2 nd crop

All bottom soil quality parameters in grow-out ponds were higher than in the reservoir. These were probably due to greater nutrient levels, especially phosphorus,

Figure 8 Organic carbon in closed recycle system



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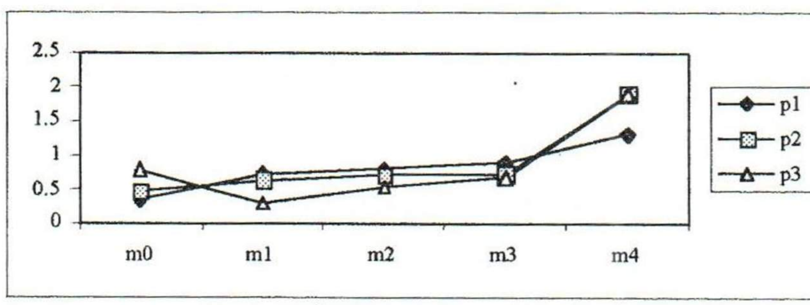
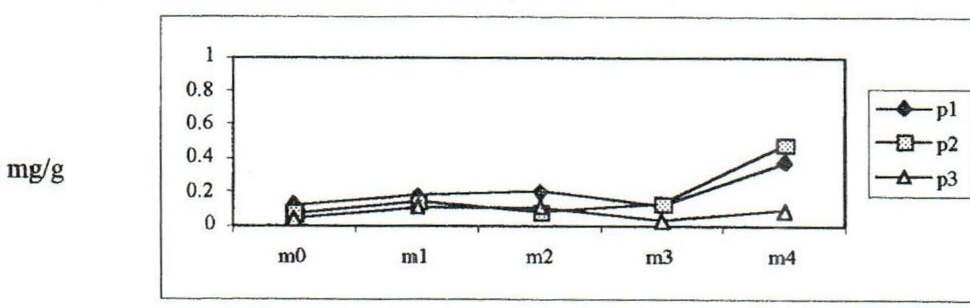


2 nd crop

Figure 9 Total ammonia in soil in closed recycle system



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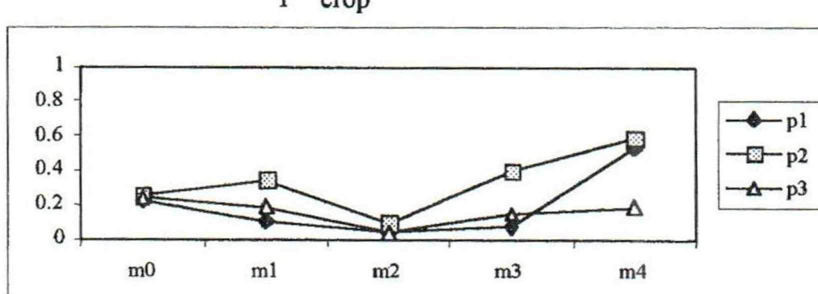
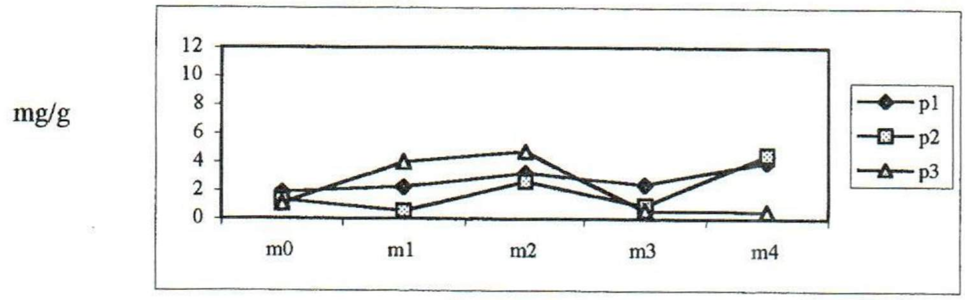


