A yearly dataset, in which the home-made feed, crop residue and excreta inputs were averaged on kg N ha^{-1} day^{-1} basis, was used for the single regression analyses. From an initial dataset from 9 ponds for 3 consecutive annual production cycles, 24 data points were involved in the models because 3 pond-year combinations with an excessively high home-made feed input level were excluded. A monthly dataset was used for the multiple regression analyses (24 pond observations × 6–10 months). The 24 annual production cycles were considered to be independent of each other because the management of the ponds differed between consecutive years and the pond sediments were removed between crops.

With single regression, the correlation between the dependent variables and crop residue and home-made feed inputs was tested to confirm the effects of the excreta input. With multiple linear regression, the correlation among the independent variables and between the dependent variable and the independent variables were examined. The normality and variance homogeneity were tested plotting residuals against independent and predicted dependent variables. The autocorrelation was tested using the Durbin–Watson statistics. The log-transformation was applied for variables that did not meet the assumptions. The multicolinearity was tested assessing tolerance values. Outliers, which exceeded ±2 times the studentized residuals, were removed. The backward stepwise method was used to select variables (Hair et al., 1998). The criteria used in the process of selecting representative models were based on (in order of importance): (1) the significance of the effect of independent variables in the model ($P < 0.05$), (2) the minimum coefficient of determination (adjusted R^2) required for statistical significance with a power of 0.8, (3) the closeness between the coefficients of the intercept value and the mean of the dependent variable, and (4) the rationality of the coefficients of the independent variables obtained in the model (Hulata et al., 1993; Milstein et al., 1993). The validity of the results from the representative models was assessed using non-parametric bootstrapping, which creates a validation sample by sampling with replacement from the original sample.

After selection of the representative models, predictive equations for the dependent variables were established. The effects on the dependent variables of excreta input levels equal to 0–5 kg N ha^{-1} day^{-1} were assessed, assuming that other independent variables in the respective equations were constant at mean values.

3. Results

3.1. The effects of independent variables

The N inputs from the excreta were closely correlated to the combined N inputs from total food and inorganic fertilizers (Fig. 1). The excreta input, of which pig manure and urine shared 91%, contributed to on average 75% of the total N inputs.

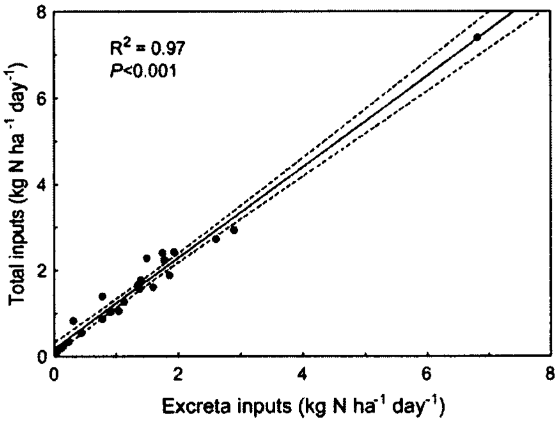

Fig. 1. The relationship between the nitrogen inputs from excreta and the total food inputs (including inorganic fertilizers). Regression line with the confident level at 95%, the coefficient of determination (R^2) and the significant level.

3.1.1. Water dissolved oxygen

The regression models of DO were significant ($P < 0.001$; Table 4). The morning DO concentrations were positively affected by pond width, and negatively by the different types of nutrient inputs ($R^2 = 0.28$). The result of the afternoon DO model was similar to that of the morning DO, but chlorophyll-*a* and afternoon DO levels were positively correlated, while there was no significant impact of crop residue addition ($R^2 = 0.41$). These results show that wider ponds, where the shading by canopies of fruit trees grown on adjacent pond dikes was less, received more sunlight during day hours for photosynthesis, and consequently had higher DO concentrations at early morning and afternoon. In contrast, applying excessive amounts of food to the pond, particularly excreta, resulted in more decomposition and reduced morning and afternoon DO concentrations. The beta coefficients indicate that excreta-nutrient input levels accounted for most of the variability of morning DO levels, whereas chlorophyll-*a* concentrations explained most of the afternoon DO variability.

