The role of a fish pond in optimizing nutrient flows in integrated agriculture-aquaculture farming systems

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Dit onderzoek is uitgevoerd binnen de onderzoeksschool Wageningen Institute of Animal Sciences (WIAS)

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. dr. M.J.Kropff,
in het openbaar te verdedigen
op woensdag 3 oktober 2007
des namiddags te vier uur in de Aula

Nhan, D.K., 2007. The role of a fish pond in optimizing nutrient flows in integrated agriculture-aquaculture farming systems.
PhD Thesis, Wageningen University,
The Netherlands

ISBN: 978-90-8504-739-1

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Chapter 1

General introduction

1. Global aquaculture production and food security

Due to population growth, food security in developing countries has become increasingly under pressure. The 1996 World Food Summit pledged to halve the number of undernourished to 410 million by 2015. The UN Millennium Development Goals (September 2000) also promised a similar reduction in the number of individuals subsisting on an income < 1 US$ a day. Currently, this group is estimated at 1134 million people, representing 25% of the population in the developing world (Thorpe et al., 2006). The supply of aquatic food contributes significantly to global food security by providing > 15 % of the animal supply. In the world excluding China, human population grew faster than the aquatic food supply, resulting in a decrease in the per capita consumption of 14.6 kg in 1987 to 13.1 kg in 2000 (FAO, 2002). Between 1998 and 2003, the global capture fisheries production fluctuated between 88 - 96 million tonnes year^{-1}, while aquaculture production, excluding seaweeds, increased from 31 to 41 million tonnes (FAO, 2004). It is generally accepted that that the scope for growth in capture fisheries is minimal, hence growth in aquatic food supply will have to be realized through aquaculture (FAO, 2002, 2004). During the past three decades, aquaculture has expanded, diversified and intensified. The Bangkok Declaration and Strategy emphasizes the need for the continuous development of aquaculture towards its full potential, contributing to global and domestic food security, economic growth, trade and improved living standards (NACA and FAO, 2000). Naylor et al. (2000) called for farming low trophic level animals (i.e. herbivores, planktivores and omnivores), for further development of integrated aquaculture systems, and for the promotion of environmentally sound aquaculture as priorities for global aquaculture development.

2. Integrated Agriculture-Aquaculture farming system in the Mekong delta

2.1. Definition

Integrated agriculture-aquaculture (IAA) farming is considered a sustainable farming model for small-scale farming households (Prein, 2002). IAA-farming is known as diversification of agriculture towards nutrient linkages between aquaculture and other terrestrial components within a farm (Little and Muir, 1987). In a broad view, IAA-farming means concurrent or sequential linkages between two or more human activity systems (one or more of which is aquaculture), directly on-site, or indirectly through off-site needs and opportunities, or both (Edwards, 1998). The key characteristic of the IAA-farming is the linking of farm components through interconnected flows of nutrients (Prein, 2002). The objective is to increase the whole farm productivity through maximized synergies and minimized antagonisms between components. The nutrient linkages also include the use of off-farm bio-resources originating from another farm or agro-industrial activities (Little and Muir, 1987; Edwards, 1998). Nutrient linkages contribute to farming intensification, efficient use of natural resources, income generation and environmental protection (Lightfoot et al., 1993; Edwards, 1998; Devendra and Thomas, 2002).

2.2. *Background and problems*

IAA-farming has a long history in various highly populated regions in Asia like China and northern Vietnam (Ruddle and Zhong, 1988; Edwards, 1993; Luu, 2001). In Vietnam, IAA-farming is commonly known as “VAC”. This acronym derives from the Vietnamese for orchard (vuon), pond (ao) and livestock pen (chuong). The farming system was expanded as a food security strategy. Recently, recognizing the importance of the aquaculture sector, the Vietnamese government has implemented a Sustainable Aquaculture for Poverty Alleviation (SAPA) Strategy and Implementation Programme as a part of a wider Hunger Eradication and Poverty Reduction Programme (Luu, 2002). Thus, IAA-farming was promoted as a strategy to improve nutritional standards and income generation of small-scale farming households (Luu et al., 2002; Pekar et al., 2002).

In the Mekong delta, southern Vietnam, rice culture is the traditional activity and the principal source of income for farmers. Alternative land use and livelihood options such as aquaculture, fruit production and livestock are minor components in a farm and are limited to meet subsistence needs. However, further improvement of rice farming to further increase farming is also limited, due to heavy use of agro-chemicals and high external capital investments requirements (Sanh et al., 1998; Berg, 2002). As a result, commercial horticulture has recently expanded rapidly in certain areas but also aquaculture has developed quickly: by 2004 22% of the agricultural space was devoted to aquaculture (Fig. 1 and 2). These changes are strongly supported by the policy of the government. Since 1999, the government has promoted the restructuring and diversification of its agricultural sector, with the goal to reduce the share of rice to the total agricultural output value while increasing the contribution of aquaculture to economic growth. This policy resulted in a growing importance of aquaculture as is reflected in the following figures: in 1999 aquaculture production contributed approximately 29% in 1999 and in 2004 47% to the total fish production in the delta. Between 1999 and 2004, annual aquaculture growth rates were 31% for production and 19% for culture area (GSO, 2003, 2005). The main drivers for this fast growth were shrimp culture in the coastal areas and intensive *Pangasius* culture inland. By 2004 coastal aquaculture was established in about 90% of the suitable sites (GSO, 2005). The export-oriented intensive *Pangasius* culture is characterized by high inputs of off-farm feeds and by high sensitivity to global trade (Hao, 2006). This farming system therefore is economically risky and is a domain of resource-rich households (Naylor et al., 2000). At the same time, techniques for integration of aquaculture within agriculture remain under developed. Rice and fruit producing areas remain under-utilized from an aquaculture point of view. Therefore, the integration of aquaculture with rice, fruit and livestock production appears to be a realizable approach for agricultural diversification but then, the potential of aquaculture in these systems need to be further optimized.

In the Mekong delta, pond aquaculture is a fairly new activity (Rothuis, 1998; Pekar et al., 2002). In the freshwater region, most farmers have a pond near the homestead. The pond culture has become common since the 1980s due to the decline of wild aquatic resources (Sanh et al., 1998). Many farmers have diversified their existing production into IAA-farming systems, shifting gradually from subsistence- to commercially-oriented. Farmers however consider pond farming a secondary activity to crop or livestock production (Pekar et al., 2002). IAA-farming has been promoted through both mass organizations such as the Vietnam Gardening Association and Government Agricultural Extension Agencies. Efforts focused on aquaculture technology of high-valued aquatic species relying on external feed inputs with the goal to improve productivity and profitability. The key essence of IAA-farming, nutrient linkages among farm components and the overall benefit of the whole system, has not received much attention.

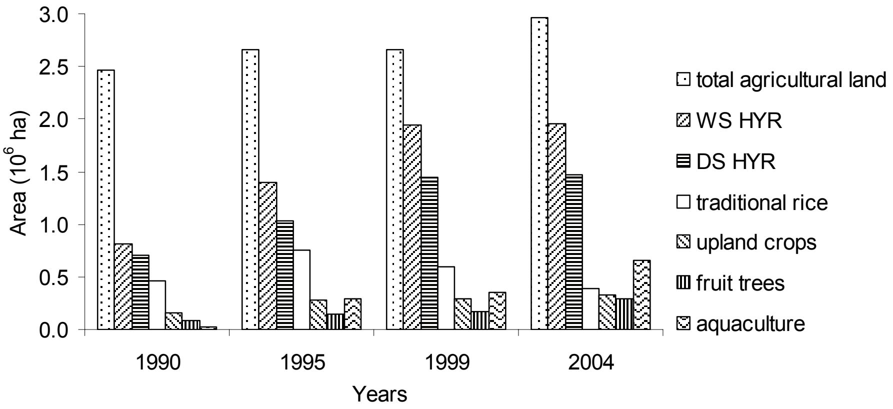

Figure 1. Changes in land use in the Mekong delta between 1990 and 2004. Total agricultural land was calculated as the surface area while areas devoted to rice, upland crops, fruit and aquaculture were based on farming areas. In rice farming areas, 2 or 3 crops of rice are practiced per year (with WS and DS HYR or traditional rice crops). DS (dry season), WS (wet season), HYR (high yielding rice) (reproduced from CSO, 2002; GSO, 2005).

Improved nutrient management of the pond is necessary to further optimize IAA-system and to increase its sustainability. The pond acts as a nutrient trap. In on-station experimental or commercial ponds, harvested fish recover approximately 11-27% nitrogen (N), 26-65% organic carbon (OC) and 30-32% phosphorus (P) of the total nutrient inputs in intensive, and 5-25% N, 2% OC and 5-18% P in semi-intensive ponds; the remaining portions of the nutrients mostly accumulates in pond sediments, respectively (Avnimelech and Lacher, 1979; Sinha et al., 1980; Boyd, 1985; Edwards, 1993; Acosta-Nassar et al., 1994; Green and Boyd, 1995a). If this occurs in IAA-ponds, a better pond management and efficient use of accumulated sediments could give dual benefits. Besides the aquatic crop, the large amounts of nutrients accumulating in the sediments can fertilize terrestrial crops, which might further improve income of farming households. Unfortunately, quantitative information on nutrient accumulation in the IAA-pond is still inadequate.

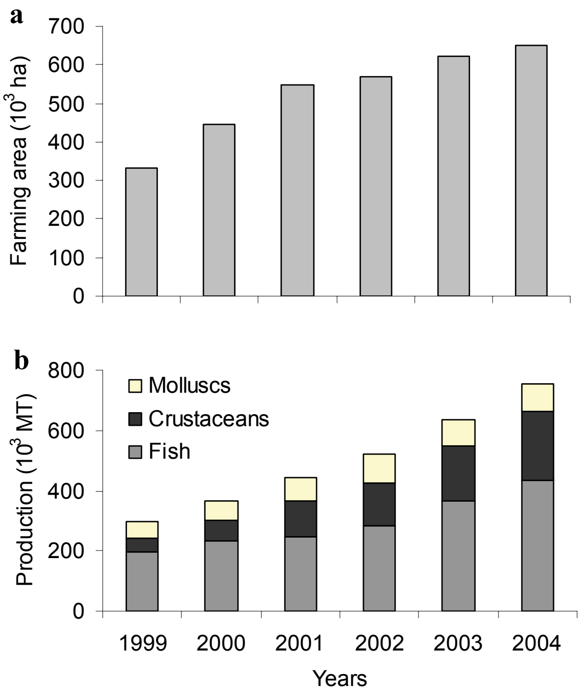

Figure 2. Aquaculture development in the Mekong delta: (a) total farming areas (10^3 ha), and (b) total production (10^3 MT) by major species groups (reproduced from GSO, 2004, 2005).

3. Research approach

Development of sustainable agricultural systems need participatory approaches (Edwards et al., 1993; Edwards, 1998; Stür et al., 2002). In the Mekong delta, agricultural extension agencies have tended to promote a rather standardized IAA-system for the region in a “one-solution-fit-all” or “conventional, linear” approach (Stür et al., 2002). IAA-farming however is diverse. The extent and nature of integrations among components within IAA-systems strongly depend on the bio-physical and socio-economic settings, and on the goals of IAA-farming households (Lo, 1996; Devendra and Thomas, 2002; Pant et al., 2004, 2005). Understanding pond nutrient recycling for optimized IAA-system should be based on on-farm research to embed interrelated variables of farmers' contexts. The Participatory Learning in Action (PLA) approach is a suitable technique for this purpose. It contains six phases: (1) expert consultation and literature reviews, (2) formulation of problems and identification of key research and development issues, (3) analysis of interactions among household's conditions and IAA-farming performance, (4) on-farm monitoring of pond nutrient flows, (5) on-farm technology interventions and (6) evaluating, sharing and dissemination of research results, and proposing further improvements (Little et al., 2007a). The approach involves farmers, extension workers, policy makers, agro-traders and researchers in the study process to produce not only the new technology, but also institutional linkages and technical support that are better geared towards farmers' needs.

The optimization strategies of the IAA-pond consider several variables interacting dynamically. Some variables are uncontrollable (e.g. weather variables) while others depend on interactions among IAA-components and farmers' decisions (e.g. pond nutrient inputs). Furthermore, the output of the pond optimization is multiple, including nutrient recycling and accumulation, nutrient and water use efficiency, and environmental sustainability rather than only aquatic production or pond profitability. To analyze simultaneous interactions between numerous parameters involved, multivariate analysis techniques could be useful (Pauly and Hopkins, 1983; Prein et al., 1993; Hair et al., 1998).

4. Objective, hypothesis and the overview of the thesis

The overall objective of the thesis is to improve the nutrient use efficiency in IAA-systems in the Mekong delta focusing on water and nutrient flows in ponds. It was hypothesized that optimization of integration between the pond and other IAA-components is the key to sustainable IAA-system development in the Mekong delta. To achieve this, pond nutrient management need to be improved first. Better management practices of the pond might differ among agro-ecologies and livelihood options of IAA-households.

This thesis presents the current status of IAA-farming in the Mekong delta thereby emphasizing on the role of the pond. It identifies problems and suggests promising strategies for further improving nutrient management practices of the pond in IAA-systems. The presented visions originated from results obtained from participatory community appraisals followed by participatory on-farm monitoring and evaluating with farmers and local stakeholders. Based on information obtained from the participatory community appraisals, Chapter 2 deals with the current status of the IAA-farming. Factors influencing the adoption of IAA-farming by farmers, major IAA-systems and different roles of the pond were identified. Based on data collected from the participatory on-farm monitoring on flows of pond water and nutrient (nitrogen, organic carbon and phosphorus), chapter 3 describes relationships between food inputs, water quality and nutrient accumulation in the sediments, and identifies three indicative IAA-pond systems using multivariate analysis techniques. Subsequently, chapter 4 analyses water and nutrient budgets in the ponds of the identified IAA-systems. The results in chapters 3 and 4 revealed weaknesses of pond nutrient management and nutrient linkages between the pond and the other IAA-components, and suggested improvements in pond nutrient management for further optimizing IAA-systems. Based on data collected from the farm monitoring for three years, chapter 5 analyses economic and nutrient discharge tradeoffs of the use of livestock and human excreta for IAA-pond farming, and suggests possible solutions to optimize positive benefits with minimal negative environmental impacts. Finally, chapter 6 integrates major findings from the previous chapters and gives practical recommendations for sustainable development of IAA-systems in the Mekong delta.

Chapter 2

Integrated freshwater aquaculture, crop and livestock production in the Mekong Delta, Vietnam: determinants and the role of the pond

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Agricultural Systems 94 (2007): 445-458

Abstract

Promotion of integrated aquaculture with agriculture, including crops and livestock (IAA-farming), requires consideration of both bio-physical and socio-economic contexts. The major factors influencing the adoption of IAA-farming by households at three sites in the Mekong delta were identified. Special attention was given to the multiple roles ponds play in IAA-farming systems. Information was collected through semi-structured interviews and discussions with focus groups and key individuals. Data were analyzed using multivariate factor analysis, analysis of variance or participatory ranking methods. Three major IAA-systems were identified: (1) low-input fish farming integrated with intensive fruit production (system 1), (2) medium-input fish farming integrated with less intensive fruit production (system 2), and (3) high-input fish farming integrated with less intensive fruit production (system 3). System 1 was commonly practiced in a rural fruit-dominated area with fertile soils, while systems 2 and 3 were more evident in peri-urban rice-dominated areas with less fertile soils. In the study area, only 6% of poor farmers adopted IAA-farming, while this was 42% for intermediate and 60% for rich households. Richer farmers tended to intensify fish farming and seek a more commercial orientation. The major factors why farmers did not start aquaculture were the inappropriateness of technology and lack of capital, insufficient land holding, poor access to extension services, limited farm management, and through a fear of conflicts associated with pesticide use on crops. The main motivations for practicing IAA-farming included increased income and food for home consumption from the available farm resources while reducing environmental impacts. Further improvements to IAA-systems can be realized by strengthening nutrient recycling between different IAA-system components while enhancing farming output and safeguarding the environment.

Keywords: Integrated Agriculture-Aquaculture; Participatory approach; Factor analysis; Nutrient recycling; Vietnam

1. Introduction

In the Mekong delta, agricultural production has been the principal farming activity. Agricultural areas remain under-utilized from an aquaculture point of view. The Vietnamese government have advocated development of aquaculture for economic growth and poverty reduction (Luu, 2002). In this context, stimulating integration between fish, shrimp/prawn, fruit, livestock and rice production on the same farm, further referred to as integrated agriculture-aquaculture (IAA) systems, is expected to contribute to agricultural diversification and enhance its sustainability. Between 1999 and 2004, the growth rate of aquaculture production was fast, due to a gradual intensification of coastal shrimp and *Pangasius* culture inland mainly (chapter 1). There are indications that, however, this growth is not sustainable. Techniques for integration of brackish water aquaculture within agriculture remain undeveloped. In contrast, aquaculture based on freshwater can, in principle, be integrated closely within diversified farming systems.

An important characteristic of IAA-farming is the recycling of nutrients between farm components (Little and Muir, 1987; Prein, 2002). Through nutrient recycling, IAA-farming allows intensification of production and income, while reducing environmental impacts (Edwards, 1998; Costa-Pierce, 2002; Devendra and Thomas, 2002). Intensive export-orientated *Pangasius* culture in both cages and ponds is characterized by large nutrient flows supported by the use of off-farm feeds and water exchange making local nutrient recycling problematic (Beveridge et al., 1997; Phillips, 2002, p. 42; Hao, 2006). Moreover, the industrial scale of the business and its sensitivity to fluctuations in global trade make it risky and the domain of the resource-rich (Naylor et al., 2000). IAA-farming in contrast appears to be a realizable approach for diversification of rice production whereby synergism between on-farm components can be realized and whole system productivity optimized rather than that of individual enterprises (Edwards, 1989; Edwards, 1998). The potential integration of farm components and attainable intensification levels of IAA-systems are in part determined by the bio-physical setting and the farmer's aspirations and decisions (Lo, 1996; Pant et al., 2005). In Vietnam the benefits of traditional integrated agriciculture-aquaculture (the so-called "VAC" in Vietnamese) systems (Luu et al., 2002) have been widely reported but the complementarity of more commercial orchard and fish production systems have yet to be investigated.

In the Mekong delta, freshwater IAA-farming is commonly practiced in the central region, where soil and hydrological conditions are favourable for aquaculture. Development agencies have tended to promote a rather standardized IAA-system for the region in a "conventional, linear" approach (Stür et al., 2002). Within the central zone of the delta, however, different agro-ecologies exist and market opportunities for farming inputs and outputs differ. In particular differences between rural and peri-urban areas are likely and might be expected to impact on optimal forms of IAA. In northeast Thailand Demaine et al. (1999) found that location relative to urban centres was more important than agro-ecology in determining farmer attitudes and any likelihood of intensification. Better market accessibility in peri-urban areas and access to nutrients often stimulates intensification of aquaculture compared to more rural areas (Little and Bunting, 2005), allowing IAA-farming to raise income and to produce cheap food for urban consumers (Edwards, 1998).

The potential benefit of IAA for poorer farming households on the delta is also an issue given the resource dependent nature of aquaculture. Pond-base diversification was found to benefit poorer farmers in Bangladesh (Karim, 2006) but many forms of integrated aquaculture are dominated by resource-rich entrepreneurs in Asia (Little and Edwards, 2003). Edwards et al. (2002) suggested that poor farmers are generally not early adopters of aquaculture technologies, and that aquaculture only becomes an option given certain predisposing conditions. The current profiles and predisposing factors of IAA for different locations and households of different socio-economic level are therefore investigated in this study to inform more contextualized approaches to its promotion.

2. Materials and methods

2.1. Study framework

The present study, carried out in 2002, investigated IAA-farming systems in the central region of the Mekong delta at community and household level considering a range of bio-physical and socio-economic settings. Three sub-areas were identified within the target areas, based on secondary data (i.e. maps, statistical data and literature) and information obtained during reconnaissance visits; one study site was selected in each sub-area (Fig. 1). At each study site, one indicative hamlet was selected, based on village statistics and participatory mapping in respect with population density (intermediate level), household wealth status (intermediate level), current practices of agriculture (aquaculture, fruit, rice and livestock) and advocacy of local government for IAA-farming. Subsequently, different wealth groups (poor, intermediate and rich) and major IAA-farming systems were identified, applying participatory wealth and farming ranking. This was followed by monitoring IAA-farming practices at household level.

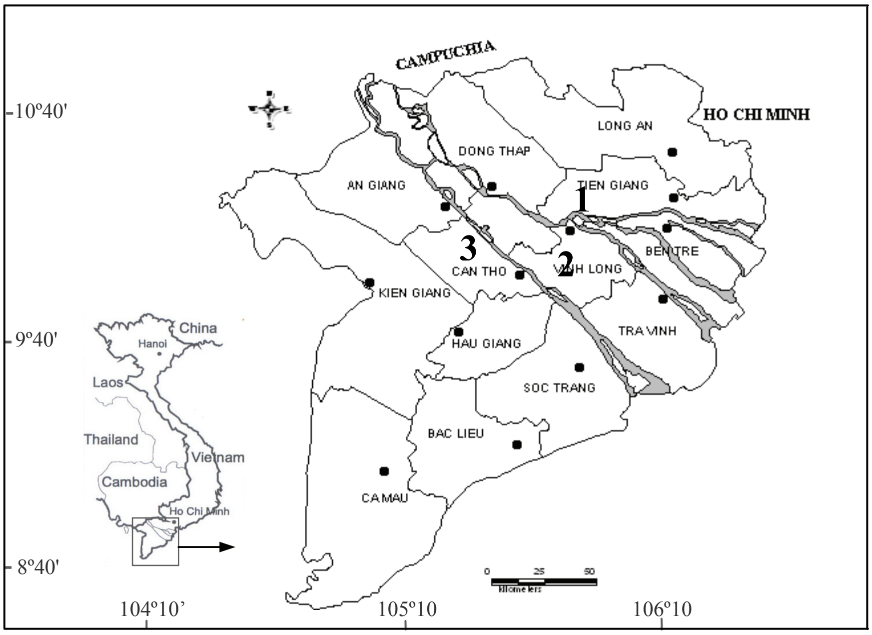

Figure 1. Mekong delta map with locations of the study sites. 1, site 1; 2, site 2; 3, site 3.

Study sites

Site 1, located in Thien Tri village (Cai Be district, Tien Giang province), is a rural area dominated by intensive fruit production (fertilizer input of ≥ 100 kg N ha^{-1} yr^{-1} and fruit production > 5000 kg ha^{-1} yr^{-1}) and fertile alluvial soil. In IAA-farming, farmers grow fish in a system of parallel trenches between fruit orchards. Rice farming is a secondary activity and yields three crops a year.

Site 2, located in Song Phu village (Tam Binh district, Vinh Long province), and site 3, located in Thoi Long village (O Mon district, Can Tho city), are peri-urban areas dominated by rice production and less fertile slightly acid sulphate soils. In IAA-farming, farmers grow fish in ponds adjacent to the homestead or in rice fields. Two rice crops a year are practiced. Fruit production is usually less intensive (fertilizer input of $\leq$ 50 kg N ha^{-1} yr^{-1} and fruit production < 2000 kg ha^{-1} yr^{-1}) than site 1, except the levees along the Bassac river at site 3. Site 2 is located closely to Can Tho city while site 3 is located in between Can Tho and Long Xuyen cities. Therefore, market accessibility is easier at site 3 than at site 2.

The study sites are located within the monsoon tropics with an annual rainfall of 1.4-1.6 m, mainly from May to November (data from provincial weather stations). The annual monsoon flood occurs between August and November. Site 1 has an elevation of 1.0-1.5 m and sites 2 and 3 are 0.5-1.0 m above mean sea level.

Identification of focus groups and IAA-farming systems

Standard participatory rural appraisals tools and methods were used (Mukherjee, 1993; van Veldhuizen et al., 1997). At each site, group semi-structured interviews and discussions with key informants were used at village level to get a general overview of socio-economic context, current farming practices and opportunities for IAA-farming. Key informants were village officials, extension workers, hamlet heads and elderly farmers who knew much about their village. Wealth ranking was carried out in each selected hamlet independently by three key informants (the head of hamlet people's committee and two selected farmers) based on the list of all households obtained from the hamlet administration. The key informants classified each household as poor, intermediate or rich using their own criteria (Table 1; Mukherjee, 1993). In addition, each household was classified by farming activity in terms of intensity of fish culture (low, medium or high input levels; Edwards, 1993), orchard (intensive or less intensive) and livestock (subsistence or commercial) production. Farm households practicing or not practicing pond culture were identified. IAA-adopters were identified as households that stock juveniles in their pond and that had nutrient linkages with other on-farm components (Little and Muir, 1987). Households not practicing aquaculture often also had a pond within their farm, but did not stock hatchery juveniles; typical such ponds used for trapping wild fish. At each site, three groups representing the most frequent combinations of wealth and IAA-farming patterns were selected for subsequent data collection (Table 2). Three IAA-farming systems, considering aquaculture intensity levels, were identified across the sites: (1) low-input, (2) medium-input, and (3) high-input aquaculture. Poor households did not participate as members of focus groups, because very few poor households practiced IAA-farming at all sites.

2.2. Data collection

Reasons why households either did or did not adopt IAA-farming were investigated through semi-structured interview conducted with household head. Based on the results from the wealth and IAA-farming ranking, stratified random sampling was used to select farmers for the interviews at each site (Gomez and Gomez, 1984). At sites 1, 2 and 3, a total of 39, 50 and 40 farmers practicing IAA-farming and 37, 48 and 40 farmers not practicing pond culture, respectively, were interviewed independently. The interviewed farmers were requested to list reasons why they adopted IAA-farming or did not start pond culture, and to score them in order of the importance on a scale from 0 (not important) to 5 (extremely important).

Current practices of and possible improvements to IAA-farming were understood through group discussions with the selected focus groups. Individual household data on farm area devoted to each farming activity were collected through interviewing households within the focus groups. Pond:dike ratios were calculated as the ratio of pond to orchard area. Nutrient linkages between the pond and other farming components were identified through bio-resource flow diagrams (Prein, 2002). The importance of pond nutrient resources and the role of the pond within the IAA-system and to household economy were evaluated by ranking according to farmer's opinions. Possible improvements to the whole IAA-system, including the pond, were discussed. As a validation and verification step, analysed results were presented to and discussed with representatives of the focus groups and other stakeholders at a stakeholder meeting in each hamlet.

Table 1. The criteria used for wealth ranking by key informants at three sites in the Mekong delta[1]

Criteria	Criteria used			Number of rankers using the criterion		
	Poor	Intermediate	Rich	Site 1	Site 2	Site 3
Land holding area (ha)	<0.3	<1.0	>1.0	3	6	6
Type of house	Nippa	Wooden	Wooden or brick	3	6	6
Recreation facilities (TV, video)	None	Yes	Yes	3	6	6
Major sources of household income	Wage labour	Farming or wage labour	Farming and non-farming activities	3	6	6
Transportation facilities	None	Yes	Yes	3	5	5
Farm equipment	None	Pump	Pump, tiller or thresher	2	4	5
Type of farming	Subsistence	Commercial	Commercial	2	4	4
Subsidy from the government	Yes	None	None	2	6	2
Receiving remittance from abroad	None	None	Yes	1	4	3
Educational level of children	Illiterate or elementary	Secondary	Secondary or higher	1	4	3
Contribution to social activities	None	Yes	Yes	0	1	0

[1] Persons doing the wealth ranking are referred to as rankers. In each hamlet or sub-hamlet, three rankers did wealth raking. At sites 2 and 3, due to hamlet size, each selected hamlet was split into two sub-hamlets for the ranking.

Table 2. Different selected focus groups with wealth, aquaculture, fruit and livestock production categories by site. n, group size

Sites	Groups	n	Categories			
			Wealth	Aquaculture systems	Fruit culture systems	Livestock culture systems[1]
1	1	7	Intermediate	Low-input	Intensive	Subsistence
	2	8	Rich	Low-input	Intensive	Subsistence
	3	7	Rich	Medium-input	Intensive	Commercial
2	1	6	Intermediate	Low-input	Less intensive	Subsistence
	2	7	Rich	Medium-input	Less intensive	Commercial
	3	9	Rich	Medium/high -input	Less intensive	Commercial
3	1	7	Intermediate	Low-input	Intensive	Subsistence
	2	8	Rich	Medium-input	Less intensive	Commercial
	3	6	Rich	High -input	Less intensive	Subsistence or commercial

[1] Subsistence = poultry production mainly for home consumption, commercial = pig production

2.3. Data analysis

Multivariate factor analysis was used to analyze cross-relationships between reasons for the adoption IAA-farming or for not starting aquaculture and to identify major underlying factors of those relationships. Two models were established: (1) one for the adoption of IAA-farming and (2) another for not starting aquaculture. The reasons perceived by farmers were considered variables and were included into the respective model. In each model, factors were extracted using principal components method with the eigenvalue ≥ 1. The factors were rotated using the varimax method so that they are independent from each other. Factor loadings about ≥ 0.5 were used for result interpretation (Hair et al., 1998).

Effects on area devoted to each farming activity and pond:dike ratio were analyzed by one-way analysis of variance (ANOVA) for the factor system and two-way ANOVA for the factors site and wealth group. Tukey HST *post hoc* multicomparisons of means were applied at 5% significant level. The ANOVA assumptions were tested applying tests for homogeneity of variances (Hartley's F_{max}, Cochran's C and Bartlett's χ^2) and for normality of residuals (Fry, 1993).

Results from the data analyses, in combination with qualitative information collected during the discussions with the key informants and farmers were used to describe the IAA-systems, to identify the role of the pond, and to suggest possible improvements to each farming systems.

3. Results

3.1. Determinants of IAA-farming adoption

IAA-farming was more common in the peri-urban rice-dominated areas (sites 2 and 3) than in the rural fruit-dominated area (site 1), more common with intermediate and rich farmers than poor farmers, and more commonly associated with low- and medium-input than high-input fish farming systems (Table 3). In the fruit-dominated area, the low-input fish farming system was most important, while in the rice-dominated areas both low- and medium-input systems were most common. The high-input system was practiced mainly at site 3, where farmers could easily access markets for aquaculture inputs and outputs. Poor farmers usually practiced the low-input system, while only rich farmers practiced the high-input system.

Farmers suggested nine reasons why they adopted IAA-farming (Table 4). The factor analysis identified four major groups of interrelated variables. These four factors accounted for 67% of the total variance (Table 4). Factor 1 included positive contributions of government's advocacy, suitability of soil and water, recycling of nutrients, pest control in rice fields, and creation of jobs for family members. Factor 1 accounted for 31% of the total variance, and showed that farmers perceived IAA-farming as a way to increase the use of on-farm resources. Factor 2 accounted for 13 % of the total variance, and reflected income generation through aquaculture. Farmers perceived that fish is a high value commodity within their IAA-system. Factor 3, accounting for 12 % of the total variance, showed that farmers are not indifferent to environmental conservation, indicated by the focus on recycling of livestock or human wastes and less agrochemical use in rice fields. Factor 4, accounting for 11 % of the total variance, showed that improved nutrition is considered an additional advantage of IAA-farming.

Table 3. Percentage of farm households practicing aquaculture by site (1, 2 and 3), wealth group (poor, intermediate and rich) and system (low, medium and high-input)

Items	n	Aquaculture systems			Total
		Low-input	Medium-input	High-input	
By site[1]					
Site 1	349	15.8	4.6	0.0	20.4
Site 2	461	18.2	34.1	2.0	54.3
Site 3	351	12.3	24.8	12.3	49.4
By wealth group					
Poor	184	4.3	1.6	0.0	5.9
Intermediate	569	20.6	19.2	2.1	41.8
Rich	408	14.0	36.3	9.8	60.0
Average by system		15.7	22.4	4.5	42.5

n, the total number of households in each community per site or in each wealth group at three sites. Percentages are always given as a fraction of n.