2 nd crop

p1 = pond 1; p2 = pond 2; p3 = reservoir; m = month

Figure 10 BOD in soil in closed recycle system



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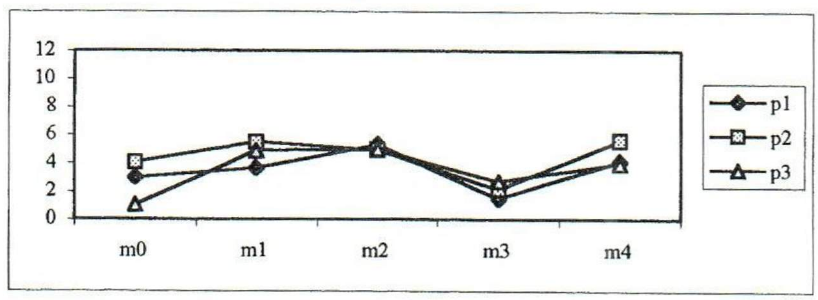


2 nd crop

p1 = pond 1; p2 = pond 2; p3 = reservoir; m = month

Nutrient budgets

Most of the nutrient gains and losses in the second crop were higher than those in the first crop. These were associated with more feed applied associated with higher shrimp stocks, water reuse, and more chemical application, particularly lime, to maintain water quality in an acceptable level in the second crop. The nutrient budgets were extrapolated to kg ha^{-1} and summarized for each pond (Table 5 and Table 6).

Table 5 Nitrogen budget for ponds in two crops

Crop 1													
Pond	In (kg ha^{-1} crop^{-1})						Out (kg ha^{-1} crop^{-1})						
	Inflow	Food	Initial	Drain	Sediment from previous	Total	Outflow	Shrimp	Sediment	Drain	Water left	Other	Total
1	60	331				391	29	97	130	41		94	391
2	60	391				451	29	116	143	41		122	451
Average	60	361				421	29	107	137	41		108	421
%	14.2	85.8				100.0	6.8	25.3	32.4	9.7		25.7	100.0
Reservoir	29		60	41	236	366	60		244		62		366
%	7.9		16.4	11.2	64.5	100.0	16.3		66.7		16.9		100.0
Crop 2													
1	105	441				546	59	131	163	45		148	546
2	105	528				633	60	166	174	45		188	633
Average	105	485				589	59	149	169	45		168	589
%	17.8	82.3				100.0	10.0	25.2	28.6	7.6		28.5	100.0
Reservoir	59		90	45	246	440	105		270		65		440
%	13.4		20.5	10.2	55.9	100.0	23.8		61.4		14.8		100.0

Table 6 Phosphorus budget for ponds in two crops

Pond	In (kg ha^{-1} crop^{-1})						Out (kg ha^{-1} crop^{-1})					
	Inflow	Food	Initial	Drain	Sediment from previous	Total	Outflow	Shrimp	Sediment	Drain	Water left	Total
crop 1												
1	2	63			55	120	1	9	106	4		120
2	2	75			71	148	2	13	130	4		148
Average	2	69			63	134	1	11	118	4		134
%	1.7	51.5			47.0	100.0	1.1	8.2	88.1	2.7		100.0
Reservoir	1		3	4	235	243	2		238		3	243
	0.6		1.1	1.6	96.7	100.0	0.9		97.9		1.1	100.0
crop 2												
1	3	84			82	169	2	13	149	5		169
2	3	100			90	193	2	16	170	5		193
Average	3	92			86	181	2	15	160	5		181
%	1.9	50.8			47.5	100.0	1.2	8.0	88.1	2.8		100.0
Reservoir	2		3	5	235	246	3		241		2	246
%	0.9		1.3	2.0	95.5	100.0	1.4		98.0		0.8	100.0

Nitrogen

Average total nitrogen of the first crop was 421 kg ha^{-1} (0.42 t ha^{-1}) and that of the second crop was 589 kg ha^{-1} (0.59 t ha^{-1}) (Table 5). Feed applied was the major source of nitrogen into culture ponds in the two crops representing 82.3%-85.8% of TN inputs, and water inflow accounted for 14.2%-17.8%% of TN inputs. Principal outputs were accumulation in the sediment (28.6%-32.4%), loss to the atmosphere by denitrification and ammonia volatilization (25.7%-28.5%), and harvested shrimp (25%). Minor output was outflow water i.e. effluent for water exchange (6.8%-10.0%) and harvest drainage (7.6%-9.7%). Nitrogen loss to the atmosphere of the second crop was higher than that of the first crop, and may be due to high aeration enhancing the diffusion of NH3 during high pH periods in the afternoon (Fig. 11).