3.1.2. Water exchange

Water exchange rates were significantly affected by the agro-ecological sites, the technological interventions, pond width, home-made feed and excreta input levels ($P < 0.001$, $R^2 = 0.66$; Table 4). Farmers practiced higher water exchange rates in ponds located in the rice-dominated areas or in ponds receiving higher input levels of excreta. The contrary occurred in ponds where technological interventions proposed in the second and third years were applied, or in wider ponds receiving higher home-made feed input levels. The beta coefficients indicate that the excreta input

Table 4
Results of multiple regression models of dissolved oxygen (DO) concentrations and water exchange rate

Independent variables and parameters	Morning DO [$\log_{10}(y+1)$]			Afternoon DO			Water exchange		
	b	S.E.	Beta	*b*	S.E.	Beta	*b*	S.E.	Beta
Independent variables									
Agro-ecology							6.04	1.01	0.31***
Intervention							−7.62	0.82	−0.39***
Pond width	0.002	0.001	0.21**	0.06	0.01	0.32***	−0.16	0.05	−0.15**
Home-made feed (log)[a]	−0.16	0.05	−0.22**	−1.67	0.75	−0.14*	−3.39	0.65	−0.23***
Crop residue	−0.30	0.11	−0.18**	−2.11	1.60	−0.07	6.40	6.78	0.04
Excreta (log)[a]	−0.19	0.02	−0.52***	−1.90	0.34	−0.32***	1.34	0.12	0.48***
Chlorophyll-*a*				0.01	0.001	0.50***			
Intercept	0.34	0.01		2.72	0.19		7.16	0.81	

Regression coefficient (*b*) with standard error (S.E.) and standardized coefficient (beta). Significance of the independent variables: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

[a] Log transformation was applied to the models morning and afternoon DO only.

level accounted for most of the variability in pond water exchange rates.

3.1.3. Nutrient discharge

The regression models of pond COD, N, P and TSS discharges showed similar results ($P < 0.001$; $R^2 = 0.63$ for COD, 0.46 for N and 0.69 for P and TSS; Table 5). The amounts of COD, N, P and TSS discharged through the outflow water were significantly affected by the agro-ecological sites, the technological interventions, excreta input levels and pond width. Higher discharges occurred in ponds located in the rice-dominated areas receiving more excreta. For all sites, lower discharges occurred in wider ponds or ponds where technological interventions were applied. In addition, lower COD and TSS discharges occurred in ponds receiving home-made feed inputs. The beta coefficients indicate that excreta accounted for most of the variability of COD, N, P and TSS discharges.

3.1.4. Fish yields

The excreta input to the pond had a strong effect on fish yield ($R^2 = 0.74$; Fig. 2). The lowest yield was about 350 kg ha^{-1} year^{-1} in ponds receiving little excreta (A1 and I2). The highest yield was about 8300 kg ha^{-1} year^{-1} corresponding to the highest excreta input level (I1). Fish yield increased linearly with excreta input between 0 and 3 kg N ha^{-1} day^{-1}. The increase in fish yield was smaller at higher than at low N input levels.

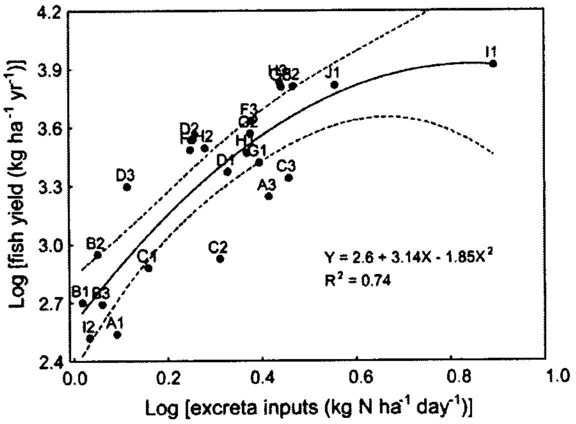

Fig. 2. The relationship between fish yields [$\log_{10}(y)$] and excreta inputs [$\log_{10}(x+1)$] across the ponds monitored for three years. Regression line with the confident level at 95%, the regression equation and the coefficient of determination (R^2). For each point, the nearby letter indicates the pond and the number indicates the year.