[1] sites 1 (rural fruit-dominated area), 2 (peri-urban rice-dominated area), 3 (peri-urban rice-dominated area with good market accessibility)

Farmers suggested eight reasons why they did not start pond culture (Table 5). The factor analysis produced four major factors, together accounting for 68% of the total variance (Table 5). Factor 1 accounted for 27 % of the total variance, and reflected that inappropriateness of technology and lack of capital were important reasons not to adopt pond culture as a farming activity. Factor 2, accounting for 17 % of the total variance, showed that either insufficient land holding or poor access to extension was an important constraint. Access to information was not problematic to take up aquaculture for farmers perceiving that their land holding was too small to take up aquaculture. Poor access to extension in contrast was perceived as being a really important constraint for farmers perceiving that small land holding was not a problem. Factor 3, accounting for 13 % of the total variance, reflected limited farm management. Insufficient availability of family labour, distance between house and farm, and poor access to extension service are important constrains to start pond culture. Finally, factor 4, accounting for 11 % of the total variance, suggests that farmers perceived that use of pesticides for rice or fruit production might undermine fish culture.

3.2. Farm components

In the freshwater areas of Mekong delta, a farm usually has three components: (1) the homestead and fruit orchard, (2) the pond, and (3) the rice field. The homestead, the fruit orchard and the pond are usually co-located. Livestock, fruit crops, vegetables and other trees are located close to the residence constituting the "homestead", which rarely exceeds an area of 400 m^2. For IAA-farms, the ANOVAs revealed differences in farm area for each component by site, wealth group or system (Table 6). At the fruit-dominated site 1, farmers had much larger fruit orchards and slightly larger ponds. They also owned smaller rice fields. The pond:dike ratio was lower at the fruit-dominated site than at the rice-dominated sites. The total farm size did not significantly differ among sites. Land holdings of intermediate farmers were considerably smaller than those of rich farmers, and the former had higher pond:dike ratios than the latter. The interaction effect between site and group was not significant for total farm size, but was for homestead and orchard, pond and rice field area. This was also reflected in a significant interaction between site and group for pond:dike ratio. At site 3, rich farmers with the high-input fish farming system had smaller homestead and fruit orchards, but larger rice fields than rich households with a medium-input fish farming system at sites 1 and 2 (Fig. 2a, 2c). At site 1, intermediate farmers residing in a relatively low-lying area with less fertile soils had to excavate larger trenches or ponds to build orchard dikes high enough to reduce the risk of flood. Thus, they had larger ponds than intermediate farmers at sites 2 and 3 (Fig. 2b). This is also indicated by the high pond:dike ratio characteristic of intermediate farmers at site 1 (Fig. 2d).

Table 4. Major factors explaining adoption of IAA-farming among households at three sites in the Mekong delta

Reasons (variables)	Factor 1	Factor 2	Factor 3	Factor 4
Government's advocacy	**0.59**	0.31	-0.23	0.28
Suitability of soil and water	**0.72**	-0.16	0.20	0.00
Recycling of nutrients	**0.73**	-0.21	-0.14	0.12
Pest control in rice fields	**0.63**	0.20	-0.22	0.12
Creation of jobs for family	**0.82**	0.04	0.06	-0.18
Income generation	0.38	**-0.69**	0.13	-0.12
Fish market value	-0.28	**-0.70**	-0.23	0.21
Environmental conservation	-0.07	0.06	**0.90**	0.08
Improved family nutrition	-0.07	0.05	-0.08	**-0.93**
Variance explained (%)	31	13	12	11
Factor interpretation	Increased use of on-farm resources	Income generation	Environmental conservation	Nutrition

Variables with bold values of factor loading were considered in interpretation of the respective factor, n = 129

Production technology and driving factors of IAA-systems

In general, three major IAA-systems were identified: (1) the low-input fish farming integrated with intensive fruit production, (2) the medium-input fish farming integrated with less intensive fruit production, and (3) the high-input fish farming integrated with less intensive fruit production system. System 1 was commonly practiced in the fruit-dominated area. System 2 was more typical of the rice-dominated areas, while system 3 was practiced in the rice-dominated areas with good market accessibility. Figure 3 illustrates the main driving factors determining the dominant farming system.

Table 5. Major factors explaining not practicing aquaculture among households at three sites in the Mekong delta.

Reasons (variables)	Factor 1	Factor 2	Factor 3	Factor 4
Inappropriate technology	**0.87**	0.10	0.02	-0.03
Lack of capital	**0.63**	-0.26	0.29	0.36
Insufficient farm size	0.08	**0.84**	0.23	0.02
Poor access to extension	0.14	**-0.62**	**0.47**	0.08
Lack of family labour	0.21	0.06	**0.77**	-0.05
Farm far from house	-0.03	-0.01	**0.70**	0.14
Poor soil and water quality	-0.35	-0.36	0.41	0.39
Pesticide use for crops	0.10	0.01	0.04	**0.94**
Variance explained (%)	27	17	13	11
Factor interpretation	Inappropriate technology and lack of capital	Insufficient farm area or poor access to extension	Limited farm management	Pesticide use for crops

Variables with bold values of factor loading were considered in interpretation of the respective factor, n = 125.

The low-input fish farming integrated with intensive fruit production system

At site 1, pond culture was introduced in the early 1990s. Farmers grew fish in low input polyculture in narrow and shallow trenches (2-3 m wide, 0.5-0.8 m deep) within the orchards (Table 7). Fish production ranged from 0.5 to 2.0 tons ha^{-1} year^{-1}. Low fish yields were mainly due to the low addition of nutrients and to the shading of the pond by the extended canopy of fruit trees grown on pond embankments. On-farm nutrient resources were the major inputs for the pond (Fig. 4a). Farmers ranked livestock or human excreta and rice by-products as important nutrient sources. However, pig manure was preferentially applied to fruit crops, and rice by-products were mainly used for livestock production.

The system is usually practiced in areas with relatively high elevation and alluvial, nutrient rich, soils favouring fruit production. While farmers focused on fruit production, they paid little attention to aquaculture, which was considered of minor economic importance.

Table 6. Farm area (ha) devoted to different farm components by site (1, 2 and 3), wealth group (intermediate and rich) and system (low, medium and high-input). n, sample size; mean ± SE

Effects[1]	n	Homestead & orchard	Pond	Rice field	Total farm	Pond:dike ratio
Two-way ANOVA significance						
Site		***	*	***	ns	*
Group		***	**	**	***	*
Site x Group		**	**	**	ns	***
Multi-comparisons of means by site[2]						
Site 1	22	0.71 ± 0.09^b	0.29 ± 0.03^b	0.33 ± 0.05^a	1.33 ± 0.10	0.58 ± 0.10^a
Site 2	22	0.40 ± 0.07^a	0.26 ± 0.04^{ab}	0.89 ± 0.10^b	1.55 ± 0.12	0.96 ± 0.11^b
Site 3	21	0.28 ± 0.03^a	0.20 ± 0.03^a	1.10 ± 0.15^b	1.58 ± 0.18	0.73 ±0.07^{ab}
Multi-comparisons of means by wealth group						
Medium	20	0.22 ± 0.03^a	0.19 ± 0.03^a	0.55 ± 0.07^a	0.96 ± 0.06^a	0.89 ± 0.09^b
Rich	45	0.58 ± 0.06^b	0.28 ± 0.02^b	0.86 ± 0.10^b	1.72 ± 0.09^b	0.70 ± 0.07^a
One-way ANOVA significance						
System		ns	ns	**	***	ns
Multi-comparisons of means by system						
Low-input	28	0.40 ± 0.07	0.20 ± 0.03	0.49 ± 0.06^a	1.09 ± 0.07^a	0.72 ± 0.08
Medium-input	28	0.56 ± 0.07	0.28 ± 0.03	0.93 ± 0.12^b	1.77 ± 0.11^b	0.75 ± 0.09
High-input	9	0.33 ± 0.06	0.31 ± 0.06	1.20 ± 0.17^b	1.84 ± 0.25^b	0.99 ± 0.13

[1] ANOVA significance: ns, not significant; *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$. Means with the same superscript in a column per effect do not differ significantly at 5% level.

[2] sites 1 (rural fruit-dominated area), 2 (peri-urban rice-dominated area), 3 (peri-urban rice-dominated area with good market accessibility)

The medium-input fish farming integrated with less intensive fruit production system

At sites 2 and 3, the systems were introduced in the late 1980s and the early 1990s, respectively. Farmers grew fish in polyculture in large or deep ponds (5 – 30 m wide, > 1 m deep) receiving on-farm nutrient resources as the major inputs (Table 7). Fish yields ranged between 2 and 10 tons ha^{-1} year^{-1}. Farmers ranked livestock or human excreta, rice by-products or snails and crabs collected from rice fields as important nutrient sources for fish production (Fig. 4a). However, the availability of the nutrient resources collected from the rice fields was seasonal. Also the availability of livestock excreta as the nutrient input for the pond was highly variable, depending on the status of pig production. In most cases, farmers did not control the waste load to their pond, and managed waste overloading through frequent water exchange.

This system was usually practiced in areas of relatively low elevation, medium or high monsoon flood levels and less fertile soils, where rice production was the major farming component. Commercial pig production, however, is gradually gaining importance, especially since 1999 when the government started to advocate market-oriented agricultural diversification.

The high-input fish farming integrated with less intensive fruit production system

The system was introduced in the mid-1990s. Farmers started growing river catfish or climbing perch (*Anabas testudineus*) with high inputs of off-farm nutrient resources in larger or deeper ponds (> 10 m wide, > 1 m deep). These fish species are highly valued in export (catfish) or local niche markets (*Anabas*). In this system, aquaculture can be considered a stand-alone system because of weak integration between the pond and the other terrestrial components on the farm. Fish production depends mainly on pelleted feed or off-farm by-products (Fig. 4b). On-farm nutrient resources like livestock excreta and crop residues were perceived as less important. For river catfish farming, fish yields ranged between 50 and 200 tons ha^{-1} year^{-1}. Farmers changed pond water daily with an average of 25% volume day^{-1}.

This system is usually practiced in areas with less fertile soil, where rice production was the major farming activity. These farms have excellent market accessibility. Site 3 lies in the peri-urban area of the cities Can Tho and Long Xuyen, where many fish- and feed-processing industries are located. Only rich farmers adopted this farming system, due to high investment costs and technical skill requirements.

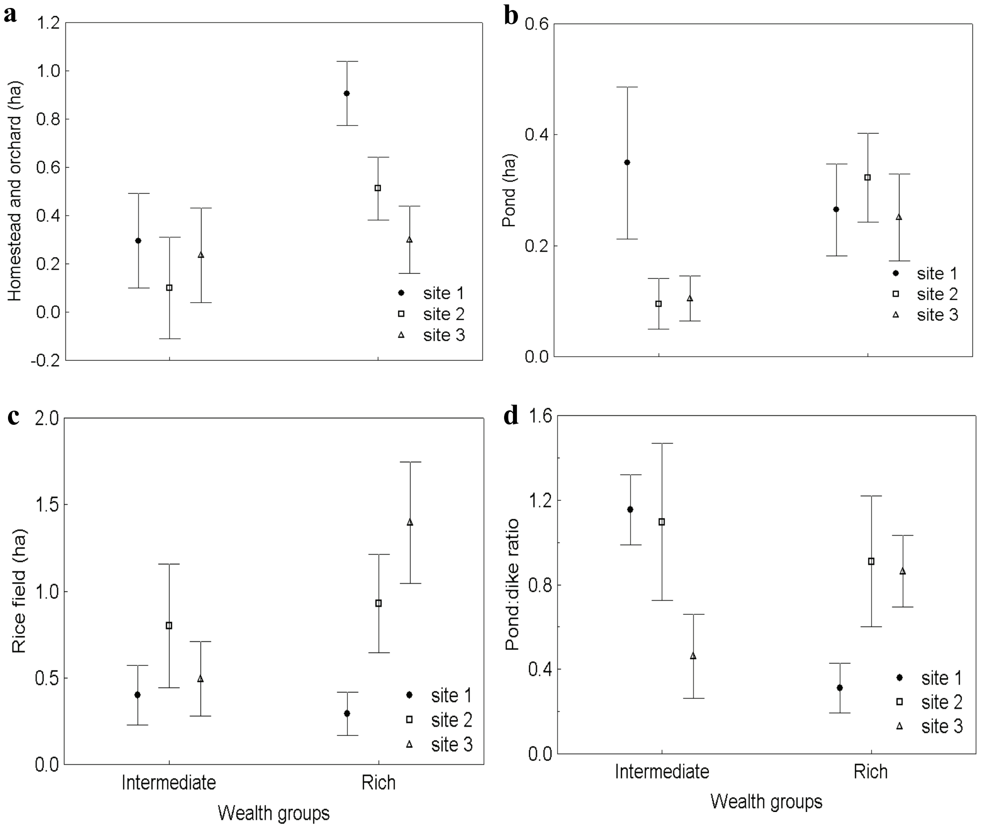

Figure 2. Site and wealth group interactions for area devoted to homestead and orchards (a), pond (b), rice field (c) and for pond:dike ratio (d). Mean ± 0.95 confidence interval.

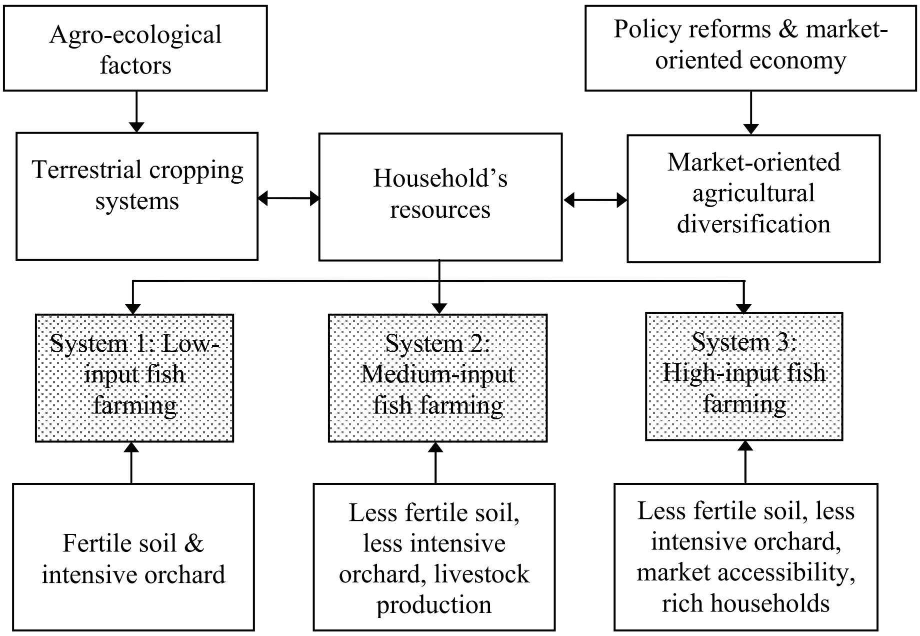

Figure 3. Three integrated fish farming systems and their driving factors.

3.3. The role of the pond

Past uses

In the past, the initial and important purposes of digging ponds or trenches included the need for soil to raise the level of low-lying ground for house construction and for establishing orchard dikes, especially for farmers with low- or medium-input fish farming systems. In addition, farmers used pond water for household purposes and for orchard irrigation. Fish farming was not considered a high priority. In contrast, among farmers engaged in high-input fish farming, fish production was the major goal from the outset, rather than the pond being an outcome of homestead and fruit dike construction.

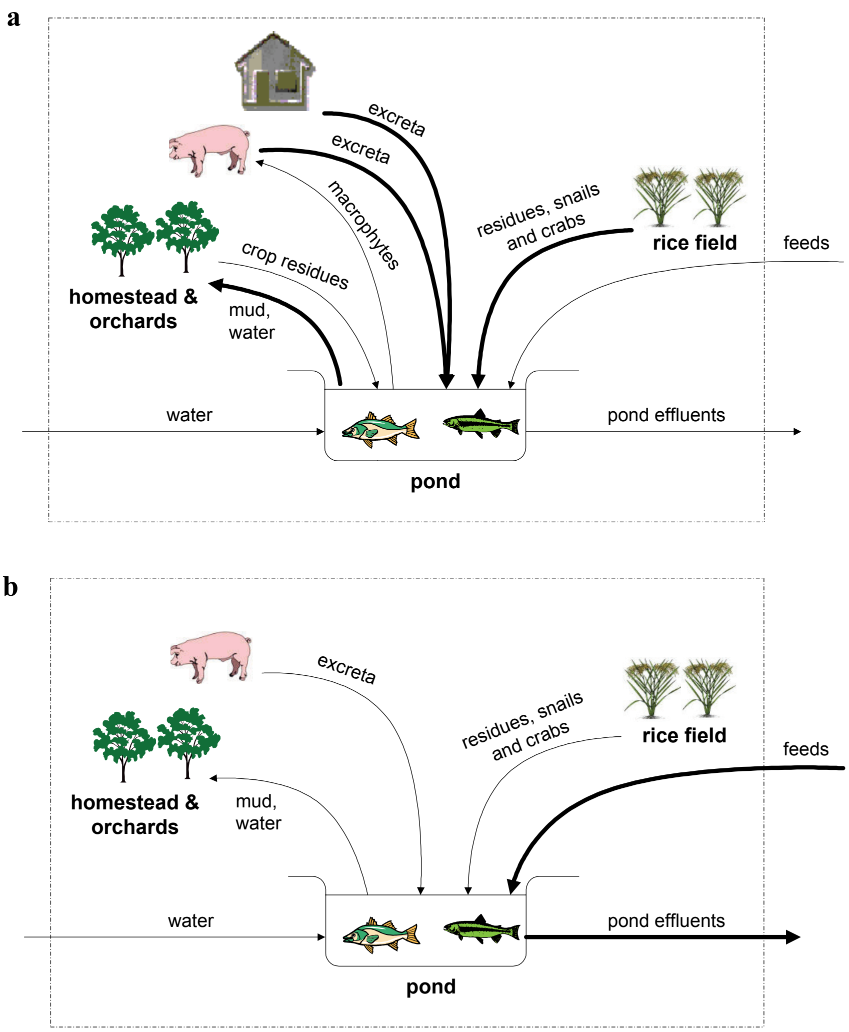

Figure 4. Diagrams of pond nutrient flows: (a) low or medium-input and (b) high-input systems. Thin and thick arrows refer to less important and important sources, respectively. Dotted lines refer to the farm boundary.

Current uses

Current uses of ponds have exceeded the original expectations of most farmers. Fish production has become an important activity in each of the systems studied. In the low-input system, about 70% of the fish produced was used for home consumption (Fig. 5). In the medium and high-input systems, in contrast, fish was primarily a cash crop. Only 30% of the fish produced in the medium-input system and 10% in the high-input system were used for home consumption, while the remaining fractions were sold.

In the low and medium-input systems, in terms of economic value, farmers considered fish as a secondary farm activity. In the high-input fish farming system, aquaculture was a primary activity. In the low-input system, supplying water for crop irrigation and extracting nutrient-rich mud as crop fertilizers were perceived as being most important. In contrast in the high-input system, these factors were considered of minor importance (Fig. 4). In the medium-input system, the pond was currently perceived as being important for crop irrigation and for disposal of animal and human excreta. In the high-input system, large amounts of pond nutrients were discharged with outflow water because high water exchange rates were practiced.

4. Discussion

4.1. Determinants of the adoption and the patterns of IAA-farming

The results of the present study confirm our initial hypothesis that the adoption of aquaculture by farmers and type of integration between farming components is influenced by a mixture of bio-physical and socio-economic factors. This is similar to the situation observed in other Asian countries (Pant et al., 2005; Thapa and Rasul, 2005; Iqbal et al., 2006). The lower levels of adoption observed among poorer households, despite attempts to promote IAA-systems as a way to reduce poverty, relate to a combination of limited availability of human and capital resources (technical and farm management knowledge/skills, small land and capital) and constrained accessibility to extension services. The problem of heavy pesticide uses on surrounding crops (factor 4) perceived by non-adopters appears to illustrate their limited technical knowledge in IAA-system practice although it is likely that use of agrochemicals was lower among adopters (Rothuis et al., 1998; Berg, 2002; the present study). These factors are often characteristic of poor farmers (Minot, 2000; AusAID, 2003; Cramb et al., 2004; Table 1). In contrast, the principal factors why farmers adopted IAA-farming are related to optimization of farm resources for income generation and food supply while positive environmental impacts are considered as an additional advantage. Such a perception is common to better-off farmers (Devendra, 2002a).

Table 7. Major fish species stocked in the different aquaculture systems in the Mekong delta

Species	Aquaculture systems		
	Low-input	Medium-input	High-input
Silver barb (*Barbodes gonionotus*)	+		
Silver carp (*Hypophthalmichthys molitrix*)	+		
Giant gourami (*Osphronemus goramy*)	+	+	
Mrigal (*Cirrhina mrigalla*)	+		
Nile tilapia (*Oreochromis niloticus*)		+	
Kissing gourami (*Helostoma temminckii*)		+	
Common carp (*Cyprinus carpio*)	+	+	
Hybrid catfish (*Clarias macrocephalus* x *C. gariepinus*)		+	
Climbing perch (*Anabas testudineus*)			+
River catfish (*Pangasianodon hypophthalmus*)	+	+	+

Differences in the pattern of IAA-farming are clearly recognisable among the study sites but within each study site most farms also diversified. First, the differences among the sites are in part related to bio-physical characteristics (elevation, soil fertility, pond conditions and crop and livestock farming practices) and farmer's options, including market accessibility. In the fruit-dominated area, fruit production is the major farming activity, and narrow and shallow orchard trenches, which are shaded by fruit canopies, are unfavorable for fish. Thus, farmers prioritized fruit production and gave little attention to fish production. This could explain the reason why at site 1 the low-input fish farming system was common, and the proportion of farmers practicing IAA-farming was lower than that at sites 2 and 3.

Pant et al. (2005) and Thapa and Rasul (2005) found that market accessibility is an important factor for terrestrial crop farming intensification. In the present study, market accessibility and intensity of aquaculture production were related. The good market accessibility in peri-urban areas boosted the intensification of aquaculture; i.e. the shift from medium-input to high-input systems (i.e. site 3). Second, the differences in the pattern of IAA-farming within each site are partly related to the household's available human and capital resources. Richer farmers tended to intensify fish production more.

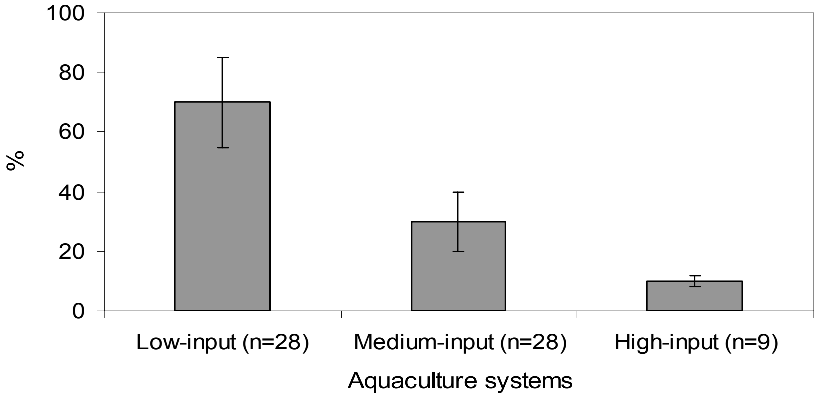

Figure 5. Percentage of fish production used for home consumption by system. n, sample size; error bars in graph represent the standard error of the mean.

In the Mekong delta, aquaculture is a recently introduced activity (Rothuis, 1998; Pekar et al., 2002), and local knowledge on aquaculture is still limited, compared with fruit, rice or livestock production. This can partly explain why only intermediate or rich farmers, with sufficient human and capital resources and strong social connections, ventured into higher input IAA-farming. The results of the present study illustrate that technical knowledge and farm management skills are in themselves not enough, and that socio-economic conditions strongly influence the adoption of IAA-farming. In turn, the pattern of IAA-farming system adopted is largely influenced by the bio-physical settings. Hence, the "conventional, linear" approach used by the development agencies to promote IAA-farming systems, which focuses mainly on technology transfer, giving little attention to the local context, might not be appropriate. It requires personal access to knowledge, technology and production resources to adapt generic advice to the local conditions. In the present study, rich farmers were earlier adopters than poor farmers. Therefore, a package of initial and long-term support including "baskets" of choices of appropriate technologies, credit provision and technical training would be advisable to pull poor farmers into IAA-farming (Edwards, 2000). Several examples show positive impacts of IAA-farming on the livelihoods of the poor in Asia, in terms of improved food supply, employment and income generation (Prein, 2002).

4.2. The role of the pond and possibilities for improving the farming systems

Successful development of IAA-farming needs a systems approach (Edwards, 1998; Naylor et al., 2000; Devendra, 2002b). Accordingly, the pond in the IAA-system should be integrated in such a way that the overall productivity is maximized while nutrient resources are used efficiently. The pond fulfils multiple roles, the benefits being more than fish production alone (Edwards, 1980; Lo, 1996; Prein et al., 1996). In the present study, the role of the pond perceived by farmers differed. The present study shows that farmers practicing the low and medium-input systems were well aware of the benefits of integration in IAA-farming and its potential effects on their livelihoods. In the high-input system, integration between the pond and the terrestrial components was relatively weak, and negative environmental impacts due to pond effluent discharges are an important problem. To strengthen the integration between the pond, other farm components and the environment requires scenario testing in combination with nutrient recycling studies. The latter is of great importance to further develop IAA-systems (Edwards, 1989; Edwards, 1998; Naylor et al., 2000). Suggestions to further strengthen linkage between farming components by system are given below:

The low-input fish farming integrated with intensive fruit production system

While fruit production is well taken care off, little attention is given to the fish component and time availability seems to be a major constraint besides the lack of any specific and appropriate technology. Currently farmers appear attempting to meet subsistence needs and intensification requiring significant additional resources would need them to be able and willing to market quantities surplus to these levels. Karim (2006) found that intensification of fish culture did not lead to greater levels of fish consumption among IAA households in Bangladesh. Appropriate changes in management such as applications of manures or inorganic fertilizers to the pond and adapted pruning of fruit tress were suggested as promising improvements. Ponds are nutrient traps as a high proportion of added nutrients accumulate in the sediment (Edwards, 1993; Green and Boyd, 1995a; Hargreaves, 1998). Thus, any improved productivity of the pond could deliver dual benefits: first more fish produced and larger amounts of nutrients stored in ponds and later to fertilize fruit crops grown on adjacent orchard dikes. If fish production can meet subsistence needs without intensification, reducing costs and risks to fruit production as a result of pond culture is an important benefit for farmers in fruit-dominated areas, particularly for poor households.

The medium-input fish farming integrated with less intensive fruit production system

The temporal availability of nutrients collected from rice fields and livestock excreta do not match well with the nutrient requirements of ponds. These temporal mismatches constrain fish production, due to either lack of nutrients or overload of nutrients. Farmers need to supplement nutrients in short supply or to fertilize their ponds during periods of insufficient manure supply. According to Prein (2002), a key to the successful operation of the IAA-farming is to organize the system in such a way that residues from each component are available at the right time in appropriate quantities and quality. In reality, however, this could be difficult for farmers because they have to deal with more than one constraint at a time. For example downturns in margins associated with pig production and dramatic short-term declines in availability of manures. A possible solution might be coordinating manure supply with pond requirements between farms located in the same area as suggested by Little and Muir (1987) and Edwards (1998). Marketing of by-products between households specialising in different enterprises appears to offer employment opportunities to poorer people as service operators and potentially increase efficiency of reuse; these services are characteristic of areas where aquaculture competes in a more modern economy such as central Thailand (Little and Edwards, 2003). The use of livestock and human waste for the pond culture is socially accepted in Vietnam and is of importance for poor farmers to reduce input and overall production costs, thus increasing net income. However, improving management of livestock and human waste inputs to the pond needs to minimise water exchange to increase both harvestable fish and nutrients stored in ponds, while reducing environmental pollution and public health risks (Piedrahita and Tchobanoglous, 1987; Wohlfarth and Hulata, 1987; Edwards, 1998).

The high-input fish farming integrated with less intensive fruit production system

The high-input fish farming system faced problems in relation to high external nutrient inputs, high financial risks, and environmental pollution. The system can be considered a non-integrated or stand-alone pond farming system. Ponds received large amounts of external nutrient inputs, and discharged large quantities of nutrients into surrounding surface waters. The investment costs and risks of the system are high, making them out of reach for poor and intermediate farmers. For example, many farmers in the Mekong delta saw revenues decline or suffered losses from pond river catfish farming in the period 1999-2002 due to quick shifts in market prices. Flushing of ponds with "clean" water from the river resulted in polluting surrounding surface waters and a loss of nutrients, which otherwise could have been used for other products. Therefore, reusing pond effluents to produce an extra crop of fish or aquatic plants before discharge back to the source is advised (Beveridge et al., 1997; Naylor et al., 2000). Yi et al. (2003) demonstrated that Nile tilapia could be semi-intensively cultured in an integrated system that recycles nutrients in effluents released from an intensively cultured hybrid catfish pond. Other possibilities include the production of aquatic plants like water hyacinth (*Eichhornia crassipes*) (Costa-Pierce, 1998; Sooknah and Wilkie, 2004), duck weed (*Lemna* spp. and *Spirodela polyrrhiza*) (Jana, 1998), water spinach (*Ipomea aquatica*) (Costa-Pierce, 1998) and rice (Lan, 1999). All these crops can extract nutrients from wastewaters, while producing food for human, fish or livestock (Fasakin et al., 1999; Azim and Wahab, 2003; El-Sayed, 2003). Although these systems look promising, they are not widely adopted by farmers in the study area. In contrast the production of aquatic vegetables using waste water is well established on the urban fringes of Ho Chi Minh City and other urban centres of Southeast Asia (Rigg and Salamanca, 2004). One possible reason is that a wastewater-fed wetland system consumes land at the expense of other, more profitable or less risky farming activities. In the present study, the possibility to recycle nutrients between farms was not explored, but could be explored in situations where land holdings are too small to allow many farming activities. Such an approach could create more jobs, food and income for the poor and reduces environmental impacts (Edwards, 1998; Edwards et al., 2002).

5. Conclusions

On average, for all study sites combined, 43% of the farmers in the central Mekong delta practiced aquaculture. Considering aquaculture was introduced about two decades ago, this is a high percentage. Wealth to a large extent influences the possibility to endeavour in aquaculture. Poor farmers usually do not adopt fish culture in the region. Important reasons perceived by the poor farmers for not practicing aquaculture included inappropriateness of technology and lack of capital, insufficient farm area, limited farm management, and pesticide use for terrestrial crops.

Considering farmers who practice aquaculture in the Mekong delta, a low-input fish farming system was commonly practiced in fruit-dominated areas while medium- and high-input fish farming systems were commonly practiced in rice-dominated areas. In a situation of good market accessibility, richer farmers tended to intensify fish farming. The adoption by farmers and the patterns of IAA-farming were strongly influenced by a combination of technical, bio-physical and socio-economic factors.

The pond fulfils various roles in IAA-systems. To further promote IAA-farming, improving linkages between the pond and other components within the IAA-system, hence, improving nutrient efficiency at farm level, will be instrumental. If the latter is not possible, seeking nutrient linkages between farms is also an option. Paying attention to farmers' contexts and needs is important for appropriate advice to households seeking to diversify, as wealth status, agro-ecology and market opportunities are important drivers for the successful application of aquaculture in IAA-systems.

Acknowledgements

This study was conducted as apart of the cooperative research projects: (1) *Improved resource use efficiency in Asian integrated pond-dike systems* (INCO Pond-Live, ICA4-2000-20034), funded by European Commission, and (2) *Optimisation of nutrient dynamics and fish for integrated agriculture-aquaculture systems* (INREF-Pond), Wageningen University and Research Centre (WUR, the Netherlands). Special thanks are due to research team members, local farmers, village officials, extensions workers, bank officers and agro-traders at the study sites for their wholehearted participation during the participatory studies.