In the reservoir, total nitrogen of the first crop was 366 kg ha^{-1} while that of the second crop was 440 kg ha^{-1} (Table 5). Sources of nitrogen input to the reservoir were sediment from the previous crop (55.9%-64.5%), initial water stocked (16.4%-20.5%), harvest drainage (10.2%-11.2%) and inflow water during water exchange (7.9%-13.4%). Outputs of nitrogen were accumulation in sediment (61.4%-66.7%) and outflow water (16.3%-23.8%). Around 14.8%-16.9% of TN retained in the water left. Total nitrogen in the sediment of the second crop increased 26 kg ha^{-1} (10.7%) from the first crop (Fig. 12).

Phosphorus

The average total phosphorus budget of the first crop was 134 kg ha^{-1} and of the second crop was 181 kg ha^{-1} (Table 6). Feed applied and sediment from the previous crop were major sources of phosphorus inputs to culture ponds accounting for 50.8%-51.5% and 47.0%-47.5%, respectively. Water inflow was a minor source at only 1.7%-1.9% of TP inputs. Major losses were in accumulation in the sediment accounting for 88.1% of TP outputs. Minor losses were harvested shrimp (8.0%-8.2%), outflow water for harvest drainage (2.7%-2.8%) and water exchange (1.1%-1.2%) (Fig. 13).