Table 5
Results of multiple regression models for pond effluent discharges (COD, N, P and TSS)

Independent variables and parameters	COD			N [$\log_{10}(y+1)$]			P [$\log_{10}(y+1)$]			TSS		
	b	S.E.	Beta	*b*	S.E.	Beta	*b*	S.E.	Beta	*b*	S.E.	Beta
Independent variables												
Intervention	−2.80	0.52	−0.25***	−0.10	0.03	−0.20**	−0.03	0.01	−0.10*	−44.80	8.05	−0.24***
Agro-ecology	3.85	0.63	0.35***	0.16	0.04	0.32***	0.04	0.01	0.16**	78.90	9.70	0.42***
Pond width	−0.07	0.03	−0.11*	−0.004	0.002	−0.15*	−0.002	0.001	−0.14**	−2.04	0.52	−0.18***
Home-made feed	−1.35	0.40	−0.16**	0.06	0.11	0.03	0.001	0.001	−0.001	−30.60	6.23	−0.21***
Crop residue	−7.47	4.26	−0.08	0.26	0.24	0.06	0.03	0.09	0.02	−81.80	66.65	−0.05
Excreta (log)[a]	0.87	0.08	0.54***	0.41	0.06	0.46***	0.04	0.002	0.78***	15.22	1.26	0.54***
Intercept	1.90	0.50		0.12	0.03		0.01	0.01		36.18	7.77	

Regression coefficient (*b*) with standard error (S.E.) and standardized coefficient (beta). Significance of the independent variables: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

[a] Log transformation was applied to the model N discharge only.

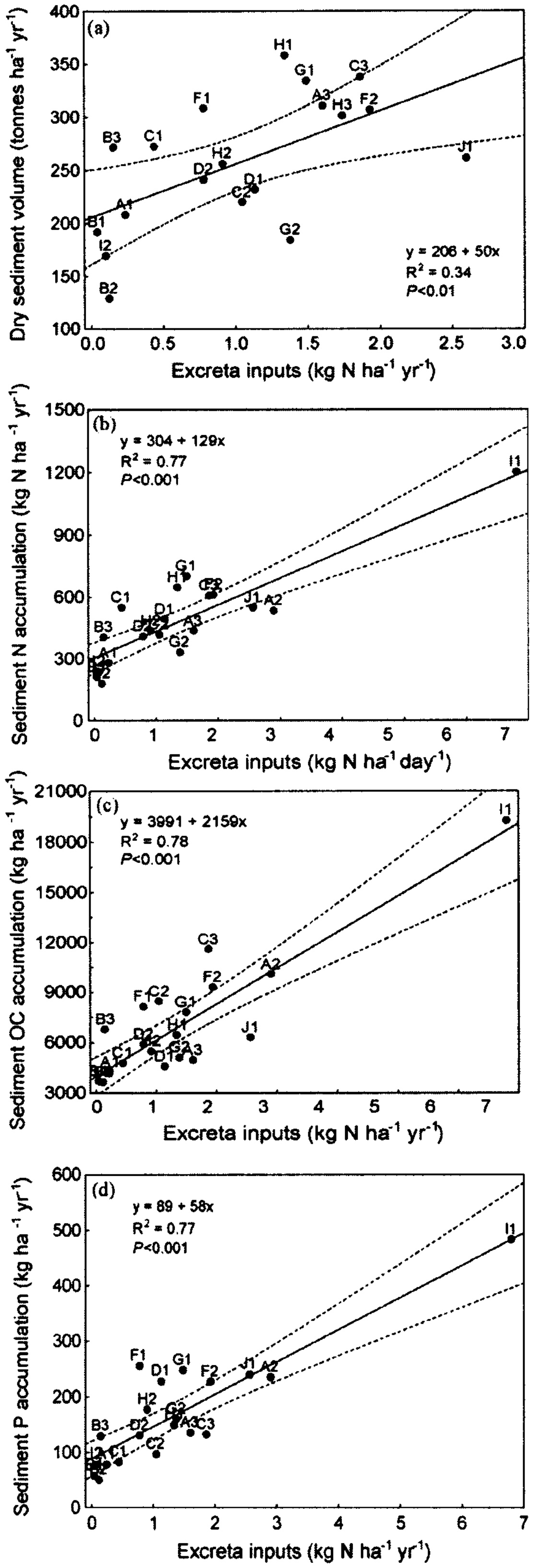

Fig. 3. The relationship between sediment accumulation and excreta inputs across the ponds monitored during the three years: (a) dry sediments, (b) sediment nitrogen (N), (c) organic carbon (OC), and (d) phosphorus (P). Regression line with the confident level at 95%, the regression equation, the coefficient of determination (R^2) and the significant level. For each point, the nearby letter indicates the pond and the number indicates the year.