Chapter 3

Food inputs, water quality and nutrient accumulation in integrated pond systems: a multivariate approach

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Aquaculture 261 (2006): 160–173

Abstract

A participatory on-farm study was conducted to explore the effects of food input patterns on water quality and sediment nutrient accumulation in ponds, and to identify different types of integrated pond systems. Ten integrated agriculture-aquaculture (IAA) farms, in which ponds associate with fruit orchards, livestock and rice fields were monitored in Mekong delta of Vietnam. Pond mass balances for nitrogen (N), organic carbon (OC) and phosphorus (P) were determined, and pond water quality and sediment nutrient accumulation were monitored. Data were analyzed using multivariate canonical correlation analysis, cluster analysis and discriminant analysis. The main variability in pond water quality and sediment nutrients was related with food inputs and water exchange rates. Water exchange rate, agro-ecological factors, pond physical properties and human excreta input were major variables used to classify ponds. Classification was into: (1) low water-exchange-rate ponds in the fruit-dominated area, (2) low water-exchange-rate ponds in the rice-dominated area receiving home-made feed, and (3) high water-exchange-rate ponds in the rice-dominated areas receiving excreta. Pond water exchange rate was human-controlled and a function of food input patterns, which were determined by livelihood strategies of IAA-households. In the rice-dominated area with deep ponds, higher livestock and human excreta were found together with high water exchange rates. In these ponds, large organic matter loads reduced dissolved oxygen and increased total phosphorus concentrations in the water and increased nutrient (N, OC and P) accumulation in the sediments. In the rice-dominated area with wide ponds, higher home-made feed amounts were added to the ponds with low water-exchange rate. This resulted in high phytoplankton biomass and high primary productivity. The contrary occurred in the fruit-dominated area, where fish were grown in shallow and narrow ponds, receiving more plant residue which resulted in lower phytoplankton biomass and lower sediment nutrient accumulation.

Key words: Integrated aquaculture, Food input, Water quality, Nutrient accumulation, Participatory research, Multivariate data analysis.

1. Introduction

Agriculture is the dominant type of terrestrial land use in Asia. Integrated agriculture-aquaculture (IAA) farming has been advocated to increase land use efficiency under increased population growth, environmental degradation, and land and water scarcity (Barg et al., 2000). IAA-farming has a long history in highly populated regions like China, northern Vietnam and elsewhere in Asia (Ruddle and Zhong, 1988; Edwards, 1993; Luu, 2001; Luu et al., 2002). The importance of IAA-systems lies within nutrient linkages between on-farm components, leading to farming intensification, food security, income generation and sustainable agriculture. In the Mekong delta of Vietnam and elsewhere, the extent and nature of such linkages in the IAA-systems strongly depend on bio-physical and socio-economic factors (Nhan et al., 2007). Efficient development of the IAA-systems depends on understanding the resource base used by aquaculture. Moreover, it seems justifiable to characterize the IAA-systems in such a way that possible routes for technological and socio-economic improvement can easily be identified. For Vietnam, this may mean exploring new paradigms, as there is still limited experience with IAA, particularly in the Mekong delta.

In the Mekong delta, aquaculture itself and associated IAA-systems are still developing (Rothuis, 1998; Pekar et al., 2002). In recent years, effort devoted to develop IAA-systems in the Mekong delta paid little attention to the resource base on which aquaculture depends and the multiple roles of ponds within integrated farming systems. Nhan et al. (2007) found that that IAA-farmers considered crops or livestock, not ponds, as the principal sub-system. Farmers add many different food-based nutrients to their ponds. The availability of the foods highly depends on season and farming intensity, which differs among areas. When farmers apply larger quantities of nutrients, they tended to discharge more effluents.

Development of sustainable IAA-systems needs a systems approach (Edwards, 1998). The pond sub-system should be integrated as much as possible with existing farming activities to maximize production while minimizing nutrient discharges. It was assumed that farmers have a limited understanding of linkages between farm components, and therefore fail to maximize benefits of the pond within their IAA-systems. The present study was conducted to explore the effects of food input patterns on water quality and sediment nutrient accumulation in ponds, and to identify different types of integrated pond systems. We also provided technological recommendations and proposed further studies for each identified type of system. Our participatory on-farm research approach was in cooperation with a small number of farmers and allowed generating technologies to be extended to other farmers (Chambers et al., 1989; Haverkort, 1991; Stür et al., 2002).

2. Materials and methods

2.1. Background and study sites

The six principle steps in the Participatory Learning in Action approach (chapter 1) were applied. The present study is a follow-up of a previous study, which analyzed predisposing factors of IAA-farming for different locations and households of different socio-economic levels in the Mekong delta (Nhan et al., 2007). That assessment identified three commonly used IAA-systems: (1) fruit-dominated low-input fish farming, (2) rice-dominated medium-input fish farming, and (3) rice-dominated high-input fish farming. This on-farm monitoring study was carried out at three sites in the Mekong delta (Nhan et al., 2007).

2.2. Ponds and fish culture

Ten indicative IAA-farms were monitored in the three study sites from August, 2002 until fish harvesting of each pond in the following year. Important criteria for farm selection were: farming representativeness with respect to IAA-farming patterns and farm size, accessibility and farmers' willingness to participate in the study and to experiment with new technologies. Monitored ponds were rectangular and measured between 222 and 1584 m^2 (Table 1). Some ponds were systems of 6-8 parallel trenches with orchard dikes in between. Except ponds I and J located in flood-prone area, most of the ponds had water depths below 1.0 m. The pond walls were eroded and nearly vertical to a depth of about 0.5 m. On dikes adjacent to the ponds, farmers grew fruit crops and raised pigs or poultry.

Table 1. Major properties of the monitored ponds

Sites	Ponds	Systems	Surface areas (m^2)	Mean widths (m)	Mean depths (m)	Stocking rates (fish m^{-2})	Fish growing period (days)	Pond: orchard ratio
1	A	1	652	2.6	0.58	6.2	294	1:4.3
1	B	1	1327	1.9	0.70	5.0	298	1:4.7
1	C	1	624	2.3	0.60	7.0	293	1:3.1
1	D	1	329	9.9	0.73	12.8	294	1:2.0
2	E	2	222	5.0	0.70	14.4	196	1:3.2
2	F	2	1584	35.4	0.65	2.7	210	1:1.1
2	G	3	1241	23.1	0.85	2.0	361	1:1.7
2	H	3	1011	5.1	0.81	7.4	286	1:2.2
3	I	3	960	13.1	1.79	17.3	562	1:0.4
3	J	3	483	9.0	1.53	3.3	648	1:0.9

During the study, farmers were encouraged to continue applying farming practices as commonly used in their communities. The farmers stocked many different fish species with fingerlings bought from local hatcheries (Table 2). Species selection depended on on-farm food availability, fish selling prices, consumer preferences and local availability of fingerlings. Before stoking the fingerlings, pond sediments from the previous fish crop were removed and disposed on adjacent orchard dikes to minimize residual effects of nutrient stores in the sediment as a result of previous farming cycles (Knud-Hansen, 1992). Wild fish and possible predators were eradicated with *Deris eliptica* root or quick lime. Average individual weights of stocked fingerlings were 1-5 g for most species and 8-15 g for *Pangasius hypophthalmus*. On-farm food sources were mainly livestock and human excreta, and residues from rice, vegetables and fruit crops. The latter were often used in combination with home-made feeds. The home-made feed was prepared from ground crab or golden snail collected from rice fields, rice bran, broken rice, fish meal and small quantities of ground high quality feed pellets. In low-input and excreta-fed ponds, fishes were fed residues of rice or home-made feed during the 1st month after stocking, and left to feed on natural food or excreta during the remaining months before harvest. Ponds were directly connected with surrounding rivers or irrigation canals with a sluice-gate controlled pipe that was equipted with a sluice-gate, serving as both inlet and outlet. The water exchange entirely depended on the tide in adjacent estuaries. Water exchange frequency and rates depended on orchard requirement or excreta loads. In each pond, fishes were harvested in batch cropping.

2.3. Data sources and calculations

Flows of pond nutrients and water

Pond mass balances of nitrogen (N), organic carbon (OC) and phosphorus (P) were calculated on a kg ha^{-1} day^{-1} basis, considering the following nutrient inputs (IP):

$$IP = Fert + Hmfeed + Lexc + Hexc + Cres + Fres + Prec + Iwater$$

where Fert: fertilizers, Hmfeed: home-made feed, Lexc: livestock excreta (manure and urine), Hexc: human excreta, Cres: crop residues, Fres: falling residues from fruit trees (leaves and fruits), Prec: nutrients introduced from precipitation, and Iwater: nutrients introduced through supply water and infiltration during the culture cycle.

The nutrient outputs (OP) considered were:

$$OP = Owater + Irr + Sn$$

where Owater: nutrients lost through intentional discharge and leakage during the culture cycle, Irr: nutrient extracted to irrigate the orchard, and Sn: the nutrients accumulated in the sediments.

Table 2. Main fish species stocked in ponds of the Mekong delta (%)

Fish species	Ponds									
	A	B	C	D	E	F	G	H	I	J
Silver barb (*Barbodes gonionotus*)	32	44	35	37	0	51	21	18	7	10
Grass carp (*Ctenopharyngodon idella*)	0	0	0	0	0	0	17	0	0	0
Silver carp (*Hypophthalmichthys molitrix)*	37	16	28	37	0	7	6	2	0	0
Nile tilapia (*Oreochromis niloticus*)	2	1	2	3	0	12	6	3	36	0
Common carp (*Cyprinus carpio*)	0	0	0	0	0	19	17	13	12	5
Mrigal (*Cirrhina mrigala)*	24	35	33	21	0	0	0	26	0	0
Kissing gourami (*Helostoma temminckii*)	0	0	0	0	5	9	6	26	37	16
Giant gourami (*Osphronemus goramy*)	2	1	0	0	0	0	1	2	0	17
Catfish (*Pangasius hypophthalmus*)	0	0	0	0	0	2	23	5	7	52
Colossoma (*Colossoma brachypomum*)	2	1	2	2	3	0	0	3	0	0
Catfish (*Clarias macrocephalus* x *C. gariepinus*)	0	0	0	0	91	0	0	0	0	0
Marble goby (*Oxyeleotris marmoratus*)	0	0	0	0	0	0	4	0	0	0

The amount of nutrient added or leaving for each input or output source was estimated by multiplying volume or weight by nutrient concentrations measured at the nearest date. For each pond, a water budget was made on a m^3 ha^{-1} day^{-1} basis considering the following sources or sinks:

$$Ip + Il + If = Oe + Oir + Ol \pm \Delta V$$

where Ip: precipitation, Il: supply water, If: infiltration through pond walls or the sediments, Oe: evaporation from the pond surface, Oir: water extraction to irrigate the orchard, Ol: intentional discharge, ΔV: change in pond volume.

Water could infiltrate into or leak out the pond. It was only possible to calculate the net leakage volume, not the absolute volumes of infiltration and leakage (Boyd and Gross, 2000). The net leakage was calculated as:

> $Ink = \Delta V - Ip + Oe + Oir$ ($Il = Ol = 0$), and could be positive (leakage) or negative (infiltration).

The inflow water from storm runoff during the rainy season and water evapo-transpiration through floating macrophytes in the ponds were disregarded. During the fish crop, daily precipitation data were collected from the nearest weather stations. For each pond, bottom area and the average depth were measured before fish stocking. A staff gauge was installed and fixed during the fish culture cycle to record pond water depths. The water depth readings were recorded daily by farmers. When farmers changed pond water or irrigated the fruit crop, they recorded pond depth. The evaporation was measured bi-weekly using 5.5-cm diameter and 30-cm high transparent plastic cylinders filled with pond water and placed near the pond surface for a 24-hour period at 3 random locations in each pond. Differences in water level in the cylinders during the sampling period were assumed to be water loss through evaporation. The volumes of all the water inflows and outflows were estimated indirectly by multiplying depths by pond surface areas.

Water parameters

Water temperature (±0.1°C), pH (±0.01 unit) and DO (±0.01 mg/l) were measured bi-weekly in the morning (07:30–08:30 h) and afternoon (13:30–14:30 h) using portable electronic probes, at five or six representative locations (inlet or outlet, livestock pens, fruit canopy areas, and the centre), each at three water depths (15 cm below water surface, mid-water column and 15 cm above pond bottom) in each pond. Chlorophyll-*a* was sampled bi-weekly, and chemical oxygen demand (COD, an index of organic matter), total nitrogen (TN), total ammonia nitrogen (TAN), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), and soluble phosphorus (PO_4-P) were sampled monthly from fish stocking to fish harvesting. Water column samples were taken using a PVC tube (5.8-cm inner diameter) from the five or six representative locations and thoroughly mixed before analysis. The mixed water sample was split up in two sub-samples. One sub-sample was filtered through a GF/C Whatman glass fiber, and the filtrate was analysed for TAN (indophenol blue) (Mackereth, et al., 1989), NO_3-N (cadmium reduction), NO_2-N (diazotization) and PO_4-P (ascorbic acid) (Clesceri, et al., 1998). The other non-filtered sub-sample was analysed for TN (persulfate digestion), P (persulfate digestion and ascorbic acid), COD (dichromate reflux) and chlorophyll-*a* (acetone extract) (Clesceri, et al., 1998).

Pond primary productivity was measured monthly using the light and dark bottle method between 10:30 h and 13:30 h (Boyd and Tucker, 1992). In ponds with green water, the bottle incubation was shorter to avoid DO super saturation in the light bottles as well as DO depletion in the dark ones. The primary productivity measurements were used to compare pond productivity and not to get detailed estimates of the daily photosynthesis rate. A photosynthetic quotient equal to 1.0 was assumed.

The canal water that was used to fill the ponds was sampled monthly at three random locations near the sluice-gate at the same date of pond sampling. The samples were thoroughly mixed for analyses of COD, TN and TP. The analytical methods applied for the canal water were the same as those for pond water. The outflow water through water exchange and leakage was assumed to have the same chemical compositions as the pond water at the nearest sampling date. The nutrient quantities from the inflow and outflow water were calculated by multiplying volumes by nutrient concentrations measured at the nearest date. Concentrations of OC were estimated from the determined COD by applying a coefficient of conversion of 0.375, which represents the oxygen amount required for organic matter oxidation to the mass of organic carbon (Filimonov and Aponasenko, 2004).

In the present study, NO_2-N concentrations were very low, and it was assumed that the contribution of inorganic species to COD was negligible (Clesceri et al., 1998).

Pond sedimentation

Pond sedimentation was sampled using an 8.4-cm inner diameter and 2.5-cm high cylindrical cup. In each pond, five cups were firmly placed at the pond bottom at the five representative locations for a 2-week period. All materials accumulated in the cups were collected and mixed for each pond. The 2-weekly composite sediment samples were air-dried at room temperature, thoroughly mixed, weighted and divided into two sub-samples. One sub-sample (1/4th) was dried at 105° C to a constant weight for the determination of bulk density (Boyd, 1995). The remaining sub-sample (3/4th) was combined with the one of the 2-weekly sample collected in the other half of the month to get a monthly composite sample for further chemical analysis. The monthly sediment samples were analysed for TN (Kjeldahl), OC (Walkley-Black) and TP (sulfuric acid digestion and ascorbic acid) (Page et al., 1982). The monthly average nutrient accumulation in the sediments was estimated by the equation:

$$\text{Sac} = (\text{BD} \times \text{V} \times \text{Ncon})/(100 \times \text{S})$$

where Sac: nutrients accumulated (kg ha^{-1} day^{-1}), BD: bulk density (kg m^{-3}); V: volume of accumulated sediment (m^3 day^{-1}); Ncon: nutrient concentration (% sediment dry weight); S: pond surface area (ha).

Other parameters

Amounts of all food inputs, included rice bran, broken rice, fish meal, concentrated feed, snail or crab and crop residues, were recorded daily by the farmers. One random sample was taken for nutrient and dry matter analysis for each type of input. The falling residues from fruit trees were sampled bi-weekly in each pond using a net-collector of 1 x 1 m dimension placed at 3 random locations near the pond surface. Plant residue samples were mixed into a composite sample, which was then dried at 105° C to a constant weight for the determination of dry mass and nutrients.

Livestock excreta were sampled monthly. Based on types of livestock feed used (concentrated feed, on-farm feed or a combination of the two) and animal ages, representative waste samples were analysed for the nutrients. Human excreta inputs were estimated at 0.4% and 1.5% of the individual body weight of household members for faeces and urine, respectively (cited in Little and Muir, 1987). Three random samples of faeces and urine were analysed for nutrient content. Fish feed and residues of crops and plants were analysed for TN (Kjeldahl), TP (photometric method) (Williams, 1984), OC (oxidation by potassium dichromate) (Walinga et al., 1989). The analysis methods for soil and water were applied for manure and urine analysis, respectively.

2.4. Statistical analysis

Different multivariate techniques were used to analyse relationships between variables, each one highlighting one type of cross relations (Table 3). Canonical correlation analysis was used to explore the effects of food input patterns on water quality and nutrient accumulation in ponds. For each pond, a monthly dataset comprising explanatory and response variables was constructed. The relationships between variables in each set were examined, and the backward stepwise method was used to select variables. Finally, an explanatory set comprising 11 variables related to pond properties and nutrient flows, and a response set comprising 14 variables related to pond water quality and sediment nutrient accumulation were selected (Tables 4 and 5). Canonical loadings of each variable were used to explain results (Hair, et al., 1998). For each pond, the average canonical scores of the two sets of the examined correlations were calculated and plotted in the canonical variable distribution to understand the effects of food input patterns in the particular ponds. For each plot, the original 94 observations were plotted to check how points belonging to each pond clustered; if well clustered, the mean value per pond is given.

Cluster analysis was applied to categorize the ponds on the basis of a set of explanatory variables. Seven explanatory variables that were important in the canonical correlation results were selected: pond depth, livestock and human excreta, home-made feed, plant residues, nutrients flows through inflow and outflow water. A yearly dataset was constructed comprising the seven explanatory variables with 10 observations (ponds) each. Average pond depths (m) during the fish crop and total nutrient flows (kg ha^{-1} $year^{-1}$) were used. A centroid clustering method with Pearson correlation measure of proximity was used to generate clusters. Data of the variables were standardized (mean = 0 and variance = 1) before generating the clusters. The N, OC and P models were run independently and the analyses generated the same results. Therefore, only the results generated by the N model are shown. Combining field observations, original data and results generated from the cluster analyses, the ponds could be categorized into three indicative pond systems.

Table 3. Relationships between study objectives, multivariate techniques and outputs

Study objectives	Multivariate techniques	Outputs
To explore relationships between pond food inputs, water quality and sediment nutrient accumulation	Canonical correlation analysis	Four or five canonical correlations showing relationships between pond physical properties, food inputs, water quality and sediment nutrient accumulation in different sites
To categorize the ponds	Cluster analysis	Identifying different degrees of similarity between the ponds in three indicative pond systems
To characterize the pond systems	Discriminant analysis	Identifying the relative contribution of variables in determining the pond systems

Discriminant analysis was applied for a monthly data set to confirm the output of the cluster analysis and to characterize the pond systems. Although the canonical correlation and the subsequent cluster analysis pointed out to the pond systems and their major characteristics, the results could not explain the relative contribution of variables in determining the patterns of the pond systems. The set of explanatory variables used for the analysis is shown in Table 4 (excluded "precipitation" variable), and the *a priori* defined groups are the three pond systems indicated by the cluster analysis. There were three pond systems, thus two independent discriminant functions exist. Discriminant loadings rather than standardized weights were used to interpret generated results to avoid inter-correlation-related instability between explanatory variables (Hair et al., 1998). The magnitude of the loading can explain the extent to which an explanatory variable contribute to the respective discriminant function. To explain the relative importance of the individual explanatory variables across the functions, the potency index for each variable was calculated (Hair et al., 1998).

Table 4. Explanatory variables used in multivariate canonical correlation and discriminant analysis. Arithmetic mean and standard deviation (SD). n = 94

		N model		OC model		P model	
Variables	Unit	Mean	SD	Mean	SD	Mean	SD
Pond width	m	10.0	9.4	10.0	9.4	10.0	9.4
Pond depth	m	0.92	0.47	0.92	0.47	0.92	0.47
Precipitation	mm day^{-1}	3.80	4.10	3.80	4.10	3.80	4.10
Home-made feed	Kg ha^{-1} day^{-1}	0.34	0.85	0.15	0.54	5.42	14.40
Livestock excreta	Kg ha^{-1} day^{-1}	2.40	5.01	1.37	2.69	17.66	35.00
Human excreta	Kg ha^{-1} day^{-1}	0.29	0.46	0.07	0.14	1.77	3.43
Crop residue	Kg ha^{-1} day^{-1}	0.03	0.06	0.01	0.03	1.43	3.71
Fruit residue	Kg ha^{-1} day^{-1}	0.04	0.09	0.01	0.02	2.35	6.12
Inflow water	Kg ha^{-1} day^{-1}	5.43	7.10	0.40	0.55	4.25	5.65
Outflow water	Kg ha^{-1} day^{-1}	7.86	12.41	1.14	2.37	6.22	8.10
Crop irrigation	Kg ha^{-1} day^{-1}	0.03	0.07	0.00	0.01	0.04	0.09

Data matrices were made with variables in columns and monthly or yearly observations per farm in rows, except when any observations were missing. Variables on water quality and pond properties had the same sampling dates, whereas variables on soil nutrients and flows were calculated daily and subsequently averaged out for each month. Outliers, normality and multicolinearity of the variables included in the models were checked. There were 94 cases of each variable included for the canonical correlation and the discriminant analysis. The validity of the results from the analyses was assessed by repeating analyses during the variable selection and using non-parametric bootstrap (Hair et al., 1998; Lattin et al., 2003).

Table 5. Response variables used in multivariate canonical correlation analysis. Arithmetic mean and standard deviation (SD), n = 94

Variables[1]	Units	Mean	SD
Secchi	cm	12.3	4.1
Morning DO	mg l^{-1}	1.11	0.73
Afternoon DO	mg l^{-1}	3.18	2.00
Morning pH		6.64	0.19
Afternoon pH		6.76	0.21
Chlorophyll-*a*	µg l^{-1}	109.8	162.8
COD	mg l^{-1}	13.62	5.91
Primary productivity	g m^{-3} h^{-1}	187.4	146.5
N	mg l^{-1}	7.14	6.55
P	mg l^{-1}	1.01	1.51
NO_{2+3}-N	mg l^{-1}	0.08	0.08
Sediment N	kg $ha^{-1}day^{-1}$	10.1	6.14
Sediment OC	kg $ha^{-1}day^{-1}$	132.4	94.2
Sediment P	kg $ha^{-1}day^{-1}$	2.9	2.5

[1] N (total nitrogen in water), P (total phosphorus in water), NO_{2+3}-N (total nitrite- and nitrate-nitrogen in water), sediment N, OC and P (nitrogen, organic carbon and phosphorus accumulation in the sediments, respectively).

3. Results

3.1. Effects of food inputs on water quality and sediment nutrient accumulation

The canonical correlation analysis for N, OC and P generated similar results revealing relationships between inputs, water quality and soil nutrient accumulation in ponds (Table

6). The canonical correlation analysis indicated four or five significant correlations, which explained 55, 61 and 61% of the total variance of the explanatory (E) set and 50, 55 and 52% of the total variance of the response (R) set of the N, OC and P models, respectively. The canonical correlation coefficients of the two sets were high in the first correlation (R = 0.81) and decreasing towards the fourth or fifth (R about 0.60). Figure 1 illustrates the distribution of the ponds along the E and R axes generated from the results of the N model. The first canonical correlation (CC1) of the three models explained the combined effects of livestock and human excreta inputs and water exchange rates on water quality and nutrient accumulation in the sediments. In this correlation, the major variables contributing to the explanatory set (E1) were pond depth, the nutrient flow through the inflow and outflow water, livestock and human excreta input; while those contributing to the response set (R1) were the accumulation of N, OC or P in the sediment, morning and afternoon DO, and water P concentration. Figure 1a shows the location of each pond (mean of all measurements) in relation to both correlation axes for N. It can be seen that in the flood-prone and rice-dominated area with deep ponds (site 3, ponds I and J), the ponds received more livestock and human excreta and a higher rate of water exchange was practiced (Fig. 2). The high level of organic matter entering the ponds reduced DO levels in water, allowed more nutrients (N in Fig. 1, OC and P in the other models) to accumulate in sediments and higher level of P to remain in the water. The contrary occurred in shallower ponds. Among them, those in rice-dominated areas (site 2, ponds E, F, G and H) were closer to site 3 than those in the fruit-dominated areas (site 1, ponds A, B, C and D). The correlation explained about 18% of the total variance of the response variable set.

The second canonical correlation (CC2) of the three models revealed seasonal effects. The falling fruit residues and pond water extraction for orchard irrigation took place in the dry season, resulting in higher pH and lower total nitrite- and nitrate-nitrogen concentrations in the water than in the rainy season. The negative correlation between pH and the nitrogenous nutrients reflects nitrification, a process that consumes alkalinity. Lower nitrification levels during the dry season can be due to irrigation, during which particles that potentially provide substrate for nitrifying bacteria are removed. More hours of sunshine, and hence photosynthetic activity, during the dry season should also have contributed to increased pH, which was measured during daytime. Figure 1b shows the distribution of the ponds in relation to E2 and R2 axes, separately for measurements done during the dry and the rainy seasons. In the rainy season, all ponds had higher total nitrite- and nitrate-nitrogen concentrations and lower pH values (points in the lower-left quadrant). The contrary occurred in the dry season (points in the upper-right quadrant), but ponds I and J showed weaker seasonal effects than the others (points in the area where axes cross). The correlation explained about 10% of the total variance of the response variable set.

The third canonical correlation (CC3) for N, forth (CC4) for OC and fifth (CC5) for P showed the effects of home-made feed input on primary productivity. Each of these canonical correlations confirmed that more home-made feed was supplied to ponds on farms where fruit production was less intensive (explanatory variable set; pond width and fruit residues in the N model; water flow in the OC model; irrigation in the P model). Variables with high coefficients in the response set were related to phytoplankton biomass and photosynthesis. Figure 1c shows the distribution of the ponds in relation to E3 and R3 axes. Ponds E and F, located in rice-dominated area, received large quantities of home-made feed and had high phytoplankton biomass and primary productivity. The opposite occurred in ponds A and B, narrow trenches located in the fruit-dominated area that received more fruit residues, and in pond J, the narrowest of the deep ponds. The correlations explained about 6-16% of the total variance of the response variable set.

The fourth canonical correlations (CC4) for N and P, and fifth (CC5) for OC, explained the combined effects of livestock excreta input and pond discharge on primary productivity. The correlations showed that farmers who used large quantities of livestock excreta flushed the ponds more frequently, which diluted the phytoplankton biomass, lowering primary productivity and hence afternoon DO concentrations. Figure 1d shows the distribution of the ponds in relation to E4 and R4 axes, with pond I in the positive extreme and pond F in the negative extreme. The correlations explained about 6% of total variance of the response variable set.

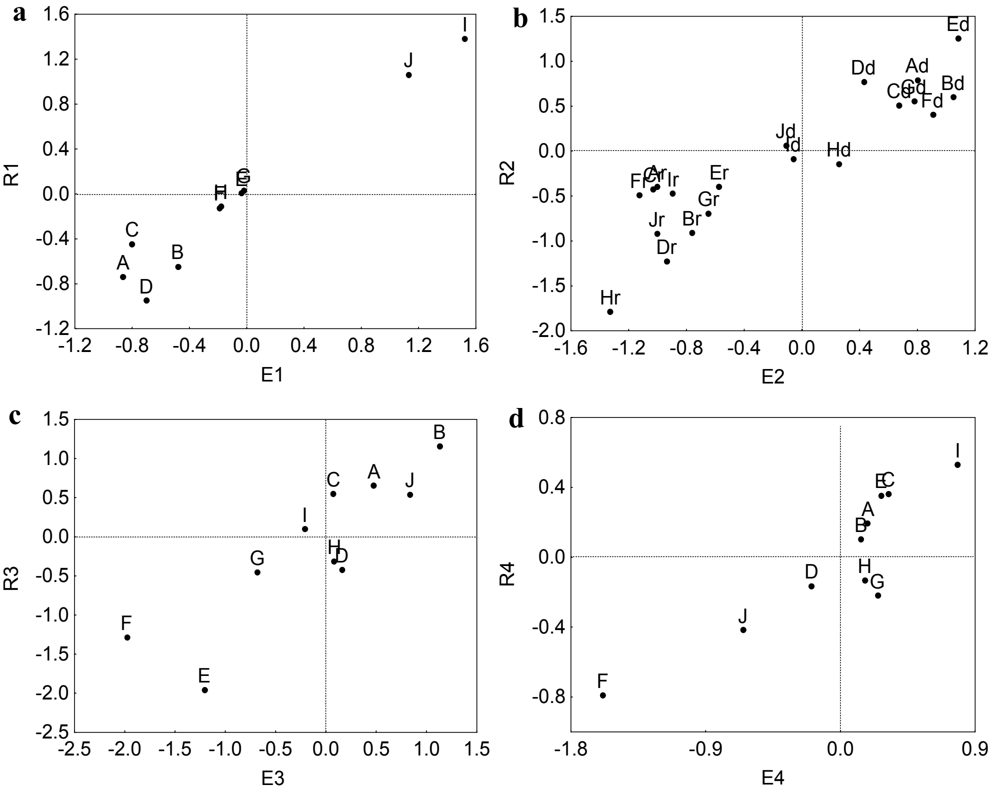

Figure 1. The distribution of the ponds along the exploratory (E) and response (R) axes. Results from N model: (a) E1 (pond depth, excreta inputs, inflow and outflow water) *vs*. R1 (DO, P in water, nutrient accumulation in sediments); (b) E2 (seasons, fruit residues and crop irrigation) *vs*. R2 (pH, total NO_{2+3}-N in the water), pond name followed by "d" or "r" meaning in the "dry" or "rainy" seasons, respectively; (c) E3 (pond width, home-made feed, plant residues) *vs*. R3 (Secchi, afternoon DO and pH, chlorophyll-a, COD, N in the water); and (d) E 4 (livestock excreta, outflow water) *vs*. R4 (afternoon DO, primary productivity).

The third canonical correlation (CC3) for OC further explained water quality in fruit-dominated ponds. In the explanatory variable set, a negative correlation between the falling fruit residues and pond widths reflects the use of the narrower ponds (so-called trenches) of the fruit-dominated area for fish farming, which are narrower than the ponds in the other systems. In this system, the ponds had lower phytoplankton productivity, which is indicated by higher Secchi visibility and lower afternoon pH, DO and chlorophyll-*a*. This correlation explained about 12% of the total variance of the response variable set.

The third canonical correlation (CC3) for P and OC were similar, but the former included a sediment component and contrasted fruit-dominated ponds and ponds receiving livestock excreta. Fruit-dominated ponds received less livestock excreta, and had lower phytoplankton biomass and nitrogen concentrations in the water, and lower accumulation of nutrients (N and OC) in the sediment. This correlation explained 13% of the total variance of the response variable set.

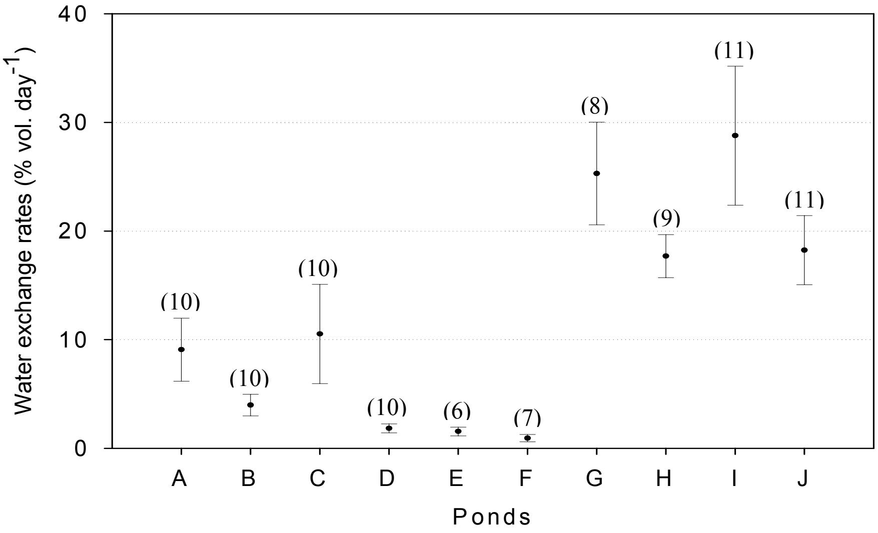

Figure 2. Mean water exchange rates (% pond volume day^{-1}) across the ponds during the fish growing period. Mean ± SE with the number of observations in parenthesis.