Figure 11. Nitrogen budget of closed recycle system farm

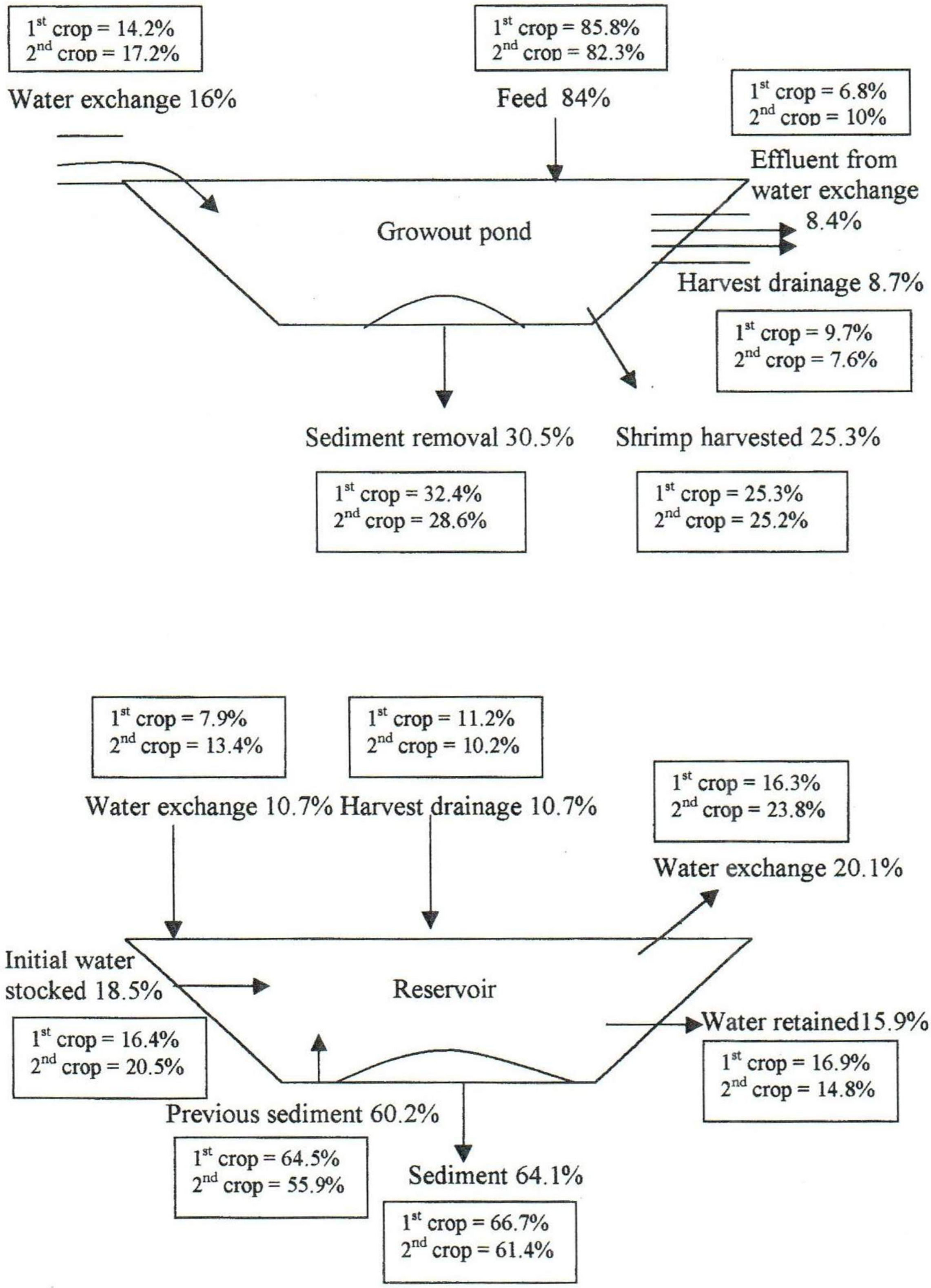
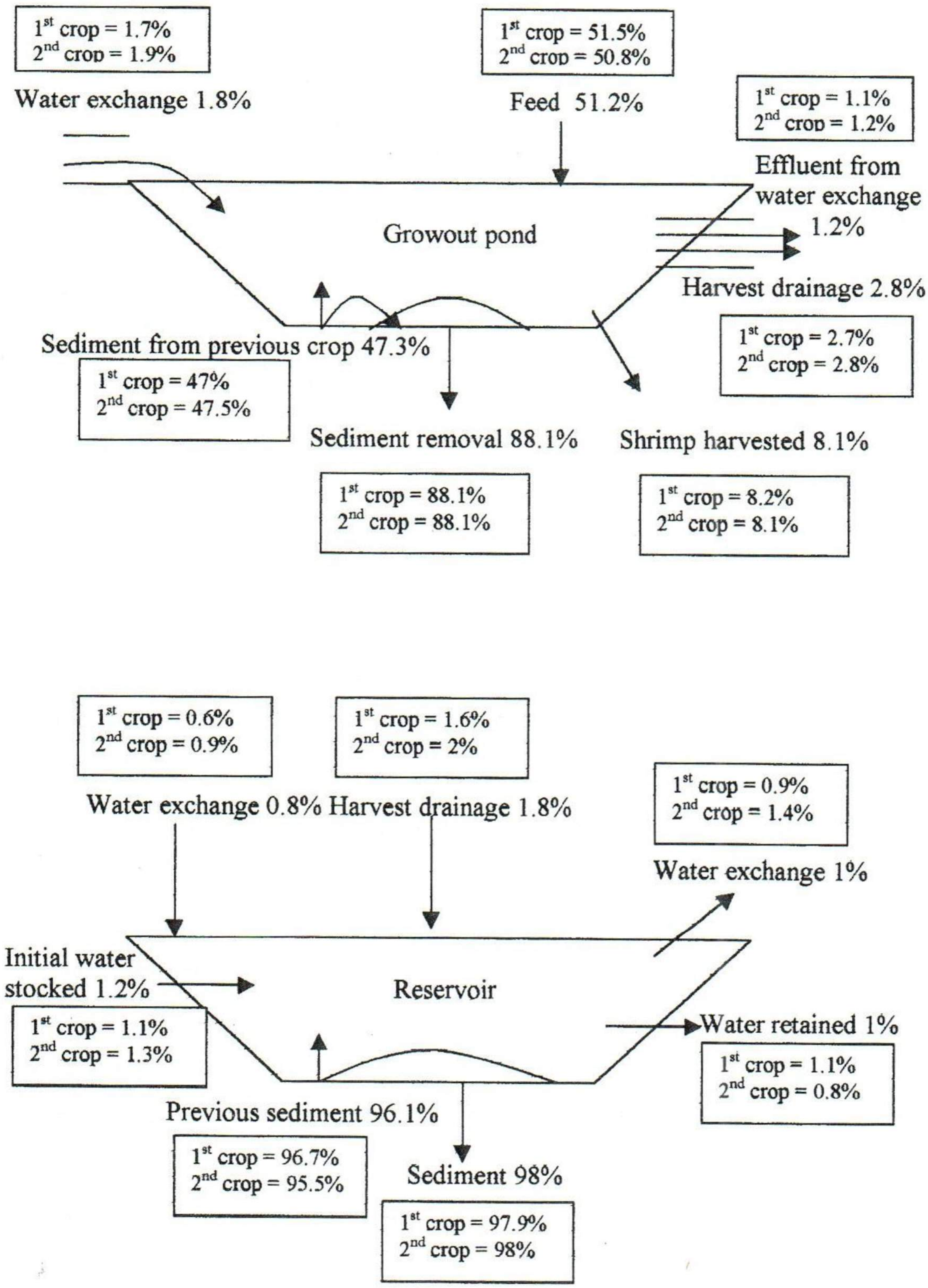