3.1.5. Sediment nutrient accumulation

The total volume of sediments and the accumulation of N, OC and P in the sediments linearly increased with the amount of excreta applied (Fig. 3). The excreta input explained 34% of the total variance of the total sediment accumulation and 77–78% of the accumulation of N, OC and P.

3.2. Predictive effects of different excreta input levels

The effects of excreta application in the pond were predicted using regression equations established from the various single and multiple regression models presented in Figs. 2 and 3, and Tables 4 and 5. To predict the effects of different excreta input levels, it was assumed that the other predictors included in the equations were constant at their mean values (given in Table 3).

The effects of the excreta application were calculated with input levels set at 0–5 kg N ha^{-1} day^{-1} (Table 6). Increasing the excreta input from 0 to 5 kg N ha^{-1} day^{-1}, the water DO concentrations decrease from 1.2 mg l^{-1} in the early morning and 3.8 mg l^{-1} in the afternoon to 0.5 and 3.0 mg l^{-1}, respectively, suggesting suboptimal levels of water DO for fish growth in excreta-fed pond systems. The daily water exchange increases from 4% without excreta input to 11% of the pond volume with an excreta input of 5 kg N ha^{-1} day^{-1}. The pond needs to be refreshed with "clean" water from canals when the excreta input level increases, which in turn results in more discharge of COD, N, P and TSS. Consequently, the environmental costs also increase.

The sediment volume and the quantities of N, OC and P accumulating in the sediments increases with increasing excreta input. For each additional kg excreta-N ha^{-1} day^{-1} added, 50 tonnes sediments accumulate in the sediment, retaining on average 130 kg N, 2160 kg OC and 58 kg P ha^{-1} year^{-1} and increasing the sediment removal cost by 0.45 million VND ha^{-1} year^{-1}.

Without excreta, 400 kg fish ha^{-1} year^{-1} are produced, resulting in a negative return above variable costs (RAVC). The highest fish yield and RAVC are obtained applying 5 kg N ha^{-1} day^{-1}, 8380 kg fish and 52 million VND ha^{-1} year^{-1}, respectively. For excreta inputs between 0 and 3 kg N ha^{-1} day^{-1} each additional kg N added daily increases the fish yield on the average by 2100 kg and the RAVC by 17 million VND ha^{-1} year^{-1}. In the input range between 3 and 5 kg N ha^{-1} the fish yield increases 900 kg and the RAVC 7 million VND ha^{-1} year^{-1} per additional kg N added daily. If the environmental cost is included, fish farming only becomes profitable at an excreta input of 2 kg N ha^{-1} day^{-1}, and the highest return above variable

Table 6
Predictive impacts of the excreta use in the pond of the IAA-system in the Mekong delta

Indicators	Excreta inputs (kg N ha^{-1} day^{-1})					
	0	1	2	3	4	5
Water parameters						
Morning DO (mg l^{-1})	1.15	0.88	0.74	0.65	0.58	0.53
Afternoon DO (mg l^{-1})	3.76	3.46	3.29	3.16	3.06	2.98
Water exchange rates (% volume day^{-1})	4.3	5.7	7.0	8.3	9.7	11.0
Discharge of effluents (kg ha^{-1} $year^{-1}$)						
Chemical oxygen demand	597	889	1181	1473	1765	2057
Nitrogen	120	279	396	491	573	645
Phosphorus	0	35	73	116	162	213
Total suspended solids	11,426	16,982	22,537	28,092	33,647	39,203
Fish yields (kg ha^{-1} $year^{-1}$)	398	2386	4754	6605	7779	8379
Sediment nutrient accumulation						
Total sediment volume (tonnes ha^{-1} $year^{-1}$)	206	256	306	356	406	456
Nitrogen (kg ha^{-1} $year^{-1}$)	304	433	562	691	820	949
Organic carbon (kg ha^{-1} $year^{-1}$)	3991	6150	8309	10,468	12,627	14,786
Phosphorus (kg ha^{-1} $year^{-1}$)	89	147	205	263	321	379
Economic parameters (million VND ha^{-1} $year^{-1}$)						
Pond sediment removal cost	1.9	2.3	2.8	3.2	3.7	4.1
Environmental cost	3.5	5.3	7.0	8.7	10.4	12.2
Return above variable costs (RAVC)[a]	−14.3	2.3	22.2	37.7	47.3	52.0
N use efficiency						
Nitrogen recovered in fish (%)[b]		12.6	12.6	11.7	10.3	8.9
Nitrogen accumulating in sediments (%)[c]		118.6	77.0	63.1	56.2	52.0

[a] RAVC = [(yield × 8600 − total sediment volume × 9000) × 10^{-6} − 15.91]; 1EUR = 22,000 VND.