3.2. Characterization of pond systems

Categorization of the ponds

Table 6. Results of canonical correlation analysis for the N, OC and P models: canonical correlation coefficients (R), loadings and variance explained

Variables	N model				OC model					P model				
	CC1	CC2	CC3	CC4	CC1	CC2	CC3	CC4	CC5	CC1	CC2	CC3	CC4	CC5
Canonical R	0.80	0.72	0.68	0.63	0.81	0.70	0.66	0.60	0.56	0.80	0.68	0.70	0.59	0.52
The E set[1]	E1	E2	E3	E4	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5
Pond width	0.21	-0.05	**-0.62**	-0.32	0.17	-0.07	**0.79**	-0.08	-0.04	0.17	-0.02	**0.57**	**0.49**	0.01
Pond depth	**0.81**	-0.32	0.32	-0.14	**0.85**	-0.29	-0.28	-0.09	0.14	**0.84**	-0.37	-0.26	0.05	0.05
Precipitation	-0.16	**-0.88**	0.02	0.00	-0.14	**-0.84**	-0.27	-0.20	-0.07	-0.19	**-0.87**	-0.08	-0.01	0.33
Home-made feed	0.15	-0.16	**-0.45**	-0.19	0.18	-0.11	0.06	**-0.56**	0.11	0.24	-0.06	0.00	0.17	**0.50**
Livestock excreta	**0.58**	-0.01	-0.15	**0.66**	**0.55**	0.07	0.05	-0.04	**-0.74**	**0.56**	-0.03	**0.43**	**-0.59**	-0.19
Human excreta	**0.60**	-0.25	0.26	-0.10	**0.58**	-0.21	-0.25	-0.06	0.16	**0.57**	-0.27	-0.27	0.06	0.06
Crop residue	-0.03	0.22	0.00	0.07	-0.07	0.27	0.05	0.03	-0.16	-0.05	0.24	-0.19	-0.10	0.31
Fruit residue	-0.25	**0.45**	**0.48**	-0.11	-0.16	**0.49**	**-0.40**	0.12	0.23	-0.21	**0.46**	**-0.57**	-0.05	-0.03
Inflow water	**0.75**	-0.32	0.12	0.19	**0.60**	-0.26	-0.09	**0.52**	-0.24	**0.58**	-0.27	-0.03	-0.39	-0.16
Outflow water	**0.63**	-0.23	-0.01	**0.52**	**0.67**	-0.29	-0.06	**0.54**	-0.29	**0.57**	-0.18	0.27	**-0.60**	-0.29
Crop irrigation	-0.16	**0.54**	-0.16	-0.01	-0.12	**0.46**	-0.15	0.02	0.13	-0.07	**0.45**	0.12	-0.02	**0.45**
Variance (%)	*0.23*	*0.15*	*0.09*	*0.08*	*0.21*	*0.14*	*0.09*	*0.09*	*0.08*	*0.20*	*0.14*	*0.10*	*0.10*	*0.07*

Variables with bold values most contribute to the respective canonical correlations (CC)

[1] The explanatory set

Table 6 (continued)

Variables	N model				OC model					P model				
	CC1	CC2	CC3	CC4	CC1	CC2	CC3	CC4	CC5	CC1	CC2	CC3	CC4	CC5
The R set[1]	R1	R2	R3	R4	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
Secchi	0.16	0.09	**0.63**	-0.10	0.21	0.16	**-0.67**	-0.11	0.33	0.23	0.06	**-0.74**	-0.10	0.37
Morning DO	**-0.54**	-0.08	0.13	-0.18	**-0.53**	-0.11	0.06	0.06	0.30	**-0.52**	-0.05	-0.10	0.19	-0.18
Afternoon DO	**-0.45**	0.23	**-0.45**	**-0.42**	**-0.46**	0.15	**0.55**	-0.34	0.28	-0.42	0.27	0.38	**0.51**	0.25
Morning pH	0.29	**0.54**	-0.23	-0.24	0.26	**0.49**	0.34	-0.14	0.13	0.30	**0.53**	0.10	0.22	0.04
Afternoon pH	-0.09	**0.58**	**-0.47**	-0.32	-0.11	**0.50**	**0.57**	-0.26	0.18	-0.07	**0.58**	0.36	0.39	0.08
Chlorophyll-*a*	-0.10	0.19	**-0.65**	-0.12	-0.14	0.05	0.37	**-0.56**	-0.05	-0.11	0.19	**0.47**	0.17	**0.51**
COD	0.13	-0.30	**-0.52**	-0.21	0.09	-0.34	0.33	-0.16	-0.09	0.05	-0.26	0.30	0.26	0.24
Primary prod[2]	-0.21	-0.09	-0.01	**-0.40**	-0.14	-0.09	0.03	**-0.48**	**0.40**	-0.16	-0.08	-0.02	0.37	0.19
N	0.20	-0.32	**-0.56**	0.13	0.13	-0.29	0.21	**-0.63**	-0.36	0.15	-0.34	**0.43**	-0.05	0.37
P	**0.47**	-0.24	-0.12	0.19	**0.47**	-0.21	-0.05	-0.38	-0.27	**0.48**	-0.30	0.20	-0.19	0.12
NO_{2-3}	0.05	**-0.54**	-0.32	-0.20	0.07	**-0.64**	0.20	-0.09	0.01	0.04	**-0.54**	0.21	0.23	0.35
Sediment N	**0.65**	0.04	-0.34	0.25	**0.63**	0.03	0.27	-0.14	-0.35	**0.63**	0.01	**0.48**	-0.14	-0.01
Sediment OC	**0.74**	0.16	-0.30	0.25	**0.71**	0.17	0.24	-0.10	-0.35	**0.72**	0.15	**0.45**	-0.16	0.00
Sediment P	**0.74**	0.15	-0.12	-0.14	**0.75**	0.12	0.20	-0.26	0.10	**0.76**	0.09	0.19	0.17	0.00
Variance (%)	*0.18*	*0.10*	*0.16*	*0.06*	*0.17*	*0.09*	*0.12*	*0.10*	*0.07*	*0.17*	*0.10*	*0.13*	*0.06*	*0.06*

[1] The response set

[2] primary productivity

Results from the cluster analysis indicated grouping of pond systems (Fig. 3). First, cutting through line A there are two group of ponds: (1) ponds A, B, C, D, E and F, and (2) ponds G, H, I and J. This solution reflects differences in water exchange rate between the groups, with group 1 associated with low water exchange rates, and the opposite in group 2 (Fig. 2). Second, cutting through line B the group of ponds with high water exchange did not change while the ponds with low water exchange rate are divided in two groups: (1) ponds A, B, C and D, located in the fruit-dominated site, and (2) ponds E and F, located in a rice-dominated area. This solution combines differences due to water exchange rates and related to fruit- or rice-dominated sites. Cutting through line C pond J, a deep pond which received more human excreta is separated from the other ponds with high water exchange rates. Cutting through line D pond I, another deep pond where more livestock excreta were applied, is separated from the shallow ponds with high water exchange rate. If the cutting line is moved further downwards, the classification of pond systems becomes less clear, indicating small differences in food input levels and between narrow and wide ponds (pond E *vs*. F, D *vs*. A, B or C; see Fig. 4 and Table 1). Line B seems to best separate the ponds into three indicative systems: (1) low water-exchange-rate ponds in fruit-dominated area (ponds A, B, C and D), (2) low water-exchange-rate ponds in rice-dominated area receiving home-made feed (ponds E and F), and (3) high water-exchange-rate ponds in rice-dominated areas receiving excreta (ponds G, H, I and J).

Characterization of the pond systems

Results from the discriminant analysis with the three pond systems as the dependent variables confirmed the validity of the pond categorization by the cluster analysis. In three independent runs for N, OC and P, results showed that the percentages of the correct classification in selected cases of the original systems were high and acceptable: 90% for N and 85% for OC and P, which are much higher than the proportional chance criterion estimated at 38%. In system 1, the percentage of the correct classification was 100%. However, cases were misclassified in systems 2 and 3.

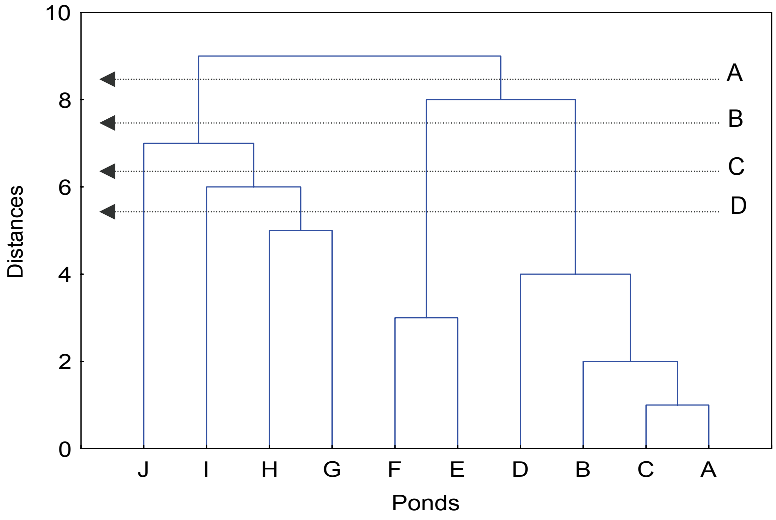

Figure 3. Dendrogram showing different degrees of similarity between the ponds (N model).

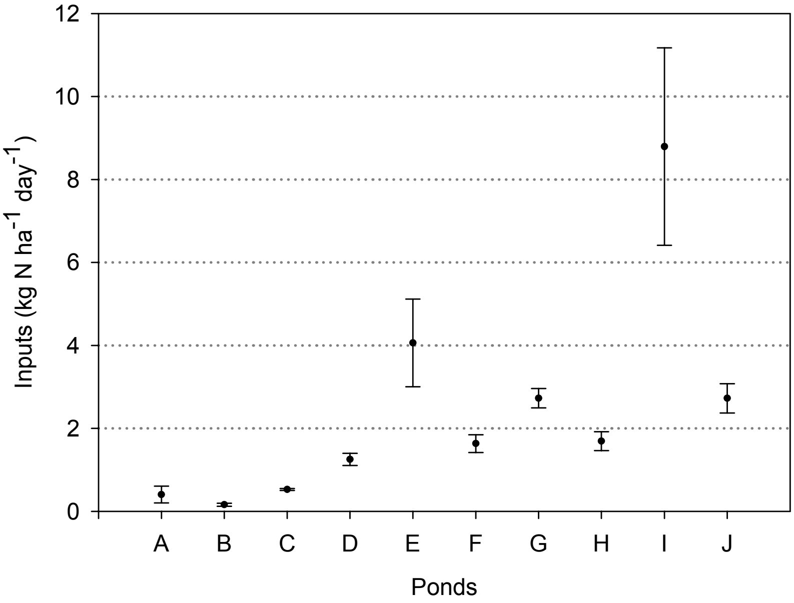

Figure 4. Mean food inputs (include inorganic fertilizers, kg N ha^{-1} day^{-1}) across the ponds during the fish growing period. Mean ± SE; the number of observations per pond as indicated in Figure 2 .

The results indicated that the three indicative pond systems are mainly characterized by water exchange rates, pond physical properties, and excreta inputs. All discriminant functions were statistically significant, meaning that the three systems can be well separated by each function (Table 7). In the three models for N, OC and P, the first function accounted for about 65-72% and the second function about 28-35% of the variability among the three systems (Table 8). Variables with higher loadings contributed relatively more to the discrimination. Looking at the group centroids across the three systems in the three models, it can be seen that system 1 and 3 had extreme and opposite centroid values in function 1, allowing this function to discriminate system 1 from 3; whereas system 2 had extreme centroids in function 2, allowing this function to discriminate system 2 from the two others. System 1 can be characterized by narrow and shallow ponds, low human excreta inputs and low water exchange rates. The contrary occurred in system 3. Similarly, the second discriminant function mainly reflects major characteristics of system 2, which had wide and shallow ponds, high home-made feed inputs, and low human excreta inputs and low water exchange rates. Looking at the potency index of each variable in the three models, it can be seen that water inflow or outflow, pond depth and width and human excreta input had a high potency index, meaning that these variables contribute most to the discrimination among the systems. This result also confirms the validity of conclusions drawn on the basis of the cluster analysis.

Figure 5 depicts discriminant score means of variables of the three systems in the discriminant space for the N model. System 1 mainly falls in the left half, system 2 mainly in the lower-right, and system 3 mainly in the upper-right quadrant.

4. Discussion

4.1. Relationships between food inputs and water quality and sediment nutrients

The canonical correlation analyses established the relationships between pond physical properties and their management in respect to food input for fish and water exchange rates. The same holds with respect to water quality and sediment nutrients. The main variability in the system was related to the management practices and food type availability in the different farm sites. In the rice-dominated area with deep ponds, ponds received excessive excreta, hence farmers applied high water exchange rates to avoid water quality deterioration within their ponds and polluted surrounding surface waters through high discharge rates of nutrient-rich effluents. In these ponds, high concentrations of total and soluble phosphorus remained in water column and considerable quantities of nutrients accumulated in the sediments. Nevertheless, about 1.5 times more N and OC, and 3.1 times more P were discharged than the amounts received through inflowing water. Algae and nutrients were flushed out before they had time to stimulate natural food production. Low primary productivity and high decomposition rates resulted in low morning and afternoon dissolved oxygen concentrations. The application of livestock and human excreta for pond aquaculture is socially well accepted in Vietnam and provides several advantages from the economical points of view (Nhan et al., 2007). In the Mekong delta, because IAA-farming is still developing, unnecessary loss of pond nutrients as a result of sub-optimal management will reduce economical benefit to farmers while causing eutrophication of the Mekong River ecosystem due to excessive nutrient discharge.

Table 7. Discirminant functions and their statistics for the N, OC and P models

Discriminant functions	Centroids			Eigen-value	Canonical R	Wilks' Lambda	*P*-level
	System 1	System 2	System 3				
N model							
1	-1.75	0.82	1.45	2.39	0.84	0.13	<0.001
2	0.17	-2.73	0.70	1.30	0.75	0.43	<0.001
OC model							
1	1.67	-0.09	-1.60	2.38	0.83	0.16	<0.001
2	-0.35	2.37	-0.41	0.93	0.69	0.52	<0.001
P model							
1	1.49	-0.42	-1.32	1.79	0.80	0.20	<0.001
2	-0.23	2.22	-0.48	0.83	0.67	0.55	<0.001

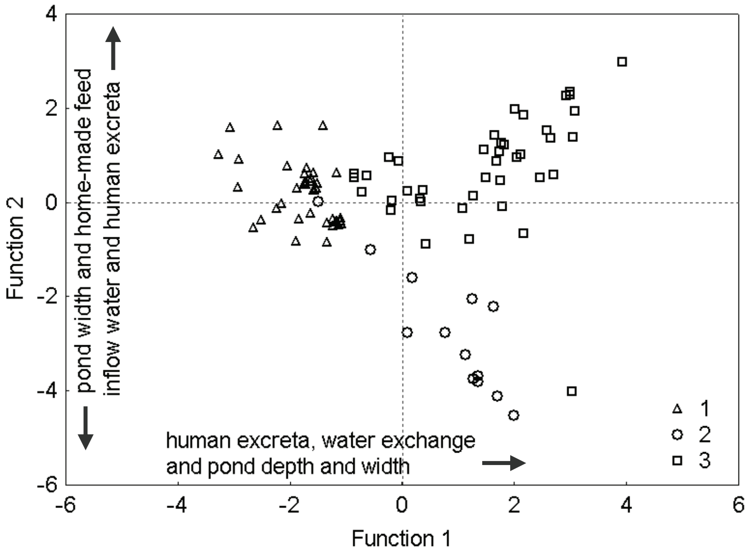

Figure 5. The distribution of variable score means of the three pond systems along the discriminant functions (N model).

In the fruit-dominated area, ponds were less productive (Nhan et al., 2007). The trenches were shaded by fruit tree canopies, which reduced photosynthesis, especially during the rainy season, when the growth of the canopy adds to the already low solar radiation. This resulted in low phytoplankton biomass in the trenches which together with low inputs of excreta and home-made feed provided little material to accumulate in the sediments of the ponds. In addition, falling leaves are fibrous and of low nutritional value for fish. Therefore, improvements in productivity and nutrient accumulation in orchard trenches are necessary.

In the rice-dominated area, ponds were more productive (Nhan et al., 2007). The wide ponds received more sunlight and more home-made feeds while water exchange rates were lower. This combination stimulated phytoplankton biomass and primary productivity and led to higher nitrogen concentrations in the water column. Farmers knew the importance of minimizing nutrient losses and did not worry about low oxygen because they cultured mainly low oxygen tolerant hybrid catfishes. Excessive growth of phytoplankton biomass, however, could result in self-shading by algae near the pond surface, which in turn reduces photosynthesis rate and primary productivity. This phenomenon probably occurred in pond E, where input levels were high, water exchange rates low and no planktivorous fishes were stocked (see Fig. 1 and Table 2). Positive relationships between home-made feed inputs (and less water exchange) and the nutrient accumulation in the sediments were unclear, suggesting fast mineralisation. The close correlation found between total nitrogen and total ammonia concentration in water also suggests mineralisation. We suggest stocking more planktivorous and less benthophagous species as a way to exploit the available food resources better.

Table 8. Results of discriminant analysis of the N model: arithmetic means ± SD, discrimimant loadings and potency index.

Variables[1]	Means			Loadings		
	System 1	System 2	System 3	Function 1	Function 2	Potency index
N model						
Pond depth	0.66 ± 0.09	0.65 ± 0.16	1.25 ± 0.54	**0.44**	0.39	**0.18**
Pond width	4.20 ± 3.40	21.40 ± 15.80	12.10 ± 6.2	**0.41**	**-0.44**	**0.18**
HM feed	0.05 ± 0.07	1.32 ± 1.41	0.31 ± 0.83	0.17	**-0.42**	0.08
H. excreta[2]	0.01 ± 0.05	0.00 ± 0.00	0.65 ± 0.49	**0.53**	**0.48**	**0.26**
L. excreta[3]	0.50 ± 0.59	1.39 ± 0.95	4.58 ± 6.99	0.25	0.15	0.05
Crop residue	0.02 ± 0.05	0.03 ± 0.07	0.03 ± 0.08	0.06	0.02	0.00
Fruit residue	0.08 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	-0.34	0.06	0.08
Inflow water	1.16 ± 0.99	0.40 ± 0.38	11.19 ± 7.48	**0.54**	**0.53**	**0.29**
Outflow water	1.09 ± 1.02	1.20 ± 1.48	16.59 ± 14.78	**0.43**	0.38	**0.17**
Crop irrigation	0.05 ± 0.07	0.05 ± 0.12	0.01 ± 0.02	-0.16	-0.15	0.02
Explained variance (%)				*64.8*	*35.2*	

Variables with bold values of loading(s) or potency index have high relative importance in the discrimination.

[1] Units of the variables presented in Table 4, the same for OC and P models in the next page.

[2] Human excreta, [3] Livestock excreta, the same for OC and P models in the next page

Table 8 (continued). Results of discriminant analysis of the OC and P models

Variables[1]	Means			Loadings		Potency index
	System 1	System 2	System 3	Function 1	Function 2	
OC model						
Pond depth	0.66 ± 0.10	0.65 ± 0.16	1.25 ± 0.54	**-0.49**	-0.32	**0.20**
Pond width	4.20 ± 3.40	21.40 ± 15.8	12.10 ± 6.20	-0.34	**0.64**	**0.20**
HM feed	2.15 ± 2.52	17.48 ± 17.79	4.78 ± 17.96	-0.06	0.37	0.04
H. excreta[2]	0.00 ± 0.01	0.00 ± 0.00	4.05 ± 4.23	**-0.44**	-0.28	**0.16**
L. excreta[3]	3.16 ± 4.58	14.94 ± 12.09	32.67 ± 48.38	-0.28	-0.05	0.06
Crop residue	0.77 ± 1.86	1.87 ± 4.93	1.93 ± 4.54	-0.10	0.05	0.01
Fruit residue	5.51 ± 8.45	0.00 ± 0.00	0.00 ± 0.00	0.31	-0.17	0.08
Inflow water	0.86 ± 0.82	0.33 ± 0.32	8.80 ± 5.98	**-0.60**	**-0.44**	**0.31**
Outflow water	1.12 ± 1.06	0.53 ± 0.59	13.00 ± 8.21	**-0.65**	**-0.46**	**0.37**
Crop irrigation	0.08 ± 0.13	0.03 ± 0.07	0.01 ± 0.02	0.24	-0.03	0.04
Explained variance (%)				*71.9*	*28.1*	
P model						
Pond depth	0.66 ± 0.10	0.65 ± 0.16	1.25 ± 0.54	**-0.54**	**-0.42**	**0.25**
Pond width	4.20 ± 3.40	21.40 ± 15.8	12.10 ± 6.20	**-0.44**	**0.61**	**0.25**
HM feed	0.04 ± 0.07	0.47 ± 0.65	1.56 ± 0.71	-0.10	0.26	0.03
H. excreta[2]	0.00 ± 0.02	0.00 ± 0.00	0.17 ± 0.16	**-0.50**	**-0.40**	**0.22**
L. excreta[3]	0.37 ± 0.53	0.95 ± 0.75	2.48 ± 3.75	-0.29	-0.13	0.06
Crop residue	0.01 ± 0.03	0.01 ± 0.02	0.02 ± 0.04	-0.04	-0.04	0.00
Fruit residue	0.02 ± 0.03	0.00 ± 0.00	0.00 ± 0.00	0.39	-0.13	0.11
Inflow water	0.12 ± 0.17	0.05 ± 0.06	0.79 ± 0.62	**-0.52**	**-0.47**	**0.26**
Outflow water	0.13 ± 0.16	0.09 ± 0.13	2.45 ± 3.14	-0.37	-0.30	0.12
Crop irrigation	0.01 ± 0.01	0.01 ± 0.02	0.00 ± 0.00	0.16	0.19	0.03
Variance explained (%)				*68.3*	*31.7*	

4.2. Pond systems, agro-ecologies and household livelihood options

The types of pond farming practiced in the Mekong delta and elsewhere were closely associated with terrestrial sub-systems in the IAA-system. The latter were to a large extent determined by agro-ecological factors and livelihood options of farm households (Lo, 1996; Pant et al., 2005; Nhan et al,. 2007). In the present study, the variables water exchange rate, pond depth and width, and human excreta inputs, which contribute most to categorising and characterising the pond systems, reflected consequences of agro-ecologies and household livelihood options for pond farming. In the fruit-dominated-low-water-exchange system 1, farmers focused on fruit production to generate income and gave no or little priority to pond intensification. In the rice-dominated systems, where less fertile soils are predominant, farmers needed to create high grounds relatively safe from flooding for housing and orchards. In the low-water-exchange system 2, farmers paid more attention to fish farming for income generation, while in the high-water-exchange system 3 farmers focused on development of livestock farming and used the pond primarily to dispose wastes. In each of the systems, farmers did not consider the pond to be the primary livelihood sustaining activity (Nhan et al., 2007).

4.3. Multivariate approach: options for future participatory on-farm research

The application of multivariate methods proved to be useful in the participatory on-farm research, allowing to make order in the huge amount of data gathered, and directing the search for inter-relationships that after their identification might look obvious but that were not palpable from the observation of the raw data. The multivariate methods allow studying relationships between numerous variables in complex systems for a limited number of farms, which is not possible with uni- or bivariate methods (Prein et al., 1993; Hair et al., 1998). The three different multivariate methods applied generated complementary and non conflicting information. In the present study, although farmers fully participated in the daily monitoring and collection of data, field visits were needed to collect additional information, which were too difficult for farmers to collect. Sample collection and subsequent analyses are labour intensive. Therefore, only a limited number of farms could be studied. Reducing the number of variables measured and increasing the number of farms monitored would be advisable to explain more variability among farms. In the present study, the same results generated from N, OC and P models with each of the multivariate techniques suggest that only the N model would have been enough. Furthermore, water TAN and PO_4-P, and gross primary productivity could have been skipped. We found that TN and TAN or TP and PO_4-P were closely correlated, and therefore TAN and PO_4-P were not included in the data analyses. In addition, gross primary productivity, which consumed time and power, could have been predicted through afternoon DO and chlorophyll-a concentrations. Thus, these measurements can be dropped in future studies.

In the present study, the canonical correlation models explained about 50-60 % of the total variance of the explanatory or response variable set. Farmers stocked many different fish species, which would certainly be an important factor to explain the resultant water quality and sediment nutrient accumulation in the ponds. To include fish-related variables in the analysis, however, was not possible because farmers did not like to sacrifice animals or spend time on selective fishing, showing one of the restrictions of on-farm research. In addition, since several samples were taken in the same farm, the samples might not be completely independent, so that perhaps the significance of some results might be only indicative.

5. Conclusions

This study confirms previous knowledge, stresses the complexity of IAA-systems and identifies areas in which knowledge is lacking. The study established the relationships between pond management practices and pond nutrient accumulation and environmental impacts, and identified three indicative integrated pond systems in the Mekong delta. Good management practices of the pond, which maximise benefits to farmers while minimise environmental impacts, are necessary, particularly in the Mekong delta, where the IAA-farming is still developing. The good management practices, however, will certainly be different among the indicative pond systems, which are determined by agro-ecologies and livelihood strategies adopted by the IAA-households.

Participatory on-farm monitoring in combination with the multivariate analytical techniques appear useful for future aquaculture research. The results from the multivariate analyses allowed giving a precise feedback to farmers on farming results, and the effects of management decisions on nutrient use efficiency, waste discharge and farming benefits. Considering the small number of farms monitored, and considering the large variation this would not have been possible with uni- or bivariate methods. The next step is to implement and follow up on the proposed refinements of pond management practices, maintaining the participatory approach and sampling procedures to further improve profitability and sustainability of IAA-systems.

Acknowledgements

The study was conducted as a part of the cooperative research project *Improved resource use efficiency in Asian integrated pond-dike systems* (INCO Pond-Live, ICA4-2000-20034), funded by the European Commission with Wageningen University and Research Centre (Aquaculture & Fisheries Group, Department of Animal Science, The Netherlands) and Can Tho University (Mekong Delta Development Research Institute, Vietnam) as project partners. Special thanks are for the ten farmers, who cooperated with their wholehearted participation in the study, and for Mekong Delta Development Research Institute’s staff, in field data collection and laboratory work. We are grateful to Dr. L.A.J. Nagelkerke, Aquaculture & Fisheries Group of Wageningen University Research Centre, for his helpful statistical advice.

Chapter 4

Water and nutrient budgets of ponds in integrated agriculture-aquaculture systems in the Mekong Delta, Vietnam

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Submitted

Abstract

Insight in water use and the fractions of input nutrients harvested and discharged from ponds facilitate the strengthening of linkages between farming components in integrated agriculture-aquaculture (IAA) farming systems. A participatory on-farm study analyzed water and nutrient budgets of six low water-exchange rate ponds practiced in fruit- or rice-dominated areas and of four high water-exchange rate ponds in rice-dominated areas. Water and nitrogen, organic carbon and phosphorus flows through the ponds were monitored during a fish culture cycle, while data on fish production and nutrient accumulation in sediments were collected. The results showed that the patterns of pond water and nutrient flows were strongly influenced by the main farming activities of the terrestrial crops (fruit, rice and/or livestock), which differed between the low and high water-exchange systems. IAA-pond management highly relied on regulated water exchange with adjacent canals. On-farm livestock manures were the most important nutrient source for ponds. Only 5-6% of total N, OC or P inputs introduced into ponds were recovered in the harvested fish. About 29% N, 81% OC and 51% P accumulated in the sediments, from where they can be extracted to fertilize terrestrial crops. The remaining fractions were lost through pond water discharges into the environment. Fish yields and nutrient accumulation rates in the sediments increased with increasing food inputs applied to the pond at the cost of increased nutrient discharges. Farmers need to better regulate water and nutrient flows between the pond and the other IAA-farm components to maximize the productivity and profitability while minimizing nutrient discharges of the whole farm. Improvements for each IAA-system were suggested. Continued monitoring of water and nutrient use efficiency in relation to productivity and profitability is necessary to judge the effectiveness of the proposed improvements, and to further fine-tune where possible.

Key words: Nutrient budgets, Water budgets, Integrated aquaculture, Integrated agriculture-aquaculture, Vietnam

1. Introduction

In the Mekong delta, rice and aquatic products constitute a major part of the diet. Rice production is highly intensive and opportunities to further intensify rice production are few (Sanh et al., 1998). The abundance of wild caught aquatic organisms has been declining while a vast area of rice fields and, increasingly, fruit orchard and ditches are created. Since the mid-1980s, farmers tended to diversify farming activities, combining aquaculture, crop and livestock production in integrated agriculture-aquaculture (IAA) systems (Bosma et al., 2005). The diversification and integration of farming activities was strongly supported by the government, which recognized the potential benefits of IAA-farming for the resource-poor. In addition, integration of farming activities also reduces environmental impacts from farming (Berg, 2002; Prein, 2002).

The major goal of IAA-farming is to improve nutrient efficiency of the farm as a whole (Little and Muir, 1987; Prein, 2002). Mostly, IAA-farming is perceived as a type of integrated resources management (Lightfoot et al., 1993). In densely populated areas of China and northern Vietnam, traditional IAA-farming has a long history and is well developed. It contributes to the livelihood for small-scale farming households (Ruddle and Zhong, 1988; Zhu et al., 1990; Luu, 2001; Prein, 2002). The common view is that these IAA-systems are almost closed and intensive, with strong nutrient linkages between IAA-components (Li, 1987; Ruddle and Zhong, 1988; Edwards, 1993; Luu et al., 2002). Therefore, IAA-farming is often suggested as a sustainable agricultural model for small-holders in developing countries (Naylor et al., 2000; Prein, 2002; Bosma et al., 2006)

In the Mekong delta, IAA-farming was recently introduced and still developing (Pekar et al., 2002; Bosma et al., 2005). Farmers in the delta consider rice, fruit and livestock production, primary income generating activities and use their fish ponds for the disposal of farm by-products, particularly manures or human excreta (Pekar et al., 2002; Nhan et al., 2007). Among pond culture adopters, about 90% of the farmers practice IAA-farming and 53% of them dispose of livestock manure through their pond (Nhan et al., 2007). In most cases, farmers do not control the manure load to their pond, and exchange water to avoid manure overloading and related fish kills (Pekar et al., 2002; Nhan et al., 2007). Even though IAA-farming reduces agricultural pollution, there are still large quantities of pond effluents discharged. If this type of aquaculture would be practiced on a large scale, then the practice becomes unsustainable. Therefore, understanding relationships between pond nutrient input and discharge levels is important to improve the sustainability of the IAA-farming. This study analyzed mass flows of water and nitrogen (N), organic carbon (OC) and phosphorus (P) through ponds of IAA-systems in the Mekong delta following an on-farm participatory approach (Nhan et al., 2006).

2. Materials and methods

2.1. Background

The present study is a follow-up of two previous studies. The first study analyzed predisposing factors of IAA-farming for different locations and households of different socio-economic levels in the Mekong delta (Nhan et al., 2007). The second study explored relationships between food inputs, water quality and sediment accumulation in ponds, and characterized IAA-pond systems (Nhan et al., 2006). Strong relationships between manure or human excreta inputs, water exchange and nutrient discharge of ponds were found and used as important determinants to categorize IAA-ponds systems. Two major pond categories were identified: (1) low and (2) high water-exchange ponds. The two categories are further referred to as low- or high-water exchange ponds. The present study estimated water and nutrient budget for these two categories of ponds used in IAA-systems.