Figure 12 Phosphorus budget in closed recycle system farm



In the reservoir, total phosphorus was 243 kg ha^{-1} in the first crop and 246 kg ha^{-1} in the second crop (Table 6). Sediment from the previous crop was the major source of phosphorus in the reservoir accounting for 95.5%-96.7% of TP inputs. Other minor inputs were harvest drainage (1.6%-2.0%), initial water stocked (1.1%-1.3%), and water exchanged from grow-out ponds (0.6%-0.9%). Output of TP was mainly accumulation in sediment (98%). Outflow accounted only 0.9%-1.4% of TP outputs and 0.8-1.1%% of TP retained in the water left. Total phosphorus in the accumulated sediment of the second crop increased 3 kg ha^{-1} (1.3%) from that of the first crop

DISCUSSION

The results showed that this system could raise shrimp for at least two consecutive culture crops without any effect on shrimp production and water quality. Shrimp yield and harvest size of the two crops were not different, though there was a greater shrimp yield with smaller harvest size for the second crop than the first. FCR results also did not differ between the two crops, ranging from 1.4 to 1.5. Survival rates were lower in the first crop, probably as it was raining during larval stocking and as changes in water salinity and/or temperature may have caused larval stress and mortalities from osmoregulatory failure (Boyd and Tucker, 1998).

Due to higher evaporation rate and no rainfall in the summer, and the higher feed levels applied to the greater stock levels, nutrients from uneaten feed, accompanied with high temperature and solar radiation resulted in excessive phytoplankton biomass in the second crop. A larger volume of water was required to replace water loss by evaporation and seepage, and reduce phytoplankton levels. Thus, average water budgets of the grow-out pond in the first crop was 25,116 m3 ha^{-1}, which was lower than that in the second crop at 30,681 m^{3}ha^{-1}.

Average inflow (i.e. influent water for exchange and replacement) and outflow (i.e. effluent water for exchange) in the grow-out pond were 12.7 mm day^{-1} and 8.4 mm day^{-1} in the first crop, and 16.7 mm day^{-1} and 12.1 mm day^{-1} in the second crop which were higher than 9.4 mm day^{-1} and 7.0 mm day^{-1} reported by Braaten and Flaherty (2000) for closed system and lower than 42.5 mm day^{-1} and 40.7 mm day^{-1} reported by Briggs and Funge-Smith (1994) for open systems.

For the second crop, with no rainfall, high evaporation rate, and greater water use in the grow-out ponds, water input to the reservoir was lower than in the first crop but water output was higher. Inflow (i.e. effluent from grow-out ponds) and outflow (i.e. water filled in grow-out ponds) waters of the reservoir were 8.4 mm day^{-1} and 12.7 mm day^{-1} for the first crop compared with 12.1 mm day^{-1} and 16.7 mm day^{-1} for the second crop.