[b] Nitrogen recovered in fish (%) = [total N recovered in harvested fish/(total excreta N inputs)] × 100. Assuming that 21.5% of the fresh fish is dry weight, and that 9% of the dry weight of fish is N.

[c] Nitrogen accumulating in sediments (%) = [total N accumulating in sediment/(total excreta N inputs)] × 100.

costs is 40 million VND ha^{-1} $year^{-1}$ achieved at input of 5 kg N ha^{-1} day^{-1} (Table 6).

At all excreta input levels, more nutrients accumulate in the sediments than are retained in fish biomass. The fractions of input excreta-N accumulating in sediment or retained in fish biomass, however, decrease with increasing input level. In consequence, relatively more nutrients are discharged at the higher input levels.

4. Discussions

The parameters DO, water exchange, effluent discharge, nutrient inputs and pond width are interrelated. High nutrient input levels stimulate natural food webs, generating considerable quantities of phytoplankton, zooplankton and benthic organisms, which stimulate fish production. A considerable fraction of the pond nutrient inputs settles directly and is complemented with organic matter from plankton and excrements produced by herbivorous and omnivorous fish species. The organic matter decay lowers DO levels, which farmers restore by replacing pond water with canal water. The higher the nutrient input levels, the higher the flushing rates applied. Such an intensive system, extended over a large area, is bound to create trouble due to the excessive nutrient discharges to the network of interconnected canals.

In fruit-based narrow ditches, photosynthesis is limited by shading produced by fruit tree canopies bordering ditches (Nhan et al., 2006). Moreover, flushing is not always effective, due to the system of connected ditches that constrains water flow, and the fact that one pipe serves both as inlet and outlet. Narrow ditches are more sensitive to DO depletion than wide and less shaded ponds. Hence, a better control of the water quality, including DO levels, is greater in narrow ditches than in larger and wider ponds.

In the second and third year, when farmers were asked to exchange less water and to control the amount of excreta entering the pond, farmers in the rice-dominated areas practiced higher water exchange rates than farmers in the fruit-dominated area. Possible reasons include: (1) water exchange is easier because the rice-dominated areas are less elevated than the fruit-dominated area, and (2) higher stocking densities were used than in the fruit-dominated area, resulting in higher fish biomass requiring higher water exchange rates to maintain favorable DO levels. Low-land rice farmers usually consider aquaculture as an important income generating activity (Luu et al., 2002; Duong et al., 2004). Often the low-DO tolerant *Pangasius* or hybrid catfish are stocked, allowing farmers to give less attention to water exchange and DO control. These farmers rely more on home-made feed and less on excreta, as input levels of home-made feed are easier to control. Further reduction of nutrient discharges from catfish farming is necessary (Nhan et al., 2007).

Large quantities of COD and TSS, including algae, are discharged from ponds where high water exchange rates are practiced, increasing the COD and TSS in the adjacent rivers or canals. In the rice-dominated areas, the average COD and TSS concentrations in canal water were above 10 and 20 mg l^{-1}, respectively (unpublished data), which exceed the Vietnamese quality standards for domestic use of surface waters (TCVN 5942-1995; Trinh, 1997). The canals serve for both, water supply and drainage. Traditional IAA-pond farming systems are considered to be a sustainable model for small-scale farmers in China (Ruddle and Zhong, 1988), northern Vietnam (Luu et al., 2002) and elsewhere in Asia (Prein, 2002). All these authors assume the water and nutrient exchange from ponds to be small. In the Mekong delta, however, there is a surplus of excreta and water allowing farmers to not only get high fish yields, but also discharge large amounts of nutrients. This contrasts with regions like northern Vietnam and northeast Thailand where there is actually a nutrient shortage because of the absence of feedlot pigs or on-farm manure preferably used for crop production (Luu et al., 2002; Pant et al., 2004).