2.1. Pond systems and fish culture

In total, ten IAA-farms were monitored at the three study sites from August, 2002 until fish harvesting in the following year (Nhan et al., 2006). Six were low water-exchange ponds (ponds A through F) and 4 were high water-exchange ponds (ponds G through J). Ponds sizes varied between 222 and 1584 m^2 (Table 1). The low water-exchange ponds A, B and C consisted each of 6-8 parallel and connected rectangle ditches with orchard dikes in between. Ponds D through J were rectangular. All ponds were less than 1.0 m deep, except ponds I and J, which were located in a flood-prone area. On dikes adjacent to the ponds, farmers maintained fruit trees and raised pigs or poultry

Table 1. Major properties of the monitored ponds

Sites	Ponds	Systems[1]	Surface areas (m^2)	Mean widths (m)	Mean depths (m)	Stocking rates (fish m^{-2})	Fish growing period (days)	Pond: orchard ratio
1	A	1	652	2.6	0.58	6.2	294	1:4.3
1	B	1	1327	1.9	0.70	5.0	298	1:4.7
1	C	1	624	2.3	0.60	7.0	293	1:3.1
1	D	1	329	9.9	0.73	12.8	294	1:2.0
2	E	1	222	5.0	0.70	14.4	196	1:3.2
2	F	1	1584	35.4	0.65	2.7	210	1:1.1
2	G	2	1241	23.1	0.85	2.0	361	1:1.7
2	H	2	1011	5.1	0.81	7.4	286	1:2.2
3	I	2	960	13.1	1.79	17.3	562	1:0.4
3	J	2	483	9.0	1.53	3.3	648	1:0.9

[1] 1 = low water-exchange, 2 = high water-exchange

During the monitoring period, common farming practices were applied. The farmers stocked many different fish species including silver barb (*Barbodes gonionotus*), silver carp (*Hypophthalmichthys molitrix*), Nile tilapia (*Oreochromis niloticus*), common carp (*Cyprinus carpio*), mrigal (*Cirrhina mrigala*), kissing gourami (*Helostoma temminckii*), giant gourami (*Osphronemus goramy*), catfish (*Pangasius hypophthalmus*) (Nhan et al., 2006). Before stoking the fingerlings, pond sediments from the previous fish crop were removed to minimize residual effects of nutrient stores in the sediment as a result of previous farming cycles (Knud-Hansen, 1992). Wild fish and possible predators were eradicated with *Deris eliptica* root or quick lime. Average individual fingerling weights at stocking were 1-5 g, except for catfish which were stocked at 8-15 g. The mixture of farm by-products used to feed the fish included livestock manures, human excreta and residues from rice fields (paddy grains, bran, broken rice, crabs or snails) and fruit orchards (vegetables, grasses, leaves and fallen fruits). Farmers prepared home-made feed from ground crab and golden snail, rice bran, broken rice, fish powder and small quantities of commercial feed pellets (Nhan et al., 2006). Ponds were directly connected with surrounding rivers or irrigation canals through a sluice-gate controlled pipe, serving as both inlet and outlet. Water exchange depends entirely on tidal action in combination with flow control at the sluice-gate. All ponds were batch harvested.

2.2. Mass flow quantification

Water budgets

In each pond, a water budget was estimated on a m^3 ha^{-1} yr^{-1} basis:

$$\sum\text{inputs} = \sum\text{outputs} \pm \text{Unaccounted}$$

The water inputs included: (1) water to fill the pond before stocking, (2) rainfall into the pond (Ir), (3) sluice-gate inflow during culture (If) and (4) infiltration (Iin). The water outputs included: (1) water extraction for crop irrigation (Oi), (2) evaporation (Oe), (3) sluice-gate outflow during culture (Of), (4) leakage (Olk) and (5) water drained at fish harvest. The calculation of the yearly water budget was based on daily changes in pond water volume (ΔV, m^3 ha^{-1} day^{-1}):

$$\Delta V = Ir + If + Iin - Oi - Oe - Of - Olk$$

It was possible to calculate the net leakage (Nlk) volume, but it was not possible to distinguish between infiltration and leakage (Boyd and Gross, 2000). When pond water exchange and crop irrigation were not practiced, the net leakage was calculates as:

$NLk = \Delta V – Ir + Oe$, and could be positive (leakage) or negative (infiltration).

The inflow from runoff during the rainy season was not considered. During the culture, daily rainfall data were collected from the nearest weather stations. For each pond, bottom areas were measured before fish stocking and after fish harvest, and a staff gauge was used to record fluctuations in water depth during the fish culture. Changes in water depth were recorded daily by farmers. When farmers changed pond water or irrigated the fruit crop, they recorded fluctuations of the water depth. The evaporation was measured fortnightly using 5.5-cm diameter and 30-cm high transparent plastic cylinders filled with pond water and placed near the pond surface for a 24-hour period at 3 random locations in each pond. The volumes of all the water inflows and outflows were estimated indirectly by multiplying the monitored fluctuations in water depth by pond surface areas (Nhan et al., 2006).

Pond nutrient budgets

Pond nutrient budgets were made for N, OC and P on a kg ha^{-1} yr^{-1} basis. In each pond, a nutrient balance was estimated with the same equation used for the water budget.

The nutrient inputs were separated into on-farm and off-farm sources. The on-farm sources included: (1) rice field residues (snails, crabs and rice by-products), (2) livestock manures (mainly from pig and included urine), (3) human excreta and (4) orchard residues (vegetables, grasses, fruit tree leaves and fallen fruits). The off-farm sources included: (1) fishes stocked, (2) inorganic fertilizers, (3) purchased feed (rice bran, fish powder or commercial fish feed), (4) nutrients introduced through filling water before stocking, (5) rainfall into the pond and (6) inflow water (sluice-gate inflow plus infiltration).

The nutrient outputs were separated into harvests and losses. The harvests included: (1) fishes, (2) accumulation in pond sediments, (3) water extraction for crop irrigation and (4) aquatic plant harvested as feed for livestock or as mulching material for orchard dikes. The losses included: (1) outflow water (sluice-gate outflow plus leakage) and (2) drainage water at fish harvest.

Organic carbon and phosphorus inputs from rainwater and losses of the nutrients through evaporation were assumed negligible. N-fixation, N-volatilization, photosynthesis and absorption were not measured. The nutrient input and output quantities were calculated by multiplying total weights or volumes by nutrient concentrations measured to the nearest date.

Water parameters

The water column was sampled monthly, starting at stocking, collecting with a PVC tube (5.8-cm inner diameter) at the 5 - 6 representative locations and mixed them into a composite sample. Chemical Oxygen Demand (COD, dichromate reflux), total nitrogen (N, persulfate digestion), total phosphorus (P, persulfate digestion and ascorbic acid) and ortho-phosphate (PO_4-P, ascorbic acid) were measured according to Clesceri et al. (1998). Concentrations of OC were estimated from COD by applying a coefficient of conversion of 0.375 (Filimonov and Aponasenko, 2004). On sampling days, also the canal was sampled at three locations close to the pipe. The analytical methods applied for the canal water were the same as for the pond water. The sluice-gate inflow water (If) and infiltration were assumed to have the same chemical compositions as the canal water. Similarly, chemical compositions of the sluice-gate outflow (Of) and leakage were assumed to be the same as those of the pond water.

Fish parameters

Quantities of N, OC and P in stocked and harvested fishes were measured. At stocking, a sample of 0.5 kg fish fingerlings per species was taken to determine individual body weight, biomass and nutrient contents for each pond. At harvesting, total biomass of each species was determined. About 2 kg per species were used to determine dry matter and nutrient contents. The samples of stocked and harvested fish were dried at 105° C to a constant weight. Three representative dried samples per species of stocked and harvested fishes were analysed for TN (Kjeldalh), TP (photometric method) (Williams, 1984), and OC (oxidation by potassium dichromate) (Walinga et al., 1989). Nutrient quantities retained in the stocked or harvested fish were calculated by multiplying dry weights by concentrations of N, OC or P. The net fish production was the difference in fish biomass between harvesting and stocking, and was calculated on a kg ha^{-1} year^{-1} basis.

Sediment parameters

In each pond, the depth of accumulated sediments was determined using graduated sticks firmly installed at 5 or 6 representative locations. At each location, the sediments were sampled using a 5.5-cm diameter soil core sampler, and the samples were sliced at an indicated depth (Boyd, 1995). For each pond, sediments taken from the different locations in each pond were thoroughly mixed into a composite sample for further analysis. The composite samples were air-dried and then analyzed for TN (Kjeldahl), OC (Walkley-Black), and TP (persulfate digestion and ascorbic acid) (Page et al., 1982).

Other parameters

The types and quantities of farm inputs were recorded daily by farmers. Nutrient contents in rainwater, fish feed, residues of crops and fruit trees, livestock and human wastes, and floating aquatic plants were determined. Samples of rainwater were collected at the beginning, middle and the end of the rainy season. An average of nitrogen contents of the three samples was used. Livestock manure and urine were sampled monthly. Representative samples of each material used as a nutrient input to the pond were analyzed for TN (Kjeldahl), TP (photometric method) (Williams, 1984) and OC (oxidation by potassium dichromate) (Walinga et al., 1989). The analytical methods for soil and water were applied for wastes and urine analysis, respectively. Nutrient inputs by type were calculated by multiplying the recorded quantity by the measured nutrient concentrations. Methods of sampling nutrient inputs of ponds were described in details in Nhan et al. (2006).

2.3. Statistical analysis

To analyze differences in water and nutrient flows through ponds between the two pre-determined pond categories, t-test analysis was applied at 5% significant level. Linear regression analysis was used to test for effects of food inputs on fish yields and on nutrient accumulation in sediments

3. Results

3.1. Pond systems

The low water-exchange system had a significant lower water exchange rates than the high water-exchange system, 4.6 ±1.6% compare to 19.5 ± 2.4% of pond volume day^{-1} (mean ± SE; $P<0.01$; Fig. 1a). More manures (pond I) or human excreta (ponds G through J) were applied to high water-exchange ponds. The low water-exchange ponds A, B and C received very low food inputs (Fig. 1b).

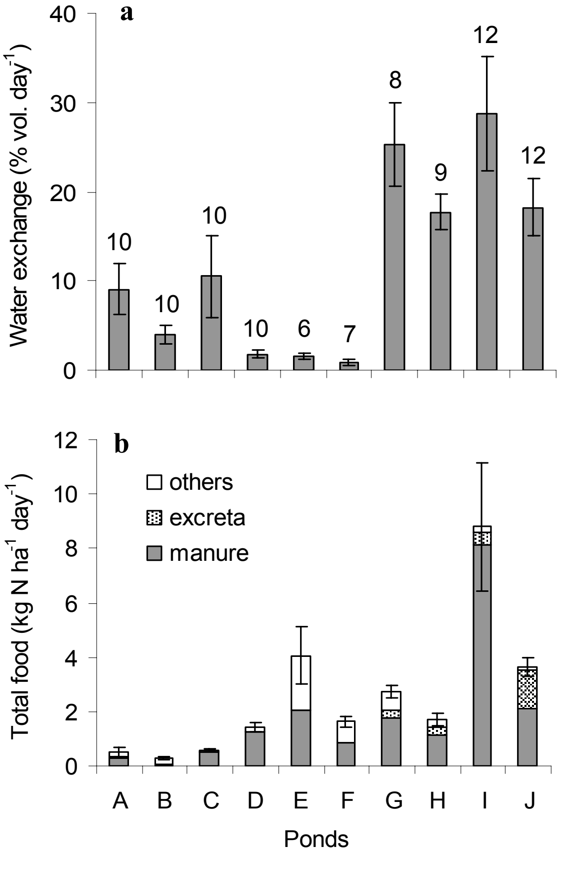

Figure 1. Mean water exchange rates (a) and total food (including inorganic fertilizers) inputs (b) across the ponds during the fish growing period. Mean ± SE with the number of observations.

3.2. Water budgets

The regulated inflow and outflows dominated the water budget (Table 2). Overall, the total water input was 415270 m^{3} ha^{-1} day^{-1}, of which 91% was the regulated inflow, 4% was infiltration and rainfall, and the initial water volume accounting for 2% of the total volume. About 92% of the total inflow volume was flushed out with the regulated outflow. Water extraction for crop irrigation, drainage at fish harvest and leakage consumed less than 2%, and water loss through evaporation accounted for 4% of the total water inputs.

The high water-exchange system had significantly higher sluice-gate inflow and outflow volumes than the low water-exchange system, where the sluice-gate inflow and outflow accounted for 73% and 72% of the total inputs, respectively, compared to 95% and 97% in the former. An average volume of 5490 m^{3} ha^{-1}, accounting for about 4% of the total inputs, was extracted to water fruit orchards during the dry season from the low water-exchange ponds, a significantly larger volume than from the high water-exchange ponds, all located in the rice-dominated areas (Table 2).

3.3. Nutrient budgets

In general, on-farm food inputs and inflow water were the major source of the nutrients for ponds (Table 3). On average, the on-farm inputs accounted for 32% of the total N inputs and 65% of OC or P. Of the on-farm inputs, manure was the most important source. The water inflow accounted for 61% of N, 13% of OC and 18% of P inputs. Off-farm feed inputs were a major source for organic carbon only, accounting for 21% of the total inputs. Fish stock and rain accounted for less than 1% of the total N, OC and P inputs. Inorganic fertilizers applied and water used to initially fill the pond accounted less than 3% of the total N, OC or P inputs. Ponds in the high water-exchange system received a higher quantity of human and livestock excreta, and hence required a higher water volume for refreshing through a higher water exchange practiced. There, the inflow water accounted for 69% of the total N input, 21% of OC and 23% of P while the corresponding figures were 35%, 4% and 9% in the low water-exchange system. Ponds in the high water-exchange system received significantly less nutrients from fruit orchard residues than those of the low water-exchange system, mostly located in the fruit-dominated area. In the latter, the orchard residues accounted for 15% of the total OC inputs.

Table 2. Pond water budgets (10^3 m^3 ha^{-1} $year^{-1}$) and use efficiency (m^3 kg^{-1} of fresh fish produced). Means ± SE

Sources/sinks	Low water-exchange (n = 6)		High water-exchange (n = 4)		Total (n = 10)	
	Mean	%[1]	Mean	%	Mean	%
Inflows						
Initial fill	7.94 ± 0.79	6.2	7.67 ± 0.97	0.9	7.83 ± 0.58	1.9
Rainfall	15.49 ± 0.11	12.1	15.67 ± 0.14	1.8	15.56 ± 0.09	3.7
Sluice-gate inflow	93.08 ± 36.29^{a}	72.8	805.40 ± 187.21^{b}	95.0	378.01 ± 136.54	90.9
Infiltration	11.27 ± 2.22	8.9	19.16 ± 11.86	2.3	14.52 ± 4.69	3.5
Total inflows	127.94 ± 35.80^{a}	100.0	847.91 ± 198.39^{b}	100.0	415.27 ± 139.63	100.0
Outflows						
Crop irrigation	5.49 ± 1.96^{b}	4.3	0.31 ± 0.30^{a}	0.0	3.42 ± 1.42	0.8
Evaporation	16.63 ± 0.27	13.0	16.30 ± 0.76	1.9	16.50 ± 0.32	4.0
Sluice-gate outflow	91.72 ± 35.42^{a}	71.7	822.15 ± 198.45^{b}	97.0	383.89 ± 141.06	92.3
Leakage	4.27 ± 1.59	3.3	1.57 ± 1.53	0.2	3.19 ± 1.16	0.8
Drainage	8.09 ± 0.46	6.3	7.50 ± 1.65	0.9	7.85 ± 0.67	1.9
Total outflows	126.20 ± 35.38^{a}	98.6	847.83 ± 199.45^{b}	100.0	414.85 ± 140.03	99.7
Efficiency[2]	201 ± 88		171 ± 8		189 ± 51	

Comparing between systems 1 and 2, means with different superscripts (a or b) on the same row significantly differ at 5% level with t-test.

[1] % of total inflows

[2] Efficiency = total inflows/total fish yields (m^3 kg^{-1} of fresh fish produced)

Nutrient accumulation in sediments and loss with the outflow water were the major sink of the nutrients (Table 3). On average, about 29% of the total N inputs, 81% of OC and 51% of P accumulated in the pond sediments. The remaining portions of the nutrients were flushed out with the outflow water except for 4-6% of the total N, OC or P that were retained in harvested fish. Organic carbon and P tended to accumulated mainly in the sediments while for N a large fraction was also flushed out. In the low water-exchange ponds, 77% of N, 97% of OC and 83% of P inputs accumulated in fish, sediments and water applied to fruit orchards. In the high water-exchange system, this was 21% of N, 78% of OC and 38% of P inputs, hence significantly higher quantities of N, OC and P inputs were discharged than in the low water-exchange ponds. As a result, to produce one kg of fish, the high water-exchange ponds discharged twice as much nutrient than low water-exchange ponds. Concentrations of COD, N, P and PO_4-P were mostly higher in the pond than in the canal water (Fig. 2). With increased nutrient inputs applied to ponds, higher water exchange rates practiced resulted in loosing more nutrients from ponds and polluting of surrounding surface waters, particularly during the flood period from September to November.

With the exception of P in low water-exchange ponds, more nutrients were measured in the output (harvests and losses) than in the inputs (on-farm and off-farm sources). The fractions of surplus nutrients were higher for N (24-27%) than for OC (3-9%) and P (5%).

3.4. Fish yields and nutrient accumulation in sediments

In the low-water exchange ponds A, B and C, fish yields ranged from 350 to 760 kg ha^{-1} per year. The low water-exchange pond E receiving a much higher feed input produced 14600 kg fish ha^{-1} yr^{-1}. If pond E, which received a lot of non-excreta inputs, was excluded, fish yields linearly increased with increasing livestock and human excreta input levels (Fig. 3). The excreta input explained about 83% of the variability of fish yields. With this relationship, each additional kg of excreta-N applied increases the yield by 3.3 kg ha^{-1} per year.

Quantities of N and OC accumulating in the sediments increased with increasing total food inputs (including the on-farm, inorganic fertilizer and purchased feed) applied to ponds

(Fig. 4). The total food input explained 74% and 97% of the variability of the sediment N and OC accumulation, respectively.

4. Discussion

4.1. Water and nutrient budgets

In the monsoon tropic irrigated areas studied, where water scarcity is not an issue, farmers used water lavishly for the pond culture, replying rely year-round on water supply from irrigation canals for rice and vegetable production. A small fraction of the pond water budget is used to water orchards mainly during the dry season between January and May. These practices contrasts with those observed in dry tropic areas like in Thailand (Pant et al., 2005) and Ghana (Prein et al., 1996), where the water stored in ponds forms an important element in farming success during dry periods. In the farms studied, the water input from rainfall almost compensated the loss from evaporation, and filling and drained water volumes were comparable. Therefore, maximization of storage volume for rain falling into ponds and minimization of excessive water exchange rates practiced should be considered as the water conservation measures in IAA-pond farming in the Mekong delta.

Pond farming highly relied on on-farm nutrient sources. They contributed to on average 90%, 76% and 81% of the total food N, OC and P inputs, respectively, of which farm manures were most important. In the Mekong delta, intensive feedlot pig production is commonly applied and pigs are mainly fed commercial feed. Therefore, farmer can get high fish yields from pig manure. In the fruit-dominated area, however, most farmers preferably use the manure for fruit orchards rather than for ponds. In northern Vietnam, wild grasses and rice bran are important nutrient inputs to ponds in IAA-farms (Luu et al., 2002). There, farm manures are usually used strategically to maintain the productivity of rice, field crops or vegetables. In northeast Thailand, on-farm sources accounted for 20-80% of total food N inputs to IAA-ponds, and in the absence of feedlot pigs, farmers have to buy fish feeds (Pant et al., 2005). This confirms that the degree of the integration between the pond and the other farming components in IAA-systems depends on resource availability and goals of the farmers (Lo, 1996; Pant et al., 2005).

Table 3. Pond nutrient budgets (kg ha^{-1} $year^{-1}$) and use efficiency (per kg of fresh fish produced). Means ± SE

a. N

Sources/sinks[1]	Low water-exchange (n = 6)		High water-exchange (n = 4)		Total (n = 10)	
	Mean	%[1]	Mean	%	Mean	%
On-farm sources						
Rice field residue	119.5 ± 75.9	12.8	99.8 ± 64.6	2.3	111.6 ± 49.9	4.8
Manure	299.5 ± 124.7	32.2	901.2 ± 483.0	20.5	540.2 ± 214.4	23.3
Human excreta	1.7 ± 1.6^{a}	0.2	211.2 ± 102.8^{b}	4.8	85.5 ± 50.8	3.7
Orchard residue	17.7 ± 6.6^{b}	1.9	0.0 ± 0.0^{a}	0.0	10.6 ± 4.8	0.5
Total on-farm	438.3 ± 185.5	47.1	1212.2 ± 431.6	27.6	747.8 ± 228.7	32.3
Off-farm sources						
Feed	92.4 ± 63.0	0.9	65.1 ± 49.7	1.5	81.5 ± 40.9	3.5
Inflow water	321.1 ± 94.8^{a}	34.5	3043.6 ± 377.1^{b}	69.2	1410.1± 468.6	60.8
Total inputs	931.4 ± 232.3^{a}	100.0	4397.5 ± 766.2^{b}	100.0	2317.9 ± 45.5	100.0
Harvests						
Fish	89.4 ± 54.9	9.6	140.4 ± 43.5	3.2	109.8 ± 36.4	4.7
Sediment	616.8 ± 171.9	66.2	774.3 ± 144.9	17.6	679.8 ± 115.4	29.3
Crop irrigation	16.5 ± 4.2^{b}	1.8	2.3 ± 1.9^{a}	0.1	10.8 ± 3.4	0.5
Total harvest	722.7 ± 225.1	77.6	917.1 ± 176.9	20.9	800.5 ± 148.6	34.5
Losses						
Outflow water	424.6 ± 92.7^{a}	45.6	4507.4 ± 621.7^{b}	102.5	2057.7 ± 706.3	88.8
Drainage	38.4 ± 11.4	4.1	19.5 ± 5.3	0.4	30.8 ± 7.5	1.3
Total outputs	1185.7 ± 301.3^{a}	127.3	5444.0 ± 778.3^{b}	123.8	2889.0 ± 71.1	124.6
Efficiency[2]	0.24 ± 0.05		0.25 ± 0.04		0.24 ± 0.03	
Discharge[3]	0.52 ± 0.16^{a}		0.98 ± 0.12^{b}		0.70 ± 0.14	

Comparing between systems 1 and 2, means with different superscripts (a or b) on the same row significantly differ at 5% level with t-test.

[1] Sources such as fingerlings, the initial fill of the pond, rainfall and inorganic fertilizers, and sink as aquatic plant harvested were not shown.

[2] Efficiency = total nutrient inputs from food/total fish yields (kg per kg of fish produced)

[3] Discharge = Total nutrient quantity flushed out with outflow water/total fish yields (kg per kg of fish produced)

Table 3 (continued)

b. OC

Sources/sinks	Low water-exchange (n = 6)		High water-exchange (n = 4)		Total (n = 10)	
	Mean	%[1]	Mean	%	Mean	%
On-farm sources						
Rice field residue	906 ± 426	11.2	1289 ± 1095	9.4	1059 ± 474	10.3
Manure	3042 ± 1525	37.7	6528 ± 3336	47.7	4436 ± 1607	43.0
Human excreta	7 ± 7[a]	0.1	1278 ± 623[b]	9.3	515 ± 365	5.0
Orchard residue	1190 ± 390[b]	14.8	0 ± 0[a]	0.0	714 ± 343	6.9
Total on-farm	5144 ± 1511	63.8	9094 ± 2857	66.5	6724 ± 1505	65.3
Off-farm sources						
Feed	2549 ± 1275	31.6	1638 ± 1127	12.0	2184 ± 856	21.2
Inflow water	296 ± 103[a]	3.7	2848 ± 624[b]	20.8	1317 ± 479	12.8
Total inputs	8059 ± 2759	100.0	13675 ± 4224	100.0	10305 ± 2399	100.0
Harvests						
Fish	534 ± 350	6.5	751 ± 237	5.5	621 ± 223	6.0
Sediment	7278 ± 2270	90.3	9958 ± 3123	72.8	8350 ± 1791	81.0
Crop irrigation	21 ± 7[b]	0.3	2 ± 2[b]	0.0	14 ± 5	0.1
Total harvest	7836 ± 2612	97.2	10713 ± 3313	78.3	8985 ± 1990	87.2
Losses						
Outflow water	409 ± 130[a]	5.1	4162 ± 837[b]	30.4	1911 ± 689	18.5
Drainage	36 ± 9	0.4	40 ± 13	0.3	38 ± 7	0.4
Total outputs	8279 ± 2600	102.7	14915 ± 3835	109.1	10936 ± 2322	106.1
Efficiency	5.15 ± 1.59		2.14 ± 0.46		3.94 ± 1.06	
Discharge	0.59 ± 0.26		0.89 ± 0.09		0.71 ± 0.16	

Table 3 (continued)

c. P

Sources/sinks	Low water-exchange (n = 6)		High water-exchange (n = 4)		Total (n = 10)	
	Mean	%[1]	Mean	%	Mean	%
On-farm sources						
Rice field residue	15.0 ± 9.4	4.3	16.5 ± 13.0	2.0	15.6 ± 7.2	2.9
Manure	195.2 ± 91.7	56.8	488.7 ± 261.9	59.7	312.6 ± 119.3	58.6
Human excreta	0.3 ± 0.3[a]	0.1	36.1 ± 17.9[b]	4.4	14.6 ± 8.8	2.7
Orchard residue	4.8 ± 1.8[b]	1.4	0.0 ± 0.0[a]	0.0	2.9 ± 1.3	0.5
Total on-farm	215.3 ± 98.5	62.6	541.2 ± 251.4	66.2	345.7 ± 120.4	64.8
Off-farm sources						
Feed	71.1 ± 47.9	20.7	59.2 ± 45.9	7.2	66.3 ± 32.4	12.4
Inflow water	29.4 ± 7.7[a]	8.5	190.3 ± 28.3[b]	23.3	93.7 ± 28.6	17.6
Total inputs	343.8 ± 146.6	100.0	818.0 ± 308.2	100.0	533.5 ± 160.7	100.0
Harvests						
Fish	19.0 ± 11.9	5.5	29.6 ± 10.7	3.6	23.2 ± 8.1	4.4
Sediment	265.2 ± 129.7	77.1	280.3 ± 70.9	34.3	271.3 ± 79.3	50.8
Crop irrigation	2.2 ± 0.7[b]	0.6	0.2 ± 0.2[a]	0.0	1.4 ± 0.4	0.3
Total harvest	286.4 ± 141.7	83.3	310.1 ± 80.7	37.9	295.9 ± 87.0	55.5
Losses						
Outflow water	40.0 ± 9.8[a]	11.6	542.1 ± 189.8[b]	66.3	107.5 ± 45.1	45.1
Drainage	5.0 ± 2.7	1.4	6.0 ± 1.2	0.7	5.4 ± 1.6	1.0
Total outputs	331.3 ± 149.0	96.4	858.2 ± 268.3	104.9	542.1 ± 156.2	101.6
Efficiency	0.13 ± 0.03		0.11 ± 0.03		0.12 ± 0.02	
Discharge	0.05 ± 0.02[a]		0.11 ± 0.02[b]		0.07 ± 0.02	

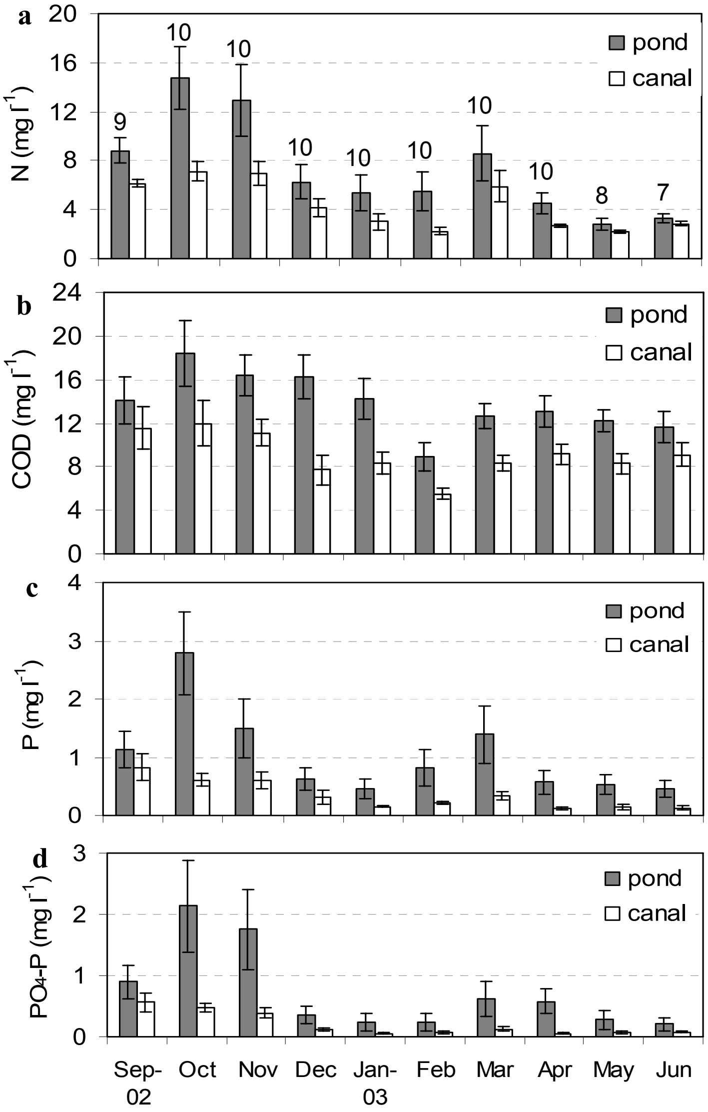

Figure 2. Mean values of water quality of ponds and inlet sources during September 2002-June-2003: (a) N, (b) COD, (c) P and (d) PO_4-P. Mean ± SE with the number of observations for both pond and canal.

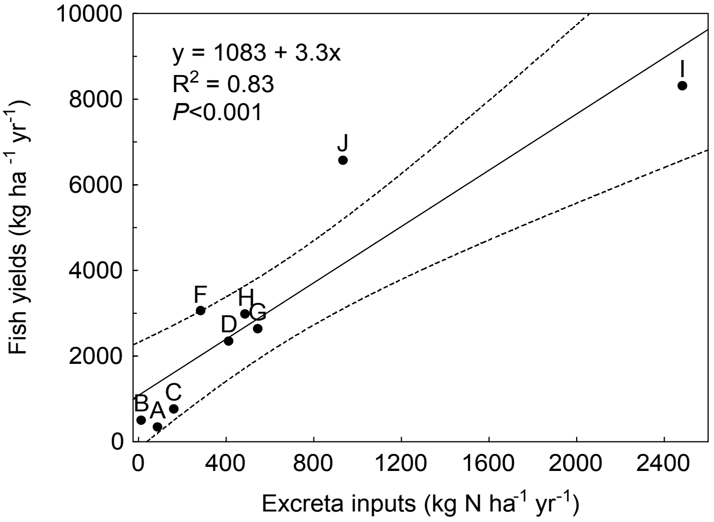

Figure 3. Relationship between livestock and human excreta inputs and total fish yields across the ponds (excluding pond E). For each point, the nearby letter indicates the pond. Regressions line with the confident level at 95%, the coefficient of determination (R^2) and the significant level.