Water quality concentrations of the grow-out ponds in the same crop were not different as water source came from the same reservoir, and nutrient inputs mainly came from the same feed type and FCR results were little different. However, most parameters of the second crop were higher than those of the first crop, probably as more lime i.e. calcium carbonate ($CaCO_3$) was applied to increase total alkalinity and control pH fluctuations (3,594 kg ha^{-1} in the first crop and 5,194 kg ha^{-1} in the second crop), and as the second crop period was in the summer with no rainfall and higher evaporation rates.

Feed was the major source of nutrient to grow-out ponds, contributing an average 361 kg ha^{-1} of N (85.8% of TN) and 69 kg ha^{-1} of P (51.5% of TP) for the first crop compared with 485 kg ha^{-1} of N (82.3% of TN) and 92 kg ha^{-1} of P (50.8% of TP) for the second crop. However, only 25.3% of TN and 8.2% of TP in the first crop and 25.2% of TN and 8.0% of TP in the second crop were removed as harvested shrimp. Thus higher nutrient losses from uneaten feed in the second crop, associated with fecal solids, dead plankton cells and other organic matters, were decomposed by microorganisms in the ponds causing releases of TAN, NO_2, NO_3, PO_4^{3-} and others which could stimulate phytoplankton production, as evidenced by greater Chl a concentrations observed in the ponds of the second crop.

Under aerobic conditions where water is aerated, some ammonia may be oxidized to nitrite and nitrate by Nitrosomonas and Nitrobacter bacteria, respectively. These nitrification processes are acid-producing and may also cause total alkalinity to decline. Thus more lime (i.e. $CaCO_3$) had to be applied in the second crop in order to control water quality by increasing total alkalinity (HCO_3^-) which could act as buffer in the system (Diana *et al.*, 1997), as in the equation below:

$$CaCO_3 + H_2O + CO_2 \longrightarrow Ca^{2+} + 2HCO_3^-$$

This may also affect TP concentrations in the pond waters, in which orthophosphate rapidly combines with free calcium ions to form calcium phosphate and then settle on the pond bottom (Hepher, 1958, cited by Ritvo *et al.*, 1999; Boyd, 1990; Boyd, 1995; Ritvo *et al.*, 1999). By making phosphorus less biologically available for phytoplankton growth, the farmer used this mechanism for controlling excessive phytoplankton production.

Due to phytoplankton, over-blooming was a major problem in the second crop and sometimes water exchange and lime application alone could not deal with the problem, with dissolved oxygen depletion often occurring at night. Formalin was applied at a rate of 10-15 mg L^{-1} in the day time to reduce phytoplankton abundance by applying in the corners where phytoplankton was at high density. Afterwards, dead phytoplankton foam was removed from the pond water surface. Though, formalin may reduce ammonia concentration by forming hexamethylenetetramine and possibly formamide (Boyd and Tucker, 1998), it is highly toxic not only to phytoplankton, but also to the shrimp, and may be also deplete dissolved oxygen. Thus vigorous aeration was employed after treatment to reduce harmful levels and increase dissolved oxygen implications for energy use, etc.

Nitrogen loss to the atmosphere was higher in the second crop, as related to higher aeration rates and higher pHs. The dominant inorganic form of nitrogen, ammonia, has weak attraction for soil particles and can be lost to the atmosphere through volatilization of ammonia during periods of high pH, aided by heavy aeration and denitrification of nitrate to nitrogen gas in anaerobic subsurfaces during sedimentation (Hopkins *et al.*, 1993; Boyd and Tucker, 1998; Teichert-Coddington *et al.*, 1999; Gross *et al.*, 2000). Thus increasing aeration associated with high pH levels could obtain higher production as the results of an average 5,253 kg ha^{-1} (range 4,652-5,854 kg ha^{-1}) in the second crop compared with 3,755 kg ha^{-1} (range 3,441-4,069 kg ha^{-1}) in the first crop.