In extensive ponds without external nutrient inputs, fish yields are about 200–800 kg ha^{-1} $year^{-1}$ (Prein, 2002). Zhu et al. (1990) reported an average fish yield of 3700 kg ha^{-1} $year^{-1}$ with an average pig manure input level of 31–48 kg dry matter ha^{-1} day^{-1} (equivalent to 0.9–1.3 kg N ha^{-1} day^{-1}, assuming that 2.8% of the dry matter is N). Lin et al. (1997) reported fish yields between 7300 and 10,950 kg ha^{-1} $year^{-1}$ with a manure input level from 2 to 4 kg N ha^{-1} day^{-1}. A maximum yield in the range of 10,950–12,775 kg ha^{-1} $year^{-1}$ can be achieved (Schroeder, 1987). A fish pond can mineralize up to 200 kg manure ha^{-1} day^{-1} (Schroeder, 1980), equivalent to 5.6 kg N ha^{-1} day^{-1} (assuming a dry manure N content of 2.8%). In the present study, excreta input levels were mostly below 3 kg N ha^{-1} day^{-1} and the yields achieved were sub-maximal. A possible explanation is that the yields reported in the previous studies were obtained from on-station experimental ponds while those in the present study were predicted from farmer-managed ponds. Moreover, ditches in the fruit-dominated area had lower yields, due to shading by the dense canopies of the fruit trees (ponds A1, A3, C2 and C3 in Fig. 2).

To produce 1 kg of fish, Edwards (1993) considers that a manure input of 103–133 g N is required while Fang et al. (1986) and Zhu et al. (1990) estimated that about 5.2–8.3 kg dry pig manure are required. In the present study, it was estimated that to produce 1 kg of fresh fish about 5.4–7.8 kg dry waste was required, equivalent to 151–219 g N (if dry manure N content is 2.8%). Most likely, the high N input levels in the Mekong delta waters are due to the high flushing rates applied in the ponds. By a better control of nutrient input levels in ponds, the discharge from nutrients could be reduced to the aforementioned level by Edwards (1993). However, whether this is a priority for farmers within the many agricultural activities with IAA-farming is not certain, at least in the short run.

Ponds act as a nutrient trap (Avnimelech and Lacher, 1979; Boyd, 1985). In the present study, large amount of organic carbon accumulated in the sediments because the excreta applied contained a large fraction of easily settleable carbon-rich organic particles (Jimenez-Montealegre et al., 2002). Similarly, fractions of the N-inputs accumulating in the sediments were reported by Edwards (1993), Acosta-Nassar et al. (1994) and Green and Boyd (1995). The percentage of applied N that accumulated in the sediments decreased with higher input levels because higher flushing rates were applied. The mineralization rate of nutrient inputs was faster when their combined amounts were small, because the DO concentrations were then higher. N fixation and N volatilization were not considered in the present study. These processes are also affected by the type, quality and quantity of nutrient inputs and more research especially in the qualitative and quantitative aspects of manures is needed.

In the Mekong delta, resource-poor farmers adopt excreta-fed aquaculture to improve their diets or to generate additional income (Nhan et al., 2007). Through excreta-fed pond culture the potential nutrient load from human and livestock excreta to surface waters was reduced by 55–65%, compared to the direct discharge of the excreta without the pond culture. However, in the long-run the system may not be sustainable, considering that many more farmers might take up excreta-fed aquaculture.

5. Conclusions

This paper demonstrates the economic interest of excreta-fed fish culture as part of IAA-farming in the Mekong delta. It calculates that a certain level of feed combined with a minimum frequency of refreshing the pond water, gives maximum returns of fish harvest. Economic and environmental interests however conflict in this farming system. The farming practice is presently economically viable, but in the long run, such an intensive widely adopted system is bound to create trouble due to the excessive discharges of nutrient. The challenge is to further reduce nutrient discharges by reducing water exchange rates while maintaining high fish production and profitability. An additional challenge is to use efficiently the nutrients that accumulate in pond sediments.

The participatory technology development approach created effective connections between stakeholders, allowing spreading the technology while raising awareness of the benefits and problems involved. The multiple regression analysis appears useful to improve nutrient management of ponds within IAA-farming systems. Further on-station research is needed to work out optimal fish species combinations and densities for excreta-fed pond culture.

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