Ponds are a nutrient trap. Proportionally, less N accumulated in the sediment than OC and P, because a large fraction of N was flushed out. P is more adsorbed in the sediment (Delincé, 1992; Boyd, 1995; Shrestha and Lin, 1996) and OC is mainly retained in larger particles of organic matter that sink to the bottom (Hargreaves, 1998; Jimenez-Montealegre et al., 2002). In semi-intensive fish ponds, nutrient accumulation in pond sediments accounts for about 66-70% N, 38-46% OC, 35-86% P of the total food input (Avnimelech and Lacher, 1979; Edwards, 1993; Acosta-Nassar et al., 1994; Green and Boyd, 1995a). In the present study, the ranges of N and P accumulation were comparable with the reports of those authors except that of OC accumulation was higher, mainly because the livestock or human excreta and crop residues applied in the present study had a high carbohydrate content. Li (1987) and Ruddle and Zhong (1988), studying Chinese IAA-systems, estimated that the energy retained in the sediments averages 46-50% of the total biological energy inputs to ponds. Nutrients accumulating in the sediments can be extracted to fertilize the orchards.

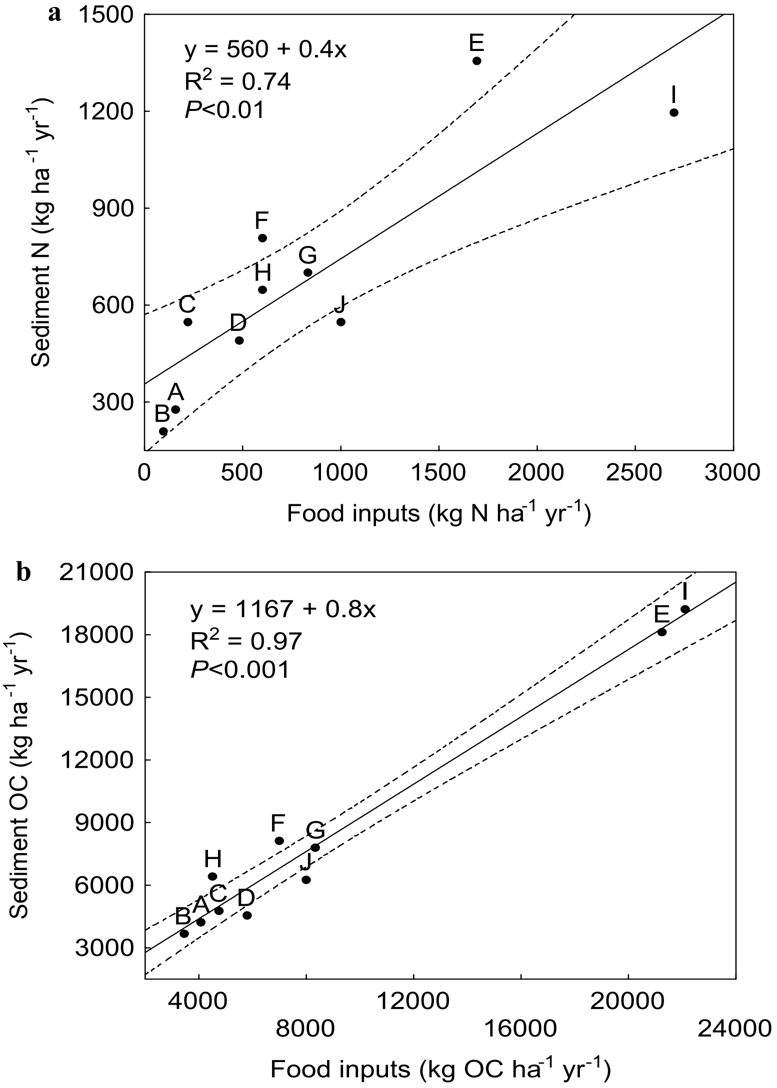

Figure 4. Relationship between total food inputs (kg N ha^{-1} yr^{-1}) and sediment nutrient accumulation (kg ha^{-1} yr^{-1}) across the ponds: N (a) or OC (b). For each point, the nearby letter indicates the pond. Regressions line with the confident level at 95%, the coefficient of determination (R^2) and the significant level.

In intensive ponds, 11-27% N, 26-65% OC and 30-32% P of the total food inputs are recovered in harvested fish (Avnimelech and Lacher, 1979; Boyd, 1985; Krom et al., 1985; Edwards, 1993). In semi-intensive ponds, harvest accounts for 5-25% of N, 2% of OC and 5-18% of P inputs (Sinha et al., 1980; Edwards, 1993; Acosta-Nassar et al., 1994; Green and Boyd, 1995a). In the present study, the percentage of input nutrient recovered in fish was comparable with that in semi-intensive fish farming systems, but much lower than that in the IAA-systems in the northeast Thailand (Pant et al., 2005) and in intensive systems. Li (1987) and Ruddle and Zhong (1988) estimated that the energy recovered in fish was 7-10% of the total biological energy inputs to IAA-ponds.

4.2. Water and nutrient use efficiency, component integration and sustainability

Pond aquaculture is an water-intensive farming (Boyd and Gross, 2000). Extensive stagnant-water ponds on the average use 45 m^3 water per kg fish produced, of which 5 m^3 are due to drainage, and the rest is lost through evaporation and seepage (Verdegem et al., 2006). Ponds D, E and F (Fig. 1a) daily exchanged a small water volume, and had a flow-through of 3-5 m^3 per kg fish produced, similar to that of a pellet-fed pond with two crops per year, and drainage between production cycles (Green and Boyd, 1995b; Verdegem et al., 2006). Water use in the low water-exchange ponds A, B and C was already higher and water use efficiency lower. Besides being profitable and nutrient-efficient, to be sustainable, pond culture should be water-efficient (Boyd and Gross, 2000).

Within IAA-farms, the terrestrial farming activities determine pond management, and hence fish yields. In low water-exchange ponds A, B and C, fish yields were lower than those recorded for IAA-ponds in the Mekong delta (Pekar et al., 2002), in northern Vietnam (Luu et al., 2002) and in the northeast Thailand (Pant et al., 2004). In these low-water exchange ponds studied, pond shading by fruit canopies (about 65% of the pond surface at noon in June), low overall nutrient input levels and the low nutritional quality of falling leaves and fruits contributed to low phytoplankton biomass (Nhan et al., 2006), and hence low fish yields and low nutrient accumulation rates in the sediments. On the contrary, the high water-exchange ponds were less shaded by fruit canopies (about 10% of the pond surface at noon in June) and more intensively managed. Pig production was an important farming activity, and the ponds were used to dispose manure. Snails and crabs collected from the fields or commercial feed significantly contributed to pond feeding. In these ponds, fish production was in the range of that recorded by Luu et al. (2002) and Pekar et al. (2002) and was higher than that reported by Pant et al. (2004).

In excreta-fed ponds, maintaining high fish production and economic profitability while minimizing nutrient discharges contributes to environmental sustainability (Edwards, 1998; Naylor, et al., 2000). In the present study, on the one hand, fish yield averaged 12 kg ha^{-1} day^{-1} and about 10.8 kg manure was required to produce one kg fish (assuming dry manure N content is 2.8%). This was lower than the 20 kg ha^{-1} day^{-1} reported by Zhu et al. (1990) with a manure conversion rate of 8.3 kg dry manure per kg of fish produced. In addition, N and P use efficiency of the study ponds was lower than that reported by Edwards (1993) for manure-fed ponds in IAA-systems. One reason of course is the high water exchange practiced in excreta-fed ponds. On the other hand, the low water-exchange system could be considered more sustainable than the high water-exchange system, since in the latter a significantly lower fraction of input nutrients was harvested and a higher fraction was discharged per kg of fish produced. In both systems, the fraction of input nutrients discharged was higher than that reported for a stagnant-water channel catfish system (Boyd, 1985) and an integrated pen-cum-pond system (Yi et al., 2003).

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 discharge from ponds to be small. This was however not the case at our study sites. Disadvantages of high water-exchange rates include: (1) flushing out algae and nutrients, otherwise retained in ponds (Nhan et al., 2007), (2) potential public heath risks involved (Colman and Edwards, 1987; Csavas, 1993) and (3) eutrophication of adjacent surface waters (Nhan et al., 2006). Nutrient concentrations of pond water were higher than those of canal water, hence pond culture contributed to nutrient enrichment of the canal water. In the study areas, the canals serve for both water supply and drainage. During the culture period the average

COD concentration was close to the maximum limit (10 mg l^{-1}) allowed by the Vietnamese quality standards for domestic use of surface waters (TCVN 5942-1995; Trinh, 1997). The results of the present study confirm our hypothesis. Considering that more resource-poor farmers might take up the IAA-farming systems, in the long run, conflicts among water users for IAA-farming, domestic and industrial purposes and environmental protection would develop. A better management of pond water outflows will therefore be necessary for future development of IAA-farming in the Mekong delta.

There remains room to further improve the fraction of pond nutrient inputs harvested as fish, accumulating in the sediments and retained in terrestrial crops within IAA-farming systems in the Mekong delta. When doing so, it is important that the improvements made also enhance economic and environmental performance. Three interrelated principles guiding improvement are: (1) optimization of the quantity and quality of on-farm nutrient inputs applied, (2) minimization of effluent reaching adjacent waterways and (3) maintaining pond water quality. Firstly, the low water-exchange narrow ditches between fruit trees like those on farms A, B and C should receive more nutrients, either manures or inorganic fertilizers. This will increase fish yield and more nutrients will accumulate in the sediments, which can be easily applied to the adjacent trees, hence soil fertility in the orchard will be maintained. In addition, reducing shading of the narrow ditches by pruning of fruit tree branches will improve primary production, resulting in more food for the fishes and more nutrients accumulating in the sediments (Nhan et al., 2006, 2007). Secondly, in the high water-exchange ponds, the nutrient load - mainly excreta - should be properly managed. Farmers should not discharge excess nutrients through their ponds but consider also alternative uses. These include composting and storage for later use, digestion for biogas production, or the production of invertebrates as live feed for farm animals or fish (Nuov et al., 1995). The nutrient-rich pond sediments could be recycled through the production of lotus (Yi et al., 2002) or other aquatic macrophytes. Restricting pond nutrient loads will reduce the need to apply high water exchange rates and when pond water exchange is practiced, the nutrient-rich outflow water from ponds can irrigate other aquatic or terrestrial crops (McMurtry et al., 1997; van de Steen et al., 1998). An aspect not considered in this study is the composition and density of the fish species stocked.

Particularly in excreta-fed ponds, species combination influences water quality and the availability of natural food resources (Zhu et al., 1990; Delincé, 1992). The performance of IAA-systems depends on several variables (Nhan et al., 2006). The systems are dynamic, adjusting rapidly to new opportunities and threats (Little et al., 2007b; Ruben, 2007). Therefore, the suggested improvements will be successful when applied following a Participatory Learning in Action approach, which is discussed in chapters 1 and 6 of this thesis.

4.3. Study limitation

In the present study, differences between the total water inflow and outflow were small. The inflow from runoff was not measured. In all farm monitored, pond watersheds were small because the pond dike top surface was slightly concave. Moreover, during the study, dikes were not flooded.

Quantities of nutrients lost through the outflow water could be over-estimated, particularly N. In tropical semi-intensive freshwater fish ponds, nitrogen fixation averages 90 kg N ha^{-1} $year^{-1}$ (Acosta-Nassar et al., 1994), a small amount compared to the N surplus. We found that the N surplus increased with the amount discharged with the outflow water (not presented in the results), suggesting that in ponds with high water-exchange rates, the amounts of nutrients discharged are easily miscalculated. The assumption was made that pond water is thoroughly mixed before discharge, but the latter is questionable in ponds where inflow and outflow passes through the same pipe(s). Consequently, nutrient concentrations of the outflow water could be much lower than those of the thoroughly mixed sample used for the estimation.

N volatilization, denitrification, photosynthesis and respiration all influence the nutrient budget in ponds, but were not measured in the present study due to manpower constraints. In future studies, partial water and nutrient budgets can be simplified considering only the major sources and sinks of N and P. The initial filling water volume, rainfall, evaporation and aquatic plant harvested, which consumed time and manpower, can be omitted.

However, the number of farms monitored should be increased to deal with variability among farms.

5. Conclusion

The present study identifies weaknesses and stresses new insights for further development of IAA-farming systems in the Mekong delta. Farmers used water lavishly in IAA-pond fish farming, particularly in high-water exchange ponds receiving livestock and/or human excreta. On-farm livestock manure was the most important nutrient source. A small fraction of the nutrient inputs was recovered in fish yields, while the largest fraction was accumulated in the sediments, or was lost with outflow water. Increased use of on-farm nutrient sources for ponds can increase fish yields and nutrient accumulation in pond sediments at the cost of large quantities of pond nutrients discharged with outflow water. Good management practices of ponds and further integration on water and nutrient flows between the pond and the other farm components can maximize productivity and profitability while minimizing environmental impacts of the farm as a whole. Continued monitoring of water and nutrient use efficiency in relation to productivity and profitability is necessary to judge the effectiveness of the proposed improvements, and to further fine-tune where possible.

Acknowledgements

The study was conducted as apart of the cooperative research project *Improved resource use efficiency in Asian integrated pond-dike systems* (INCO Pond-Live, ICA4-2000-20034), funded by the European Commission. Special thanks are for the ten farmers and Mekong Delta Development Research Institute’s staff with their wholehearted participation in the study.

Chapter 5

Economic and nutrient discharge tradeoffs of excreta-fed aquaculture in the Mekong Delta, Vietnam

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Submitted

Abstract

The present study quantifies the effects of the use of livestock or human excreta for pond farming on pond dissolved oxygen (DO), water exchange, nutrient accumulation, fish yields and economic return. On-farm data from various studies were integrated and analyzed applying single and multiple regression methods. Results from the multiple regression analysis showed that pond DO concentration, water exchange and effluent discharge interacted and were strongly affected by input level. Increased input levels coincided with farmers exchanging more water and discharging more chemical oxygen demand (COD), nitrogen (N), phosphorus (P) and total suspended solids (TSS). Results from the single regression analyses showed that fish yield and the accumulation of organic carbon, N and P in pond sediments were positively affected mainly by the excreta input level. Using a regression model, it was predicted that with an excreta input of 5 kg N ha^{-1} day^{-1}, a fish yield of 8379 kg and an economic return of 52 million VND ha^{-1} yr^{-1} can be obtained while about 2057 kg COD, 645 kg N, 213 kg P and 39203 kg TSS ha^{-1} yr^{-1} are discharged. At this input level, it was estimated that about 9% of input-N is recovered in harvested fish while 52% accumulates in the sediments. Hence, fish culture reduces the direct nutrient discharge from human and pig excreta by 61% while generating income for farmers. Further development of excreta-fed pond farming should focus on a further reduction of nutrient discharge while maintaining a favorable economic return.

Key words: Excreta-fed aquaculture; Integrated Agriculture-Aquaculture; Economics, Environment; Vietnam

1. Introduction

In northern Vietnam, integrated aquaculture-agriculture (IAA) farming has a long tradition (Luu et al., 2002). In contrast, in southern Vietnam, particularly the Mekong delta, IAA-farming was recently introduced and is still developing. Mostly, IAA farms include a pond or ditch, a fruit orchard, a rice field and livestock (pigs, chicken or ducks) (Pekar et al., 2002; Nhan et al., 2007). An important advantage of IAA-farming is the potential to cycle nutrients between farming activities (Little and Muir, 1987; Prein, 2002). Pond-based diversification of farming activities was effective in improving food security and income of poor farming households in developing countries (Prein, 2002; Karim, 2006). Recognizing the importance of aquaculture as part of integrated farming systems, since 1999, the Vietnamese government promotes IAA-farming as a means to improve income of small-scale farmers and to enhance agricultural sustainability (Luu, 2002; Nhan et al., 2007). In Vietnam, extension agencies usually put emphasis on aquaculture technology with the goal to improve productivity and profitability. In consequence, pond culture is gradually intensifying and commercializing (Bosma et al., 2005).

In Vietnam, the use of animal and human excreta in fish ponds is socially accepted (Luu, 2001; chapter 4) and in the Mekong delta human and animal excreta are the principal pond nutrient input. IAA-farmers usually perceive terrestrial crops and livestock as primary activities, viewing pond culture as the secondary activity that is useful to dispose of human and animal excreta (Pekar et al., 2002; Nhan et al., 2007). In general, farmers do not control the excreta load to the pond as the goal is to dispose them of. In case of excreta overloading the water quality in the pond is maintained by flushing (Pekar et al., 2002; chapter 4). As a result, high quantities of nutrients are discharged from excreta-fed ponds (Nhan et al., 2006). Nevertheless, if the human and animal excreta would be discharged directly to surface waters, the pollution would be much larger. High input levels of excreta result in large amounts of nutrients that accumulate in the sediment, from where they can be extracted to fertilize crops within IAA-systems. In consequence, a major fraction of the potential pollution from excreta is mitigated through aquaculture.

Several studies reported the effects of manures on water quality (Boyd, 1990; Delincé, 1992; Lin et al., 1997), fish yields, economic returns (Wohlfarth and Schroeder, 1979; Zhu et al., 1990; Diana, 1991) and public health risks (Colman and Edwards, 1987; Piedrahita and Tchobanoglous, 1987). In these studies, little emphasis was put on integration of farming activities. In the Mekong delta, the type of farming activities in IAA-system are strongly determined by agro-ecological factors (Nhan et al., 2007), household's livelihood options (Bosma et al., 2005, 2006), and seasonal matching of activities (Nhan et al., 2006). Within this context each IAA farmer should aim at maximizing productivity of the whole farm (Edwards, 1998). As part of a broader research project aiming to improve the nutrient use efficiency in IAA-systems in the Mekong delta, this study quantifies the effect of the use of pig and human excreta in pond farming on dissolved oxygen levels, water exchange, nutrient accumulation, fish yields and economic return. This information will allow to conceptualize further improvements to IAA-farming systems in the Mekong delta

2. Materials and methods

2.1. Background

The dataset covered a three-year monitoring period between August 2002 and May 2005. During these 3 years, the mass flows of water, nitrogen (N), organic carbon (OC) and phosphorus (P) through ponds were quantified, and fish production and economic returns were recorded. The Participatory Learning in Action approach was followed to generate improved technologies adapted to farmers needs (Haverkort, 1991; Stür et al., 2002). The first year was a situation appraisal (Nhan et al., 2007), analyzing the water and nutrient mass flows through the pond, and identifying different indicative IAA-systems located in fruit- and rice-dominated areas (Nhan et al., 2006). In the second year, based on results obtained from the first year, improvements to the various IAA-systems were proposed, tested and monitored. The results of the improvements were analyzed and suggestions for further improvements were made. This cycle of intervention, monitoring, analyzing and evaluation was continued in the third year.

The study was carried out at three sites in the Mekong delta (latitude 9°40'-10°40' N, longitude 105°10'-106°10' E) (Fig. 1, chapter 2). The study sites are characterized as monsoon tropics with an annual rainfall of 1.4-1.6 m, mainly from May to November (data from provincial weather stations). Site 1 was an area dominated by intensive fruit production and fertile alluvial soils, and with an elevation of 1.0-1.5 m above mean sea level. Farmers perceived fruit production as the principal farming activity for economic value. Farms from sites 2 and 3 were pooled. Both sites are rice-dominated areas with less intensive fruit farming in less fertile soils and with an elevation of 0.5-1.0 m above sea level. Farmers perceived rice production as the principal farming activity for economic value.

2.2. Pond systems

The present analysis employed the dataset of nine farms, where livestock and human excreta were used as the major source of nutrients for the pond. The farms were fixed over the three consecutive years (Table 1). The monitored ponds were rectangular and measured between 329 and 1584 m^2. The shading by canopies by fruit trees was on average 65% of the pond surface at noon in June in the fruit-dominated area while it was less than 10% in the rice-dominated area (unpublished data). The monitored ponds were described in chapters 3 and 4.

The farmers stocked many different fish species with fingerlings bought from local hatcheries (Table 2). Species selection depended on on-farm food availability, fish selling prices, consumer preferences and local availability of fingerlings. Before stocking the fingerlings, pond sediments from the previous fish crop were removed and disposed on adjacent orchard dikes to minimize residual effects of nutrient stores in the sediments as a result of previous farming cycles (Knud-Hansen, 1992). Wild fish and possible predators were eradicated with *Deris eliptica* root or quick lime. Average individual weights of stocked fingerlings were 8-15 g for *Pangasianodon hypophthalmus* and 3-8 g for the other species. Food sources were mainly on-farm by products from other farming activities, including human and animal excreta, rice or fruit by-products, and home-made feed. The home-made feed was prepared from ground crab and golden snail collected from rice fields, rice bran, broken rice and fish powder or commercial feed. Chemical fertilizers were not the important input of all the farms monitored, which is typical in the Mekong delta (Pekar et al., 2002).

Table 1. Major properties of the ponds monitored for three years

Sites	Ponds	Monitoring years	Surface areas (m^2)	Mean widths (m)	Mean depths (m)	Range in stocking rates (fish m^{-2})	Range in growing period (days)	Pond: orchard ratio
1	A	1, 2, 3	652	2.6	0.58	1.5 – 6.2	192 – 340	1:4.3
1	B	1, 2, 3	1327	1.9	0.70	1.4 – 5.0	192 – 340	1:4.7
1	C	1, 2, 3	624	2.3	0.60	1.2 – 7.0	192 – 341	1:3.1
1	D	1, 2, 3	329	9.9	0.73	2.0 – 12.8	244 – 294	1:2.0
2	F	1, 2, 3	1584	35.4	0.65	2.7 – 4.8	115 – 239	1:1.1
2	G	1, 2, 3	1241	23.1	0.85	2.0 – 4.8	302 – 361	1:1.7
2	H	1, 2, 3	1011	5.1	0.81	4.8 – 7.4	286 – 315	1:2.2
3	I	1, 2	960	13.1	1.79	6.8 – 17.3	517 – 562	1:0.4
3	J	1	483	9.0	1.53	3.3	648	1:0.9

During the first year, farmers applied livestock and human excreta and practiced pond water exchange as routinely applied in their communities. In the second and third years, farmers were encouraged to control the manure input and the water exchange. Manure and urine collected from 30 to 85 pigs per ha were applied (Delmendo, 1980; Little and Muir, 1987), and the water exchange was only practiced when the Secchi disk depth dropped below 10 cm coinciding with fishes surfacing and gulping for air in the early morning. Ponds were directly connected with surrounding rivers or canals with a pipe, serving as both inlet and outlet. The water exchange depended on the tide in adjacent estuaries. Fishes were harvested in batch cropping.

Table 2. Main fish species stocked in the ponds during the three monitored years (%)

Fish species	Ponds								
	A	B	C	D	F	G	H	I	J
Silver barb (*Barbodes gonionotus*)	10–23	10–44	9–35	17–37	0–51	11–21	18–41	0–7	10
Grass carp (*Ctenopharyngodon idella*)	0	0	0	0	0–7	17–30	0	0	0
Silver carp (*Hypophthalmichthys molitrix)*	37–45	0–16	28–51	22–37	7–8	6–9	2–13	0	0
Nile tilapia (*Oreochromis niloticus*)	0–15	1–15	2–15	3–15	12–21	6–36	3–41	36–38	0
Common carp (*Cyprinus carpio*)	0	0	0	0	0–19	0–17	2–25	3–12	5
Mrigal (*Cirrhina mrigala)*	20–43	35–53	33–43	21–43	0	0	0–26	0	0
Kissing gourami (*Helostoma temminckii*)	0	0	0	0	9–67	6–18	0–26	0–7	16
River catfish (*Pangasianodon hypophthalmus*)	0–6	0–6	0–6	0–6	0–2	5–23	5–23	5–7	52
Hybrid catfish (*Clarias macrocephalus* x *C. gariepinus*)	0	0	0	0	0–43	0	0	0	0

2.3. Sampling and data calculations

Water exchange and net discharge

Each year, the surface and bottom area of each pond was measured before stocking. A staff gauge was installed in each pond so that the farmer could record daily the water depth, as well as changes during filling or draining. The volumes of the water supply and discharge were estimated indirectly by multiplying depth changes by surface area. The water exchange rate was calculated as a percentage of the pond volume (% volume day^{-1}). Pond net discharge of chemical oxygen demand (COD), N, P and total suspended solids (TSS) was calculated as the difference between inflow and outflow and expressed in kg ha^{-1} day^{-1}. The inflow and outflow quantities were calculated by multiplying the respective water volumes by the concentrations measured on the nearest date.

Water quality parameters

Dissolved oxygen (±0.01 mg/l) was measured fortnightly in the morning (07:30–08:30 h) and afternoon (13:30–14:30 h) using portable electronic probes at 5 - 6 representative locations (inlet or outlet, livestock pens, fruit canopy areas, and the centre) at three water depths (15 cm below the surface, mid-water column and 15 cm above the bottom) in each pond. Chlorophyll-*a* was sampled fortnightly. COD, N, P and TSS were sampled monthly starting at stocking. Water column samples were taken using a PVC tube (5.8-cm inner diameter) from the 5 - 6 representative locations were mixed, and used to analyze chlorophyll-*a* (acetone extract), COD (dichromate reflux), N (persulfate digestion), P (persulfate digestion and ascorbic acid) and TSS (Clesceri et al., 1998). On sampling days, also the canal used to fill the ponds was sampled at three random locations close to the sluice-gate. The analytical methods applied for the canal water were the same as for the pond water.

Fish yield

The net fish yield was calculated as the difference in total fish biomass between stocking and harvesting and expressed in kg ha^{-1} $year^{-1}$. At stocking, per pond, 0.5 kg fish fingerlings of each species stocked was collected to determine the average individual body weight. At harvesting, the total biomass per species was recorded.

Sediment nutrient accumulation

In each pond, bottom sediments were collected at fish harvesting. A reference level and the depth of the accumulated sediments were determined using graduated sticks firmly installed at 5 - 6 locations in each pond. At each location, the sediments were sampled using a 5.5-cm diameter soil core sampler (Boyd, 1995). Sediments taken from the different locations in each pond were thoroughly mixed into a composite sample for further analysis. The composite samples were air-dried and then analyzed for N (Kjeldahl), OC (Walkley-Black), and P (persulfate digestion and ascorbic acid) (Page et al., 1982). Quantities of the nutrients accumulating in the pond sediments were expressed in kg ha^{-1} yr^{-1}.

Pond nutrient inputs

Nitrogen was used to explore the effect of pond nutrient inputs. Reasons include: (1) fish N assimilation efficiency has important implications for sustainability of pond aquaculture (Hargreaves, 1998), (2) N can be used as a proxy for organic carbon and phosphorus in understanding relationships between pond, food inputs, water quality and nutrient accumulation (Nhan et al., 2006), and (3) N is one of the major nutrients in the pond ecosystem (Delincé, 1992). Amounts of all inputs, including rice bran, fish meal, concentrated feed, snail or crab and crop residues, were recorded daily by the farmers. Samples of each material used as the food input were analyzed for N (Kjeldahl) following Williams (1984) for the different food types and manures and Clesceri et al. (1998) for urine. Livestock manure and urine were sampled monthly. The daily feces and urine production by household members were estimated at 0.4% and 1.5% of body weight, respectively (cited in Little and Muir, 1987). The combined livestock and human excreta were the largest input of nitrogen and are further referred to as "excreta". Nitrogen inputs by type were calculated by multiplying the recorded quantity by the measured N concentrations and expressed in kg N ha^{-1} day^{-1}.

Economic parameters

Economic return and costs were calculated as a function of excreta input level. It was assumed that gross return from fish production and the costs for sediment removal and effluent discharge are a function of excreta input levels. The return above variable costs (RAVC) of fish farming is the difference between gross return and total variable costs. The gross return was indirectly estimated by multiplying the fish yield by an average farm-gate price of 8600 VND kg^{-1} (Vietnamese currency; 1 Euro = 20,000 VND, June 2005). The total variable costs include pond sediment removal (9,000 VND ton^{-3} dry sediments) plus fish production costs. The latter was estimated at 15.91 million (mil) VND ha^{-1} yr^{-1}, including fingerling, purchased feeds, chemical fertilizers, lime, hired labour, on-farm feeds and family labor with the exception of labour devoted to fish feeding and water management. On-farm food and family labor costs were based on opportunity costs. In 2003, the Vietnamese government put a tax of 200 VND per kg COD and 300 VND per kg TSS discharged to surface waters by the industry. No levies were put on N and P discharge. These values were used to estimate environmental costs of pond nutrient discharges.

2.4. Statistical analysis

Single regression analysis was used to analyze the effects of the excreta input (independent variable) on fish yield and N, OC and P accumulation in the sediments. The following dependent variables were used in multiple linear regression analysis (Table 3): (1) morning DO, (2) afternoon DO, (3) pond water exchange rate, and (4) net discharge of COD, (5) N, (6) P, and (7) TSS. Previous studies found that farmers base the water exchange rate on nutrient input levels, and that fish production and nutrient input levels are influenced by the agro-ecological setting (fruit- or rice-based areas) (Nhan et al., 2006, 2007). It was assumed that the dependent variables are determined by the independent variables (Table 3): (1) technological intervention, (2) agro-ecological setting, (3) pond width, (4) home-made feed input, (5) crop residue input, (6) excreta input and (7) chlorophyll-*a* concentration.

A yearly dataset, in which the home-made feed, crop residue and excreta inputs were averaged out on a kg N ha^{-1} day^{-1} basis, was used. An initial dataset from 9 ponds for 3 consecutive annual production cycles was used, but in 3 pond-year combinations the input level of home-made feeds was excessively high, and these data were not used. The yearly dataset was used for the single regression analysis (n = 24) while a monthly dataset was used for the multiple regression analysis (24 pond observations with 6-10 months each). 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, erasing residual effects from previous crops.

Before applying 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 the multiple linear regression models, 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 multicollinearity 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 strength of the coefficient of determination (adjusted R^2), (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 (Hair et al., 1998).

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, 1, 2, 3, 4 and 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 in the regression models

Dissolved oxygen

The excreta N inputs were closely correlated to the total N inputs, including inorganic fertilizers (Fig. 1). The excreta, to which livestock manures contributed 91%, on average provided 75% of the total N inputs.

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

Table 3. Arithmetic mean, standard deviation (SD) and sample size (n) of variables used in multiple regression models. n, sampling size

Variables	Models													
	Morning DO (n = 200)		Afternoon DO (n = 200)		Water exchange (n = 209)		COD discharge (n = 188)		N discharge (n = 193)		P discharge (n = 190)		TSS discharge (n = 191)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dependent var[1]	1.02	0.51	3.02	1.75	7.39	9.69	3.07	5.50	0.93	1.61	0.25	0.74	59.1	93.0
Independent var[2]														
Intervention					0.50	0.50	0.48	0.50	0.48	0.50	0.47	0.50	0.47	0.50
Agro-ecology					0.56	0.50	0.52	0.50	0.52	0.50	0.52	0.50	0.52	0.50
Pond width	9.37	9.12	9.20	8.90	9.32	8.97	8.55	8.52	8.65	8.47	8.60	8.53	8.58	8.45
Home-made food	0.29	0.66	0.27	0.66	0.27	0.65	0.24	0.65	0.24	0.65	0.24	0.65	0.24	0.65
Crop residue	0.03	0.06	0.03	0.06	0.03	0.05	0.03	0.06	0.03	0.06	0.03	0.06	0.03	0.06
Excreta	2.11	3.55	2.12	3.65	2.09	3.48	1.99	3.43	1.97	3.18	1.75	2.65	1.98	3.32
Chlorophyll-*a*			110	123										

[1] Dependent variables: DO (mg l^{-1}), water exchange (% pond volume day^{-1}), COD, N, P and TSS discharge (kg ha^{-1} day^{-1})

[2] Independent variables Intervention (dummy; 0 = without intervention, 1 = with interventions), agro-ecology (dummy; 0 = fruit-dominated, 1 = rice-dominated area), pond width (m), home-made food, crop residue, excreta (kg N ha^{-1} day^{-1}), and chlorophyll-*a* (µg l^{-1})

of the nutrient input (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 mean 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 in 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 nutrient input levels accounted for most of the variability of morning DO levels, whereas chlorophyll-*a* explained most of the DO variability in the afternoon.