In the reservoir, all water quality parameters of both crops were lower than in the culture ponds. These meant that the reservoir could reduce all water quality parameter levels, mainly by settling. The retention time of water in the reservoir was approximately eight days for the first crop and seven days for the second. However, Funge-Smith and Briggs (1998) reported that retention time of one hour is sufficient for routine water exchange settlement. In one hour settlement achieved 22-44% settlement of suspended solids depending upon initial loading (100-300 mg L^{-1}). They also commented that harvest effluents are more easily settled because they are a mixture of resuspended accumulated sediment and the suspended solid fraction of the water. Briggs (1994) recommended that > 10% of farm area should be devoted to settlement ponds for optional removal of settleable nutrients. This can be effected by shunting the last 10-20% of discharge through a settling pond with six to eight hours of water detention time, which 60-80% of TSS and 15-30% of BOD5 can be removed (Teichert-Coddington *et al.*, 1999 and Boyd, 2000).

Though pond bottom quality of the reservoir was not significantly different between the two crops, sediment of the second crop was 1,809 kg ha^{-1} greater than from those of the first crop as no sediment was removed between the two crops.

Funge-Smith and Briggs (1994) reported nutrient budgets of open intensive system shrimp ponds, with an average stocking density of 72.1 PLm^{-2}, survival rate of 46%, FCR of 1.98 and yield of 6,533 kg $ha^{-1}cycle^{-1}$ and stated that feed applied was the main source of N and P inputs accounting for 92% of TN and 51% of TP, respectively, while pond soil erosion was the major source of SS inputs accounting for 91% of TSS. Other inputs were inflow water (i.e. water exchange and replacement) contributing 5% of TN, 2% of TP, and 2.8% of TSS, fertilizers accounting for 3% of TN, 21% of TP, and 0.2% of TSS, and lime representing 1% of TSS. Sediment accumulation was the major sink of nutrients and suspended solids accounting for 31% of TN, 84% of TP and 93% of TSS. These were lost to shrimp harvested at 21% of TN, 6% of TP, and 0.7% of TSS. In addition, 13% of TN was lost to the atmosphere.

In this study, with an average stocking density of 43.75 PL m^{-2}, survival rate of 58%, FCR of 1.5, and yield of 4,504 kg ha^{-1} $cycle^{-1}$, feed applied was also the main N and P inputs to the ponds ranging from 82.3% to 85.8% of TN and 50.8% to 51.5% of TP and pond soil erosion contributed 90.8% to 92.5% of TSS. Inflow water contributed 14.2% to 17.8% of TN, 1.7% to 1.9% of TP, and 0.7% of TSS. Lime applied accounted for 2.8% to 3.7% of TSS. These were lost to the sediment accumulation of 28.6% to 32.4% of TN, 88.1% of TP, and 97.6%-98.1% of TSS. Approximately 25.7% to 28.5% of TN were lost to the atmosphere.

Total production from the first crop was lower than from the second, but harvested sizes in the former were larger, and therefore more profitable. Although stocking densities at the beginning were the same as 43.75 PL m^{-2}, survival rates were higher in the second crop resulting in higher stocking densities. In practice, it was shown to be difficult to maintain the water quality in ponds, stocking at high densities (Sandifer *et al.,* 1987; Hopkins *et al.,* 1988). Many authors have reported an inverse relationship between the growth of shrimp and the stocking density (Lee *et al.*, 1986; Sandifer *et al.*, 1987; Ray and Chien, 1992; Daniel *et al.*, 1995; Martin *et al.*, 1998). Many authors have also suggested that using stocking densities of 25-40 PL m^{-2} and obtaining production of 5,000-6,000 kg ha^{-1} could reduce the level of pond deterioration and disease incidence, yet still achieve optimum profitability over the longer term (Csavas, 1990; Anon., 1992 and Boyd, 1992).

The above results demonstrated the feasibility of the system in culturing shrimp for at least two consecutive crops with no effect on shrimp production and water quality. The system could obtain high feeding efficiency, and low water exchange was used per production.

However, increased levels of nutrients and sediment in the reservoir may create problemsin the subsequent crops. This needs to be further studied regarding the effects of the long term accumulation on the shrimp production.

The problem of excessive water salinity in this farm was less significant since it was located in the low salinity area, which had both saline water and fresh water supplies. To operate this system in the areas where the water sources come from the sea, the farms should have a reservoir to keep low salinity water during the rainy season in order to maintain water salinity in the ponds during dry season.

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