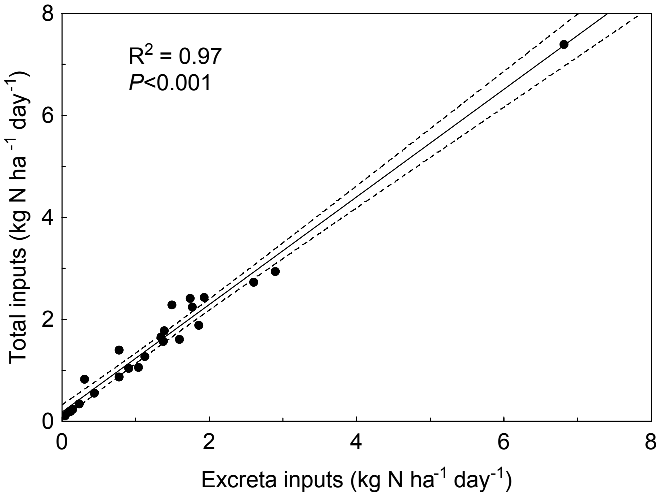

Figure 1. The relationship between the N inputs from excreta and the total N inputs (including inorganic fertilizers). Regression line with the confident level at 95%, the coefficient of determination (R^2) and the significant level.

Water exchange

Water exchange rates were significantly and positively affected by agro-ecological zone and excreta input levels, and negatively by technological interventions, pond width and home-made feed inputs ($P<0.001$, $R^2 = 0.66$; Table 4). Farmers practiced higher water exchange rates in ponds located in the rice-dominated areas or in ponds receiving higher input levels of crop residues or 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 accounted for most of the variability in pond water exchange rates.

Effluent 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). Amounts of COD, N, P and TSS discharged through the outflow water were significantly affected by agro-ecological sites, excreta inputs, technological interventions and pond width. In addition, COD and TSS discharge were negatively correlated with home-made feed inputs. Higher discharges occurred in ponds located in the rice-dominated areas receiving more excreta. For all sites, in general, lower discharges occurred in wider ponds or ponds where technological interventions were applied or ponds receiving home-made feed. The beta coefficients indicate that excreta accounted for most of the variability.

Fish yields

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

Sediment nutrient accumulation

The total volume of *sediments* and accumulation of N, OC and P in the sediments linearly increased with the amount of excreta applied (Figure 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.

Table 4. Results of multiple regression models of dissolved oxygen (DO) concentrations and water exchange rate. Regression coefficient (b) with standard error (SE) and standardized coefficient (beta)

Independent variables and parameters	Morning DO [$\log_{10}(y+1)$]			Afternoon DO			Water exchange		
	b	SE	beta	b	SE	beta	b	SE	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)[1]	-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)[1]	-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***	7.16	0.81	
Intercept	0.34	0.01		2.72	0.19		7.16	0.81	

Significance of the independent variables: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

[1] log transformation is applied for morning and afternoon DO

Table 5. Results of multiple regression models for pond effluent discharges (COD, N, P and TSS). Regression coefficient (b) with standard error (SE) and standardized coefficient (beta)

Independent variables and parameters	COD			N [$\log_{10}(y+1)$]			P [$\log_{10}(y+1)$]			TSS		
	b	SE	beta	b	SE	beta	b	SE	beta	b	SE	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)[1]	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	

Significance of the independent variables: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

[1] log transformation for the N model only

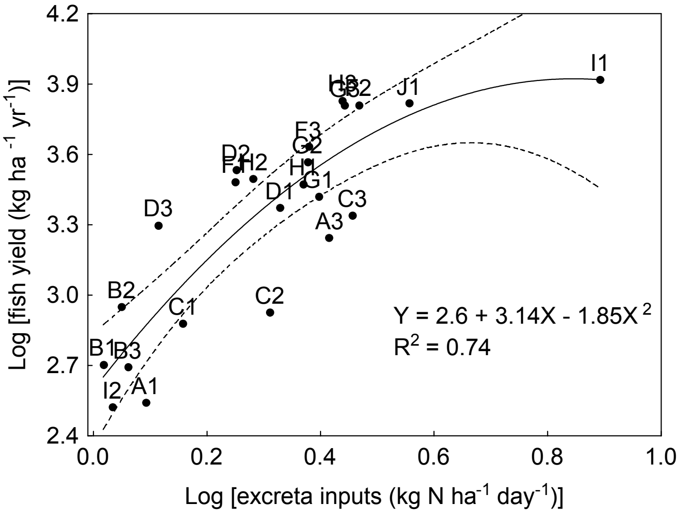

Figure 2. The relationship between fish yields [$\log_{10}(y)$] and excreta inputs [$\log_{10}(x+1)$] across the ponds monitored for 3 years. Regression line with the confident level at 95%, the coefficient of determination (R^2) and the regression equation. For each point, the nearby letter indicates the pond and the number indicates the year.

3.2. Predictive effects of different excreta input levels

The regression equations established for the various dependent variables are given in Table 6. To predict the effects of different excreta input levels, it was assumed that the other predictors included in the equations are constant at their mean values (given in Table 3).

The effects of excreta application were calculated with input levels set at 0, 1, 2, 3, 4 and 5 kg N ha^{-1} day^{-1} (Table 7). 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 3.7 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.

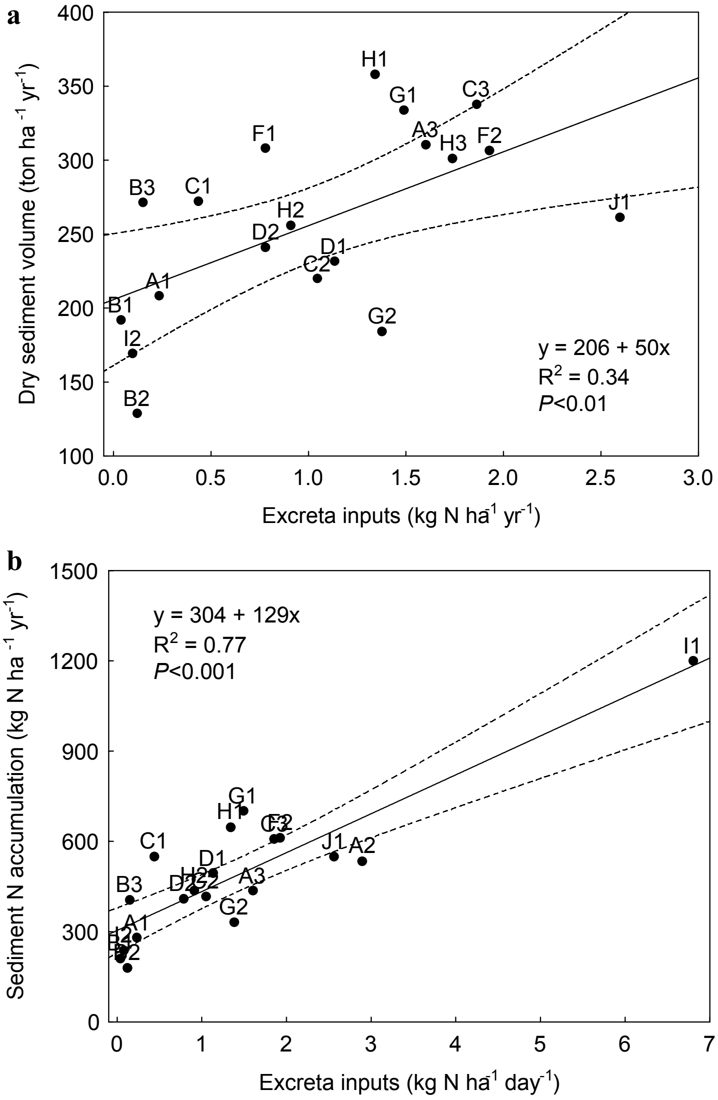

Figure 3. The relationship between sediment accumulation and excreta inputs across the ponds monitored during the 3 years: (a) dry sediments and (b) sediment nitrogen (N). For each point, the nearby letter indicates the pond and the number indicates the year. Regression line with the confident level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

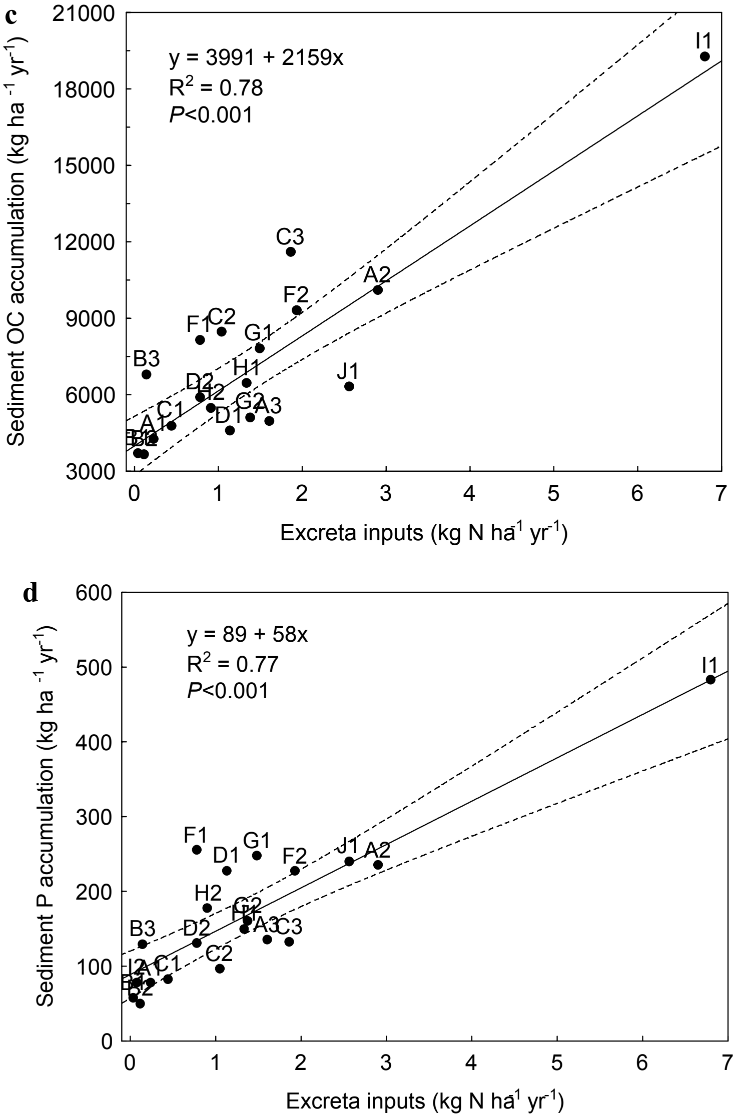

Figure 3 (Continued): (c) organic carbon (OC), and (d) phosphorus (P).

Table 6. Predictive equations of the dependent variables

Dependent variables	Predictive equations[1]
Morning DO (AMDO, mg l^{-1})	$\mathrm{Log}_{10}(\mathrm{AMDO}+1) = 0.34 + 0.002\ \mathrm{PWID} - 1.63\ \log_{10}(\mathrm{HMF}+1) - 0.30\ \mathrm{CRES} - 0.19\ \log_{10}(\mathrm{EXC}+1)$
Afternoon DO (PMDO, mg l^{-1})	$\mathrm{PMDO} = 2.72 + 0.06\ \mathrm{PWID} + 0.006\ \mathrm{CHLO} - 1.67\ \log_{10}(\mathrm{HMF}+1) - 1.90\ \log_{10}(\mathrm{EXC}+1)$
Water exchange rate (WEXC, % volume day^{-1})	$\mathrm{WEXC} = 7.16 - 7.62\ \mathrm{INTV} + 6.04\ \mathrm{AGRO} - 0.16\ \mathrm{PWID} - 3.39\ \mathrm{HMF} + 1.34\ \mathrm{EXC}$
Effluent discharge (DIS, kg ha^{-1} day^{-1})	
COD (CODDIS)	$\mathrm{CODDIS} = 1.90 - 2.80\ \mathrm{INTV} + 3.85\ \mathrm{AGRO} - 0.07\ \mathrm{PWID} - 1.35\ \mathrm{HMF} + 0.87\ \mathrm{EXC}$
N (NDIS)	$\mathrm{Log}_{10}(\mathrm{NDIS}+1) = 0.12 - 0.10\ \mathrm{INTV} + 0.16\ \mathrm{AGRO} - 0.004\ \mathrm{PWID} + 0.41\ \log_{10}(\mathrm{EXC}+1)$
P (PDIS)	$\mathrm{Log}_{10}(\mathrm{PDIS}+1) = 0.01 - 0.03\ \mathrm{INTV} + 0.04\ \mathrm{AGRO} - 0.002\ \mathrm{PWID} - 0.04\ \mathrm{EXC}$
TSS (TSSDIS)	$\mathrm{TSSDIS} = 36.2 - 44.8\ \mathrm{INTV} + 78.9\ \mathrm{AGRO} - 2.04\ \mathrm{PWID} - 30.6\ \mathrm{HMF} + 15.2\ \mathrm{EXC}$
Fish yield (YIELD, kg ha^{-1} yr^{-1})	$\mathrm{Log}_{10}(\mathrm{YIELD}) = 2.6 + 3.14\ \log_{10}(\mathrm{WAST}+1) - 1.85\ [\log_{10}(\mathrm{EXC}+1)]^2$
Sediment accumulation (ACC, kg ha^{-1} yr^{-1})	
Sediment volume (SV)	$\mathrm{SV} = 206 + 50\ \mathrm{EXC}$
N (NACC)	$\mathrm{NACC} = 304 + 129\ \mathrm{EXC}$
OC (OCAC)	$\mathrm{OCAC} = 3991 + 2159\ \mathrm{EXC}$
P (PACC)	$\mathrm{PACC} = 89 + 58\ \mathrm{EXC}$

[1] AGRO (agro-ecological zone), CHLO (chlorophyll-a), CRES (crop residue), INTV (technological intervention), HMF (home-made feed), PWID (pond width), EXC (excreta).

The sediment volume and the quantities of N, OC and P accumulating in the sediments increased with increasing excreta input. For each additional kg excreta-N ha^{-1} day^{-1} added, 50 tons sediments accumulated in the sediment, retaining on average 130 kg N, 2160 kg OC and 58 kg P ha^{-1} yr^{-1}.

Without excreta, 400 kg fish ha^{-1} yr^{-1} are produced corresponding with a negative RAVC. The highest fish yield and RAVC are obtained applying 5 kg N ha^{-1} day^{-1}, 8380 kg fish and 52 mil VND ha^{-1} yr^{-1}, respectively. For excreta input between 0 to 3 kg N ha^{-1} day^{-1} each additional kg N added daily increases the fish yield by 2100 kg and the RAVC by 17 mil VND ha^{-1} yr^{-1}. In the input range between 3 to 5 kg N ha^{-1} the fish yield increases 900 kg and the RAVC 7 mil VND ha^{-1} yr^{-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 RAVC is 40 mil VND ha^{-1} yr^{-1} achieved at the highest input level (Table 7).

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 highest input levels.

4. Discussions

4.1. The regression models

Studying well-managed experimental ponds, Prein (1993) and Costa-Pierce et al. (1993) established regression models explaining about 59% of total variance of morning DO in ponds. In the present study this was less, but the independent variables used did not relate directly to photosynthesis, respiration or gas exchange. Similarly for the N discharge, variables related to nitrogen cycle in ponds were not measured or included.

In all the multiple regression models, the obtained R^2 are much higher than the minimum R^2 required for statistical significance with a power of 0.8 (Hair et al., 1998). The estimates of the coefficients of the intercept value are close to the mean of the respective dependent variable, and values found for the standardized beta coefficients of the independent variables are logical. For the single regression models (i.e. fish yield and the sediment nutrient accumulation), each of the dependent variables was highly dominated by excreta input.

Table 7. Predictive impacts of the excreta use in the IAA-pond 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} yr^{-1})						
COD	597	889	1181	1473	1765	2057
N	120	279	396	491	573	645
P	0	35	73	116	162	213
TSS	11426	16982	22537	28092	33647	39203
Fish yields (kg ha^{-1} yr^{-1})	398	2386	4754	6605	7779	8379
Sediment nutrient accumulation						
Sediment volume (ton ha^{-1} yr^{-1})	206	256	306	356	406	456
N (kg ha^{-1} yr^{-1})	304	433	562	691	820	949
OC (kg ha^{-1} yr^{-1})	3991	6150	8309	10468	12627	14786
P (kg ha^{-1} yr^{-1})	89	147	205	263	321	379
Economic parameters (mil VND ha^{-1} yr^{-1})						
RAVC [1]	-14.3	2.3	22.2	37.7	47.3	52.0
Environmental costs (mil VND ha^{-1} yr^{-1})	3.5	5.3	7.0	8.7	10.4	12.2
N use efficiency						
N recovered in fish (%)[2]		12.6	12.6	11.7	10.3	8.9
N accumulating in sediments (%)[3]		118.6	77.0	63.1	56.2	52.0

[1] RAVC = [(yield*8600) – (15.91 + total sediment volume*9000]*10^{-6}; 1EUR = 20,000 VND

2 N 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.

[3] N accumulating in sediments (%) = [total N accumulating in sediment/(total excreta N inputs)]*100

4.2. The effects of the excreta

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 settle directly on the sediment, and is complemented with organic matter from uneaten plankton and from the large amount of excrements produced by herbivorous and omnivorous fish species (Delincé, 1992). 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. Flushing is not always effective, due to a system of connected ditches and because often one pipe serves both as inlet and outlet. Farmers could pay more attention to the design of the pond water inlet and outlet systems, separating them physically, which will allow a better control of the water quality, including DO levels.

Photosynthesis is limited by shading produced by fruit tree canopies bordering ditches, particularly in narrow ditches (Nhan et al., 2006). Such ditches are more sensitive to DO depletion than wide and less shaded ponds. Hence, the need for even a better control of inflow and outflow structures and water quality is greater in narrow ditches than in larger and wider ponds.

In the second and third year, farmers were asked to exchange less water than in the first year, and to control the amount of excreta entering the pond. Still, in the rice-dominated areas, higher water exchange rates were practiced. 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). 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 with the high water exchange rates practiced, increasing the COD and TSS in 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 (Ruddle and Zhong, 1988; Edwards, 1998). In northern Vietnam, wild grasses and rice bran are important nutrient inputs to ponds in IAA-farms, because farm manures are usually strategically used to maintain the productivity of rice, field crops or vegetables (Edwards et al., 2002; Luu et al., 2002). In northeast Thailand, farm manures are limited for ponds in IAA-farms because of the absence of feedlot pigs (Pant et al., 2004, 2005). This was however not the case at our study sites, where intensive feedlot pig production is commonly practiced and canal water is accessible year-around. Therefore, farmers can get high fish yields from pig manure using water lavishly to dilute metabolites in the pond. Several authors reported public health risks from pathogens into the food chain originating from the animal and human excreta (Little and Muir, 1987; Csavas, 1993), fish food safety risks from antimicrobials and antimicrobial residues in livestock feeds entering ponds (Petersen and Dalsgaard, 2003), and water pollution due to excessive nutrient discharges (Nuov et al., 1995; Nhan et al., 2006). More attention therefore should be given to these problems when planning future development of IAA-farming in the Mekong delta.

In extensive ponds without external nutrient inputs, fish yields are about 200–800 kg ha^{-1} yr^{-1} (Prein, 2002). Zhu et al. (1990) reported an average fish yield of 3,723 kg ha^{-1} yr^{-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 7,300 and 10,950 kg ha^{-1} yr^{-1} with a manure input level from 2 to 4 kg N ha^{-1} day^{-1}. A maximum yield in the range of 10,950-12775 kg ha^{-1} yr^{-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} (if dry manure N content is 2.8%). In the present study, excreta input levels were mostly below 3 kg N ha^{-1} day^{-1} and lower yields were achieved. 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. 3). In the Mekong delta, manure-fed ponds yield on average 4,700 to 11,600 kg ha^{-1} yr^{-1} (Pekar et al., 2002). These yields are higher than the 4,000 to 7,000 kg ha^{-1} yr^{-1} obtained from IAA-pond systems in northern Vietnam (Luu et al., 2002).

To produce 1 kg of fresh fish, Edwards (1993) considers that a manure input of 103 to 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 to 7.8 kg dry waste were required, equivalent to 151-219 g N (assuming that 2.8% of dry weight of manure is N). 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; Edwards, 1993; Acosta-Nassar et al., 1994; Green and Boyd, 1995a). In the present study, large amounts of OC 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 (1994) and Green and Boyd (1995a). The percentage of applied N that accumulated in the sediments decreased with input level because higher flushing rates were applied at higher input levels.

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 in especially the qualitative and quantitative aspects of manure application to ponds is needed.

4.3. Reducing pollution from integrated -farming systems through a Participatory Learning in Action approach.

The results indicate that the excreta inputs are necessary to generate income from the pig and human excreta in IAA-farming systems in the Mekong delta. In the long-run the system is not sustainable, considering more farmers might take up excreta-fed aquaculture. In the Mekong delta, poor farmers adopt excreta-fed aquaculture to improve their diets or to generate additional income (Nhan et al., 2007). Extension workers saw the need to improve the nutrient use efficiency and to reduce nutrient discharge from manure-fed ponds in IAA-system. The present study quantified the relation between the nutrient input and output in this system. Through excreta-fed pond culture, the potential nutrient load from human and livestock excreta to surface waters in the Mekong delta was reduced by 55-65%. Still, through a better control of nutrient input levels and water exchange, the environmental impacts could be reduced even more.

A combination of possible solutions should be considered to further develop IAA-farming. The solutions differ between fruit- and rice-dominated agro-ecological zones. Technologically, the goal is to integrate the pond with other terrestrial sub-systems within the IAA-system in such a way that the whole system becomes more productive while less nutrients are discharged. Nhan et al. (2006, 2007) suggested possible options of nutrient management of IAA-ponds guided from three interrelated principles: (1) optimization of the quantity and quality of on-farm nutrient input applied (2) minimization of effluent reaching adjacent water ways and (3) maintaining water quality. Using the Participatory Learning in Action approach, in a coordinated effort between farmers, researchers, policy-makers, extension workers and traders, the obtained results were quickly spreading in the study area. Thus, effective connections were established between politicians, managers, traders, technicians and farmers. Such connectivity between stakeholders is considered necessary in the development of "ecological aquaculture" (Costa-Pierce, 2002).

4.4. Regression analysis method: a tool for the development of IAA-systems

Regression analysis was used to interpret data obtained from a limited number of highly diverse farms. Considering the lack of replicate observations, the use of analysis of variance would not be appropriate in this case (Smart et al., 1998). By using the different regression models, complementary and non-conflicting results were obtained.

In the present study, major drawback were pseudo-replication and the lack of fish-related variables measured. Only a limited number of farms were studied because manpower was lacking to monitor nutrient flows on more farms. Since several samples were taken in the same farm, the samples are not completely independent. The results of the present study, however, can be considered acceptable because the representative models met the assumptions in multiple regression (Hair et al., 1998). In addition, the differences between farms were still increased by the variation in species and densities used. Species compositions and stocking densities certainly affected dissolved oxygen availability, nutrient accumulation in sediments, effluent discharge and fish yields. It was unfortunate that not more fish-related variables could be monitored, because farmers did not like to sacrifice animals or spend time on selective fishing. Therefore, on-station research is recommended to work out optimal species combinations and densities for excreta-fed pond culture in the Mekong delta.

5. Conclusions

This paper demonstrates the economic interest of integrating excreta-fed fish culture in the IAA system 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 essentially a short-term economic interest. In the long run, such an intensive system, extended over a large area, is bound to create trouble due to the excessive nutrient discharges of ponds, particularly in the rice-dominated areas. The challenge is to further reduce nutrient discharges through pond water exchange while maintaining high fish production and profitability, and efficiently using the nutrients accumulating in the sediments of ponds. The use of a participatory technology development approach allowed to make small improvements to the technology used and to visualize the benefits and problems involved. The challenge is to maintain this Participatory Learning in Action approach with the goal to gradually solve the identified problems while maintaining the benefits.

Acknowledgements

The study was conducted as a part of the cooperative research project *Improved resource use efficiency in Asian integrated pond-dike systems* (INCO Pond-Live, ICA4-2000-20034), funded by the European Commission. Special thanks are for the nine farmers and Mekong Delta Development Research Institute’s staff with their wholehearted participation in the study for three years.

Chapter 6

General discussion

1. Introduction

This study monitored and analyzed water use and nutrients flows through ponds that are part of integrated agriculture-aquaculture (IAA) farming systems. The information obtained was linked to the decision level of farmers to explain why a specific IAA-system is adopted. At the decision level, attention was also given to the various roles of ponds in IAA-systems and the economic and environmental effects of pond culture. During the first year of the study, existing IAA-farming practices were analyzed. During the two following years, farmers were asked to make small changes in pond management with the objective to improve the water and nutrient use efficiency of the whole farm. This was done following a Participatory Learning in Action approach (see chapter 1 and below). Focus was put on water and nutrient efficiencies, because strengthened nutrient linkages IAA-farm components is considered the essence in the development of sustainable farming (Little and Muir, 1987; Edwards, 1989; Edwards, 1998; chapters 3-5). Impacts and the potential benefits of IAA-systems to agricultural diversification, people's livelihoods and rural poverty alleviation have been reported earlier (Edwards, 2002; Prein, 2002; van der Zijpp et al., 2007). The Mekong delta offers excellent opportunities for IAA-farming (chapter 2) and the practice is still spreading and developing. By improving the sustainability of IAA-farming, the integrated farming remains an important contributor to the overall food security by providing food, employment and income, especially for the resource-poor.

In this final chapter, the results from the separate studies are integrated and future perspectives and practical implications for the further sustainable development of IAA-systems in the Mekong delta are discussed. Where possible, the consequences to resource-poor households are discussed. The overarching question is what this study contributed to our general knowledge of IAA-systems and if it helped to improve impacts and relevance of services provided by extension agents, policy-makers and researchers. To answer this, the discussion focuses on:

- Contexts and characteristics of IAA-farming systems;

- The roles of ponds, strengths and weaknesses in water and nutrient uses in existing IAA-pond systems;
- Actions that will contribute to the promotion and further development of sustainable IAA-farming; and
- Knowledge gaps and approaches for development of IAA-systems.

2. Contexts and characteristics of IAA-farming systems

The context and major characteristics of commonly practiced IAA-systems in the Mekong delta were described in chapters 2 and 3. The type of IAA-farming was determined by a combination of bio-physical, socio-economic and technological settings at community, household and at farm level (Figure 1). At community level, agro-ecology and market accessibility are major driving factors for farmers to take up aquaculture as a farming activity. At the household level, the decision to do so is influenced by the household's wealth status and the resource base. How the pond will be managed for fish production largely depends on the physical characteristics of the pond, the inputs available and the options for managing outputs, including water and livestock and human excreta. The combination of the aquatic and terrestrial farming activities then determines the IAA-farming systems. In our study areas, three IAA-systems were identified: (1) low-input fish farming in fruit-dominated area, (2) medium-input fish farming in rice-dominated areas, and (3) high-input fish farming in rice-dominated areas with better-off households having good market accessibility. Lewis (1997) reported that aquaculture is likely resource-intensive, so its practice tends to be dominated by the better-off. In this study, the household's wealth status was indeed an important factor in the decision to take up IAA-farming as mainly intermediate and rich households practiced IAA-farming (Nhan et al., 2007). This implies that technical packages alone are not enough to trigger farmers for taking up or for adjusting their existing IAA-farming.

Technical packages, roles and functions that might influence the uptake of IAA-farming differs with wealth groups of households and their related goals (Nhan et al., 2007; Ruben, 2007). For poorer households, the low- or medium-input farming system, which contributes to activity diversification, reduced labour requirement, fish consumption, and risk spreading, could be more attractive. This is an entry point to poverty alleviation and further transition towards production intensification (Little et al., 2007b; Ruben, 2007). For the better-off, on the contrary, profitability-enhancing technologies and management could be more suitable. In Vietnam, particularly in the Mekong delta, these driving factors were paid little attention to when promoting of IAA-systems. Consequently, between 2000 and 2004, the percentage of poor households practicing aquaculture increased only 2%, while 12% and 15%, more households of intermediate and rich farmers, respectively, took up aquaculture (unpublished data).

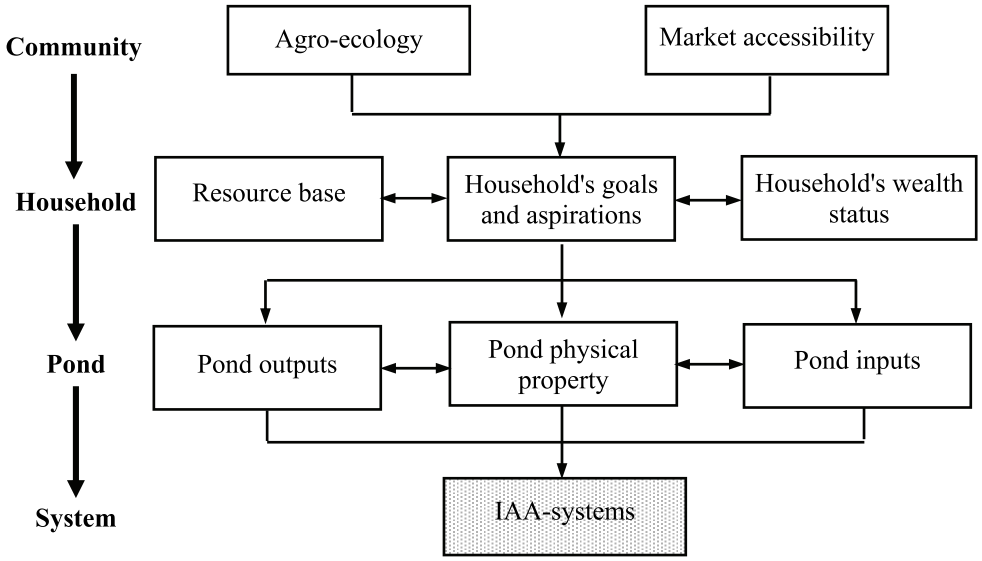

Figure 1. Major determinants of IAA-farming at different levels (community, household and pond) in the Mekong delta: (1) bio-physical (agro-ecology and resource base), (2) socio-economic (market accessibility, household's wealth status, goals and aspirations) and (3) technological (pond physical property and nutrient inputs and outputs) settings.

In the Mekong delta and elsewhere in Asia, IAA-systems are diverse and dynamic (Little and Muir, 1987; Devendra and Thomas, 2002; Prein, 2002; Bosma et al., 2006). To develop

IAA farming, it is important to consider the heterogeneity of the local contexts and resource systems, which influence the pond management and resultant outcomes of farmer's livelihoods. In fact, there is not a standardized model IAA-system that can be universally promoted. Hence, local contexts should be explored first, especially when the goal is to convince resource-poor farmers to take up IAA-farming and making them successful in doing so (chapters 2 and 4).

3. The role of ponds in IAA-systems

In IAA-farming systems, ponds fulfill different and multiple functions and hence contribute in numerous ways to income generation and poverty reduction (Prein, 2002; Little et al., 2007b). In the Mekong delta context, Nhan et al. (2007) found that increased farm resource use, through increasing the (re)cycling of nutrients between farm components, is the most important motivation of IAA-adopters. Consequently, the overall productivity and income of the whole farm rather than the pond is improved while reducing environmental impacts (Edwards, 1998; Devendra and Thomas, 2002; Nhan et al., 2007; this study, chapter 5).

The role of ponds in IAA-systems differs between agro-ecologial zones. In the fruit-dominated area, the supply of water for fruit irrigation and the extraction of nutrient-rich mud to fertilize fruit orchards are important additional benefits from ponds besides the production of food-fish. In rice-dominated areas, farmers use their pond to dispose excreta resulting from animal production and household members to produce fish for both household food supply and marketing. On average only 6% of the nutrients administered to aquaculture ponds was recovered in harvested fish. The remaining fractions accumulated in the pond mud, from where nutrients can be extracted to fertilize crops grown on dikes and adjacent fields, or were discharged to adjacent surface waters through outflow water (chapters 4 and 5). Fish production and sediment nutrient accumulation increased with increasing food inputs applied to ponds. On-farm nutrient source availability is probably not an important limitation for pond productivity. Farmers in the Mekong delta perceived aquaculture an activity of secondary economic importance, except when itdealt with intensive aquaculture. Agricultural commercialization and specialization limit the roles of ponds. Intensification of fruit production on pond dikes reduces sunlight and pond productivity, and commercial feedlot pig production flushes a large amount of manure into ponds, making sub-optimal conditions for fish and discharging high quantities of nutrients to surface water surrounding the farm (Nhan et al., 2006; this study, chapters 4 and 5). By stressing and improving the pivotal role of ponds in water and nutrient use efficiency of the IAA-farm as a whole, the perceived importance of the pond to the livelihoods of the farming household might be enhanced.

Identifying the multiple roles that ponds fulfill in IAA-farming systems is important. In fruit-dominated areas, low- or medium-input forms of aquaculture are promoted. Aquaculture can contribute to the subsistence needs for animal protein at nearly no cost while reducing costs for nutrients and minimizing risks in intensive fruit production (Nhan et al., 2007). This is of great importance for fruit farmers as flood-protection embankments decrease alluvial deposition. Recently, other studies also indicated that nutrient-rich sediments from ponds contribute to sustain soil fertility of dikes and hence improve farming income (Shamsul et al., 2007; Yakupitiyage et al., 2007). In rice-dominated areas with commercial livestock production, medium-input pond culture is used to improve on-farm nutrient use efficiency, increasing farming income and reduce nutrient discharge (chapter 4). Proper management of pond nutrient and water exchange is necessary to minimize excessive discharge of nutrients and to further improve the efficiency of water and nutrient use.

4. Strategic actions to pond nutrient management

In the Mekong delta, key challenges for development of IAA-farming are to ensure that farmers and consumers benefit, environmental problems do not run out of control and public health is safeguarded. Advantages and disadvantages of controlling nutrient flows through ponds in the major IAA-systems in the Mekong Delta were reviewed. Results showed that efforts to improve pond nutrient management in IAA-systems are successful when the specific contexts of the farm and household are considered (Nhan et al., 2006). A possible tool in identifying strategic options to pond nutrient management in IAA-farms is through analyzing "strengths, weaknesses, opportunities and threats" to each system (Weihrich, 1982; Hill and Westbrook, 1997). Strengths and the weaknesses focus on internal factors while opportunities and threats focus on external factors.

In the Mekong delta, IAA-farming has major strengths:

- Still a large area suitable for IAA-farming (Duong et al., 1998; Nhan et al., 2007);
- Recycling of potential farm bio-resources for ponds to produce low-cost fish (chapters 4 and 5);
- Increasing income, securing food supply and generating employment from low-cost fish production (Little et al., 2007b; this study, chapter 5)
- Diversifying activities, reducing environmental impacts and spreading economic risks (Duong et al., 1998; Berg, 2002).

Major weaknesses are:

- Discharging more water and nutrients with increasing nutrient input levels applied to ponds (Pekar et al., 2002; Nhan et al., 2006; this study, chapters 4-5);
- Mismatching between farm bio-resources availability and quality and nutrient requirement of ponds (Prein, 2002; Nhan et al., 2006);
- Causing potential human risks and aesthetical problems from the use of raw livestock and human excreta (Petersen and Dalsgaard, 2003; Nhan et al., 2006); and
- Requiring high labour inputs (Ruben, 2007)

Major opportunities are:

- Strong support by the government (Luu, 2002; Nhan et al., 2007);
- An increasing demand for animal-protein because of population growth and increased nutritional standards (Devendra, 2002b; Verdegem et al., 2006);
- An increasing availability of off-farm by-products and market development from agricultural commercialization, industrialization and urbanization (Prein, 2002; Little et al., 2007b; Ruben, 2007);

Major threats are:

- Restraining of opportunities for farm integration from commercial specialized agriculture/aquaculture (Devendra, 2002b; Little et al., 2007b);
- Lack of on-farm labour from increasing opportunity for off-farm employment (Ruben, 2007); and
- Stringent environmental quality, food safety and aesthetic objections (Edwards, 1998; Naylor et al., 2000; Costa-Pierce, 2002).

Considering the above analysis of strengths, weaknesses, opportunities and threats, major actions to improve pond nutrient management include:

- Fine tuning the pond nutrient management to the needs of the IAA-farming systems considering the various roles of the pond, reducing remaining imbalances between IAA-components while considering off-farm effects;
- Reducing the direct use of livestock and human excreta as pond nutrient inputs and using IAA-pond products as inputs for other farming activities or industries (Little and Muir, 1987; Prein, 2002);
- Develop IAA-farming towards three major patterns of farming diversification (Ruben, 2007): (1) improving on-farm nutrient integration for poverty alleviation, risk management and vulnerability reduction purposes (the worse-off with passive integration), (2) improving on-farm nutrient use in parallel with developing off-farm integration for modernization of agricultural activities and market engagement (the better-off with active integration), and (3) improving nutrient integration for high yields with low labour inputs (households lacking labor or considering IAA-farming as a temporary livelihood).

5. Knowledge gaps

Lack of knowledge still constrains further development of IAA-farming in the Mekong delta. A lot of information is available on pond ecology and nutrient dynamics at pond level (Delincé, 1992; Egna and Boyd, 1997; chapters 3-5). Gut insights in adjusting pond nutrient management to the whole farming system and community level are still limited.

Thus, options to respond adequately to the various combination of objectives and constraints in IAA-arming development are difficult to identify. There are numerous options to improve the nutrient management on IAA-farms due to the multitude of possible combinations of different IAA-farming components and farmer's livelihoods (Bosma et al., 2006; Ruben, 2007). However, IAA farmers need to respond quickly to new arising opportunities and threats (Little et al., 2007b). In our study, the focus was on the role(s) and impacts of pond farming; how can water and nutrient management of ponds be optimized considering objectives in relation to productivity, economics, environmental impacts and social aspects. Concurrently, constraints to consider include space allocation to each IAA farm component, nutrient availability, labour availability and opportunities, market prices and household's options. Considering each of these objectives or constraint in isolation, specific paths or solutions can be outlined. However, no problem or constraint occurs in isolation. The development of sustainable IAA-farming is not straight forward and needs compromising and time and effort to consider the local contexts.

6. Approaches for IAA-farming research and development

In this study, a Participatory Learning in Action approach was followed (Little et al., 2007a). Chapters 2 and 3 aimed at context understanding, while chapters 4 and 5 addressed system understanding. It turned out that our study rather focused on "problem-determined systems" in stead of "system-determined problems" (Ison et al., 1997). Possible improvements of IAA-systems strongly embedded in local bio-physical and social contexts can be identified through the conscious participation and input of all stakeholders (chapters 4 and 5). The resulting problem-determined IAA-systems and their solutions greatly varied according to different driving factors and levels (see Figure 1). An on-station approach alone, cannot deal completely with the complexity of these problem-determined IAA-systems. Although participatory on-farm research has also its disadvantages (chapters 3-5), provided good participation of all stakeholders and appropriate implementation of the PLA approach, chances for adoption of the identified solutions are high.

The pond in each of the studied IAA-farming systems was treated rather as a number of small "black boxes" than as a big "black box" (Pauly and Hopkins, 1983). Each of the IAA-systems was identified by a set of explanatory and response variables interacting dynamically (chapters 2, 3 and 5). For data analysis within the PLA approach, a multivariate approach proved more useful than univariate or bivariate approaches. Drawbacks of univariate or bivariate include the difficulty in dealing with the lack of replicate observations (Smart et al., 1998), and the exclusion of part of the variance imbedded in the dataset, making it difficult to distinguish differences between farms or treatments (chapters 3, 4 and 5). Nowadays, multivariate analytical tools are included in most of the commonly used statistical packages. Applying a multivariate approach to analyze data from participatory on-farm research allowed extracting valuable conclusions that are applicable, practical and well documented scientificly.

The combination of PLA and multivariate approaches applied in our study was an attempt to address the knowledge gap. The results are encouraging. With much more practical work and experience, it should be possible to shape this approach into a practical, adaptable to local contexts and hence widely applicable methodology allowing IAA-farmers and their stakeholders to respond adequately to future challenges.

7. Conclusions

This thesis investigated the current situation of IAA-farming in the Mekong delta and suggested and tested strategies for further development. The adoption of one type of IAA-system by farmers is determined by a mixture of biophysical, socio-economic and technological factors at different scales ranging from the individual pond to community or village level. Interventions should therefore be based on a profound understanding of the local contexts and the functioning of IAA-systems. Within each IAA-system, each pond fulfils multiple roles, in part influenced by the existing resource base, agricultural development pathways and the household's goals and aspirations. An important function of ponds is the trapping and storage of nutrient for subsequent reuse within IAA-systems, which otherwise would be lost. Optimizing nutrient storage in ponds also concurs with best management practices from an environmental and economic point of view.

The participatory and multivariate approaches applied in this study proved useful for developing sustainable IAA-systems, documenting the generation of adaptive technologies in a scientific way. The situation in the Mekong delta is changing rapidly, and constantly balancing economic, environmental and social interests while adapting IAA-farming under local, national and international pressures is mandatory to the wellbeing of its inhabitants.

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Summary

In the Mekong delta, the Vietnamese government promoted integrated agriculture-aquaculture (IAA) farming systems as an example of sustainable agriculture. An important advantage of IAA-farming is the nutrient linkage between the pond and terrestrial components within a farm, which allows to improve resource use efficiency and income while reducing environmental impacts. This study monitored and analyzed water use in and nutrient flows through ponds that are part of an IAA-farming system. The goal was to improve the nutrient management of ponds which in turn lead to improved water and nutrient use efficiency of the whole IAA-farm. The study included three main parts: (1) understanding the context and characteristics of IAA-systems (chapters 2 and 3), (2) analyzing the performance of IAA-systems, suggesting and testing improvements (chapters 4 and 5), and (3) recommending procedures for the continuous upgrading of existing IAA-farming systems (chapter 6). The research was done on-farm in freshwater areas of the Mekong delta and followed a Participatory Learning in Action approach. Different multivariate statistical methods were applied for data analysis.

At community and household level, results showed that the type of IAA-farming systems applied was determined by a mixture of bio-physical, technological and socio-economic factors (chapter 2). Three major IAA-systems were identified: (1) low-input fish farming in fruit-dominated area (system 1), (2) medium-input fish farming (system 2), and (3) high-input fish farming (system 3) in rice-dominated areas. System 1 was commonly practiced in a rural and intensive fruit production area with fertile soils, while systems 2 and 3 were more frequent in peri-urban and in rice production areas with less fertile soils. In the study areas, poor farmers usually did not adopt IAA-farming. With good market accessibility, richer farmers tended to intensify fish farming. The principal factors why farmers did not start aquaculture were the inappropriateness of the technology available, lack of capital, insufficient land holding, poor access to extension services, limited farm management, and a fear of conflicts associated with pesticide use on crops. The main motivations to practice IAA-farming were increased farm resource uses, which resulted in improved income, a

better supply of foods for home consumption and a reduction of the environmental impacts from the farming.

In low- and medium-input ponds, nutrient inputs, the accumulation of nitrogen (N), organic carbon (OC) and phosphorus (P) and environmental impacts were closely linked (chapter 3). Parameters related to nutrients input levels and water exchange rates in ponds explained most of the variability between farms. Parameters linked to agro-ecological sites, pond physical properties and livestock or human excreta inputs explained most of the remaining variability. A combination of these variables allowed to characterize three indicative integrated systems: (1) the low water-exchange-rate ponds in the fruit-dominated area, (2) the low water-exchange-rate ponds in the rice-dominated area receiving home-made feed, and (3) the high water-exchange-rate ponds in the rice-dominated areas receiving excreta. These systems concurred to a large extend with the systems identified on the basic of the community and household survey. In the rice-dominated area with deep ponds, more livestock or human wastes were supplied, and high water exchange rates were practiced. In these ponds, large excreta-OC loads reduced dissolved oxygen and increased total phosphorus concentrations in the water column and nitrogen, organic carbon and phosphorus accumulation in the sediments. In the rice-dominated area with wide ponds, more home-made feed was applied and low water-exchange rates were practiced, which resulted in a high phytoplankton biomass and primary productivity. On the contrary, in the fruit-dominated area fish were grown in shallow and narrow ditches with a low phytoplankton biomass and only a small fraction of the nutrient input accumulated in the sediments.

The water and nutrient budgets of a selected number of ponds, representing either low or high water-exchange systems were determined (chapter 4). The sluice-gate water inflow and outflow largely dominated the total pond water budgets, accounting for 72-97% of the total water budget. On-farm livestock manures were the most important nutrient source for ponds. High water-exchange rate ponds received larger quantities of livestock and/or human excreta and had significantly higher volumes of water passing through ponds than low water-exchange rate ones. Only 5-6% of the total N, OC and P inputs were retained in the harvested fish, but 18-91% accumulated in the pond sediments, the rest was lost through pond water discharges. Fish yields and the quantity of nutrients accumulating in the sediments increased with increasing on-farm nutrient input levels at the cost of higher nutrient discharges. Its was concluded that farmers need to manage water and nutrient flows between the pond and the other IAA-farm components with the goals to maximize productivity and profitability while minimizing nutrient discharges of the farm as a whole.

Excreta were the principle type of nutrient input applied to ponds in the study areas. Therefore, the economic and nutrient discharge tradeoffs stemming from the use of livestock and human excreta were analyzed (chapter 5). Data collected during three consecutive production years were combined in the analysis. Results showed that increased excreta input levels resulted in lower dissolved oxygen concentrations, higher water exchange rates practiced, and increased discharge of chemical oxygen demand (COD), N, P and total suspended solids (TSS). Fish yields and the accumulation of N, OC and P in pond sediments, however, increased with increasing excreta input levels. Through regression analysis, it was predicted that with an input of 5 kg N ha^{-1} day^{-1}, a fish yield of 8379 kg and an economic return of 52 million VND ha^{-1} yr^{-1} will be obtained while about 2,057 kg COD, 645 kg N, 213 kg P and 39,203 kg TSS ha^{-1} yr^{-1} will be discharged from the farm. At this input level, about 9% of input-N will be retained in harvested fish, 52% will accumulate in the sediments and 39% will be discharged. Further development of IAA-farming practices should focus on reducing nutrient discharges while maintaining favorable economic returns.

In brief, this study demonstrated that the adoption of one type of IAA-system by farmers is determined by a mixture of factors at different scales ranging from the individual pond to community or village level. Within each IAA-system, the pond fulfils multiple roles, in part influenced by the existing resource base, agricultural development pathways and the household's goals and aspirations. An important function of ponds is the trapping and storage of nutrients for subsequent reuse within IAA-systems, which otherwise would be lost. Optimizing nutrient storage in ponds also concurs with best management practices from an environmental and economic point of view. The key challenge to the further

development and optimization if IAA-farming is to balance economic, environmental and social interests within a highly dynamic setting of the Mekong delta today.

Samenvatting

De Vietnamese regering promoot geïntegreerde landbouw-visteelt (integrated agriculture-aquaculture: IAA) bedrijfssystemen in the Mekong delta als een voorbeeld van duurzame landbouw. Een belangrijk voordeel van IAA-systemen is de nutriënten uitwisseling tussen de water- en de landgebonden componenten. Dit verhoogt zowel de efficiëntie waarmee natuurlijke hulpbronnen gebruikt worden, als wel het inkomen, terwijl schadelijk milieu effecten verminderen. Deze studie volgde en analyseerde het watergebruik en de nutriëntenstromen door vijvers van IAA-bedrijven Het doel was het nutriëntenbeheer in de vijvers zodanig te verbeteren dat de gebruiksefficiëntie van water- en nutriënten binnen het totale geïntegreerde bedrijf toeneemt. De 3 belangrijkste onderzoeksactiviteiten waren: (1) inzicht krijgen in de context en de eigenschappen van de IAA-systemen (hoofdstuk 2 en 3), (2) het analyseren van de water- en nutriëntenefficiency van IAA-systemen en het suggereren en testen van verbeteringen (hoofdstuk 4 en 5), en (3) het formuleren van procedures die een permanente verbetering van bestaande IAA-bedrijfssystemen bevorderen (hoofdstuk 6). Het onderzoek is uitgevoerd op bedrijven in drie alluviale zoetwater gebieden van de Mekong delta volgens de principes van "Participatory Learning in Action". Voor de analyse van gegevens zijn verschillende multi-variate statistische methodieken gebruikt.

Resultaten op zowel gemeenschaps- als gezinsniveau laten zien dat het type IAA-systeem bepaald wordt door een samenspel van bio-fysische, technologische en sociaal-economische factoren (hoofdstuk 2). De IAA-bedrijven waren te onderscheiden naar visteeltsystemen met een laag inputniveau in gebieden waar fruitteelt de belangrijkste activiteit is (systeem 1) versus gebieden waar rijstteelt domineert. In de rijstgebieden worden visteelt systemen onderscheiden met een gemiddeld inputniveau (systeem 2) of een hoog inputniveau (systeem 3). Systeem 1 was gebruikelijk in landelijke gebieden met vruchtbare gronden, terwijl systeem 2 en 3 vaker voorkwamen in peri-urbane gebieden met minder vruchtbare gronden. In het studiegebied waren het vooral de armste boeren die niet toekomen aan het integreren van visteelt binnen hun bedrijf. Vooral daar waar de toegang tot de markt goed is zijn het de rijkere boeren die investeren in visteelt als onderdeel van

een IAA-systeem. De belangrijkste reden voor boeren om niet met visteelt aan de slag te gaan waren de onaangepastheid van de beschikbare technologie, het gebrek aan kapitaal of land, slechte toegang tot voorlichting en training, beperkte mogelijkheden om het bedrijf te beheren, en de mogelijke negatieve effecten van pesticidengebruik in de landbouw op de visteeltopbrengst. De belangrijkste redenen om visteelt met landbouw te integreren waren een betere benutting van de bedrijfseigen middelen waardoor het inkomen stijgt, een betere voedselvoorziening voor het gezin, en een vermindering van de milieu-effecten.

In visvijvers met een laag of gemiddeld inputniveau bestond er een sterk verband tussen inputniveau, de ophoping van stikstof (N), organische koolstof (OC) en fosfaat (P) en de milieu-impact (hoofdstuk 3). Parameters gerelateerd aan inputniveau en waterverversingsnelheid verklaarden het leeuwendeel van de variatie tussen bedrijven. Parameters gerelateerd aan agro-ecologische zone, fysieke vijvereigenschappen en het inputniveau van excrementen van dierlijke of humane oorsprong, verklaarden bijna alle resterende variatie. Door deze variabelen te combineren werden 3 indicatieve geïntegreerde landbouw-visteelt systemen geïdentificeerd: (1) vijvers met een lage waterverversingsnelheid in fruitteelt gebieden met als belangrijkste input excrementen, (2) vijvers met een lage waterverversingsnelheid in rijst gebieden met als belangrijkste input zelfgemaakt voer, en (3) vijvers met een hoge waterverversingsnelheid in rijst gebieden met als belangrijkste input excrementen. Deze indeling komt in sterke mate overeen met de systemen die werden geïdentificeerd op basis van de initiële algemene verkenning op gemeenschap- en gezinsniveau. Daar waar in rijstgebieden de beschikbare vijvers diep waren werden meer excrementen van dierlijke of humane oorsprong gebruikt, en was de waterverversingsnelheid hoger. De hoge belasting met organische koolstof afkomstig van mest verminderde de zuurstofbeschikbaarheid en verhoogde de fosfaatconcentratie in de waterkolom en de stikstof-, organische koolstof- en fosfaatconcentratie in het sediment. Daar waar in rijstgebieden de vijver relatief breed is werd meer zelfgemaakt voer gegeven en werd de waterverversing laag gehouden. Daardoor groeide de massa fytoplankton en steeg de primaire productie. In fruitteeltgebieden daarentegen werd vis vooral gekweekt in ondiepe en smalle geulen gekenmerkt door een lage fytoplanktonbiomassa. De fractie van de nutriëntinput die ophoopt in het sediment was hier lager dan in rijstgebieden.

Van een beperkt aantal vijvers met een lage of een hoge waterverversingsnelheid werd het water- en nutriëntbudget bepaald (hoofdstuk 4). Water in- of uitstroom door de enige sluis van elke vijver bepaalde het totale waterbudget van de vijver voor 72-97%. Mest geproduceerd op het eigen bedrijf was de belangrijkste nutriëntbron voor de vijvers. Vijvers met een hoge waterverversingsnelheid kregen meer excrementen van dierlijke of humane oorsprong dan vijvers met een lage waterverversingsnelheid. Slechts 5-6% van de stikstof, organische koolstof of fosfaat input werd geoogst als vis, en 18-91% hoopte zich op in het sediment. De rest ging verloren met de waterverversing. Hoe hoger het nutriënt-inputniveau hoe hoger de visproductie, hoe meer nutriënten ophopen in het sediment en hoe meer nutriënten verloren gaan met de waterverversing. De conclusie was dat boeren de water- en nutriëntstromen op hun IAA-bedrijf moeten beheren met als belangrijkste doelen de productiviteit en winstgevendheid te verhogen en de nutriëntverliezen te minimaliseren.

Mest was de belangrijkste nutriëntenbron voor de vijvers in het studiegebied. Daarom werden de voor- en nadelen van het gebruik van excrementen van dierlijke of humane oorsprong geanalyseerd (hoofdstuk 5). Data van 3 opeenvolgende jaarcycli werden gecombineerd. Een hoger inputniveau leidde tot lagere zuurstofconcentraties, het instellen van een hogere waterverversingsnelheid, en een hogere lozing van organische stof (uitgedrukt als chemisch zuurbindend vermogen (COD)), N, P en zwevende vaste stof (ZVS). Daarentegen namen de visopbrengst en de hoeveelheden N, organische koolstof en P die zich ophopen in het sediment, toe met het inputniveau. Op basis van regressieanalyse werd bepaald dat een input van 5 kg N ha^{-1} dag^{-1} leidt tot een visopbrengst van 8.379 kg en een winst van 52 miljoen VND (Vietnamese Dong) ha^{-1} jaar^{-1}. Dit komt overeen met een lozing per hectare per jaar van 2.057 kg COD, 645 kg N, 213 kg P en 39.203 kg ZVS. Bij dit inputniveau zal slechts 9% van de N-input worden geoogst als vis, zal 52% zich ophopen in het sediment en zal 39% worden geloosd. Toekomstige ontwikkelingen van IAA-systemen zouden zich moeten richten op het verminden van de nutriëntlozingen met behoud van de winstgevendheid.

Deze studie toonde aan dat de adoptie van een bepaald type van IAA-systeem bepaald wordt door een mix van factoren op verschillende schaalniveaus, variërend van één enkele vijver tot het niveau van de gemeenschap of dorp. Binnen elk IAA-systeem vervult de vijver verschillende functies die ten dele bepaald worden door de beschikbare middelen, ontwikkelingspatronen in de landbouw, en de doelstellingen en wensen van het gezin. Het vangen en opslaan van nutriënten in vijvers voor later hergebruik op het geïntegreerde bedrijf is een belangrijke functie van vijvers. Zonder vijver zouden deze nutriënten grotendeels verloren gaan. Het streven naar het verbeteren van de nutriëntenopslag in vijvers zal leiden tot een beter beheer, zowel vanuit milieu als economisch standpunt. De belangrijkste uitdaging m.b.t. de verdere ontwikkeling van IAA-systemen is een goede balans te vinden tussen de belangen op economisch, milieu en sociaal gebied, en dit binnen de dynamische omgeving die de Mekong delta vandaag is.

Tóm lược

Nhà nước có chủ trương và chính sách phát triển các hệ thống canh tác nông nghiệp-thủy sản kết hợp để chuyển dịch cơ cấu sản xuất và phát triển nông nghiệp bền vững ở Đồng bằng Sông Cửu Long (ĐBSCL). Ưu điểm của hệ thống canh tác này là chu trình dinh dưỡng giữa ao và các thành phần cây trồng vật nuôi khác trong hệ thống, góp phần làm tăng hiệu quả sử dụng tài nguyên và giảm tác động môi trường. Nghiên cứu này giám sát và phân tích việc sử dụng nước và dòng dinh dưỡng của ao trong hệ thống canh tác vườn-ao-chuồng (VAC) kết hợp. Mục tiêu chung của nghiên cứu là cải tiến quản lý dinh dưỡng của ao và từ đó cải tiến hiệu quả sử dụng nước và dinh dưỡng của cả hệ thống canh tác. Nghiên cứu gồm 3 nội dung chính: (1) nghiên cứu bối cảnh và đặc tính của các hệ thống VAC (chương 2 và 3), (2) phân tích kỹ thuật, đề xuất và thử nghiệm kỹ thuật cải tiến và (3) khuyến cáo cải tiến và phát triển hệ thống canh tác. Trong nghiên cứu này, phương pháp tiếp cận phát triển kỹ thuật có sự tham gia (Participatory Learning in Action) được áp dụng và thí nghiệm được tiến hành trực tiếp trên ruộng của nông dân ở vùng nước ngọt của ĐBSCL.

Ở mức độ cộng đồng và nông hộ, kết quả nghiên cứu cho thấy có nhiều yếu tố kỹ thuật, tự nhiên, kinh tế và xã hội ảnh hưởng đến việc áp dụng hệ thống canh tác (chương 2). Có 3 hệ thống chính được xác định: (1) hệ thống nuôi cá quảng canh ở vùng thâm canh cây ăn trái (hệ thống 1), (2) nuôi cá quảng canh cải tiến hoặc bán thâm canh (hệ thống 2) và (2) nuôi cá thâm canh (hệ thống 3) ở vùng sản xuất lúa. Hệ thống 1 thường thấy ở vùng nông thôn, đất tốt và thâm canh cây ăn trái. Hệ thống 2 và 3 phổ biến ở vùng gần thành thị, đất kém màu mở hơn và canh tác lúa là chủ yếu. Trong vùng nghiên cứu, nông dân nghèo thường ít nuôi cá. Khi có điều kiện tiếp cận thị trường, nông dân khá và giàu thường nuôi cá thâm canh để tăng thu nhập. Lý do quan trọng tại sao nông dân không áp dụng thủy sản là kỹ thuật chuyển giao không phù hợp, thiếu vốn, đất ít, khó tiếp cận khuyến nông, năng lực quản lý hạn chế và sợ cá chết khi phun thuốc hoá học cho cây trồng. Trong khi đó, nông dân áp dụng các hệ thống canh tác thủy sản kết hợp là để tăng hiệu quả sử dụng tài nguyên, từ đó cải thiện thu nhập và dinh dưỡng cho gia đình, và bảo vệ môi trường.

Trong hệ thống nuôi quảng canh và bán thâm canh, đầu tư dinh dưỡng cho ao, lắng tụ đạm (N), chất hữu cơ (OC) và lân (P) trong bùn ao và vấn đề môi trường có liên quan chặt chẽ với nhau (chương 3). Sự khác biệt giữa các hệ thống ao chủ yếu phụ thuộc vào mức độ bổ sung dinh dưỡng và thay nước ao, kế đến là điều kiện sinh thái nông nghiệp, đặc điểm ao và mức độ sử dụng chất thảy từ chăn nuôi và gia đình để nuôi cá. Kết hợp các yếu tố này, 3 hệ thống canh tác chính được phân loại: (1) hệ thống nuôi thay nước ít ở vùng vườn thâm canh, (2) hệ thống thay nước ít và bổ sung thức ăn và (3) hệ thống thay nước nhiều và sử dụng chất thảy để nuôi cá ở vùng sản xuất lúa. Kết quả phân loại này phù hợp với kết quả khảo sát ở phạm vi cộng đồng và nông hộ. Ở vùng sản xuất lúa, ao sâu hơn thường được bổ sung nhiều chất thảy nên nông dân thay nước nhiều hơn. Ở những ao này, hàm lượng P trong nước cao nhưng oxy hoà tan thấp và sự lắng tụ của N, OC và P trong bùn ao nhiều. Trong khi đó, ao rộng thì thường được bổ sung thức ăn tự chế và ít thay nước, kết quả là tảo phát triển và năng suất sinh học sơ cấp tăng cao. Trái lại, ao ở vườn cây ăn trái thâm canh thường hẹp và cạn, ít được đầu tư dinh dưỡng, tảo kém phát triển và dinh dưỡng lắng tụ trong bùn ít.

Việc sử dụng nước và dinh dưỡng ở 2 hệ thống ao thay nước ít và nhiều được phân tích ở chương 4. Kết quả cho thấy sử dụng nước và dòng dinh dưỡng của ao phụ thuộc chủ yếu vào việc sử dụng chất thảy từ chăn nuôi và gia đình để nuôi cá. Lượng nước thay hàng ngày chiếm đến 72-97% tổng lượng nước đi vào ao. Nhìn chung, nuôi cá trong mô hình VAC, nông dân sử dụng phân chuồng là chủ yếu. Trong tổng lượng N, OC và P đi vào ao, cá chỉ chiếm 5-6%, 18-91% lắng tụ trong bùn ao và phần còn lại mất ra ngoài sông do thay nước. Đầu tư nhiều dinh dưỡng cho ao, năng suất cá và dinh dưỡng lắng tụ trong bùn tăng lên nhưng lượng nước thảy ra ngoài môi trường cũng tăng lên. Do đó, nông dân cần quản lý ao tốt hơn và tái sử dụng nước và dinh dưỡng của ao trong hệ thống VAC thích hợp nhất để gia tăng sản lượng và lợi nhuận kinh tế của cả hệ thống sản xuất đồng thời giảm ảnh hưởng đến môi trường.

Chất thảy từ chăn nuôi và gia đình là nguồn dinh dưỡng chính cho ao trong vùng nghiên cứu. Do đó, nghiên cứu trong chương 5 phân tích lợi ích về kinh tế và tác hại về môi trường khi sử dụng chất thảy để nuôi cá. Số liệu từ 3 vụ cá liên tục trong 3 năm nghiên cứu được tổng hợp và phân tích. Kết quả chỉ ra rằng khi gia tăng lượng chất thảy vào ao, hàm lượng oxy hoà tan giảm xuống, nông dân thay nước nhiều hơn, và do đó COD, N, P và tổng chất rắn lơ lững (TSS) từ ao thảy ra ngoài sông tăng lên. Tuy nhiên, khi đó năng suất cá nuôi và lượng dinh dưỡng lắng tụ trong ao cũng tăng lên. Qua phỏng đoán bằng các mô hình hồi quy, kết quả cho thấy khi đưa vào ao 5 kg N/ha/ngày, năng suất cá đạt 8.379 kg, lợi nhuận là 52 triệu đồng, nhưng khoảng 2.057 kg COD, 645 kg N, 213 kg P và 39.203 kg TSS/ha/năm được thảy ra ngoài sông. Ở mức bổ sung dinh dưỡng này, cá chỉ chiếm 9% tổng lượng dinh dưỡng cho vào ao, 52% lắng tụ trong bùn ao, và 39% mất ra ngoài sông qua thay nước. Do đó, phát triển nuôi cá trong hệ thống VAC cần chú ý hạn chế tối đa mất dinh dưỡng do thay nước và duy trì hiệu quả kinh tế sản xuất.

Tóm lại, các nghiên cứu đã chứng minh rằng việc áp dụng một hệ thống canh tác VAC nào đó của nông dân tùy thuộc vào nhiều yếu tố ở các phạm vi khác nhau từ cấp độ nông hộ đến cộng đồng và xã. Trong mỗi hệ thống canh tác, ao có nhiều vai trò quan trọng và vai trò này phụ thuộc vào hệ thống tài nguyên hiện hữu, hướng phát triển nông nghiệp và mục tiêu của nông hộ. Vai trò quan trọng của ao là tích tụ dinh dưỡng mà có thể sử dụng cho trồng trọt. Tối ưu tích tụ dinh dưỡng trong ao thông qua những biện pháp quản lý tốt nhất nên chú ý cả hai khía cạnh kinh tế và môi trường. Cân bằng kinh tế, môi trường và lợi ích xã hội phù hợp với thay đổi liên tục của thời đại là thử thách quan trọng cho sự phát triển hệ thống canh tác nông nghiệp-thủy sản kết hợp ở ĐBSCL.

Acknowledgements

This thesis is realized from the combined efforts, directly or indirectly, of many persons and institutions. I am greatly indebted to all of them. In particular, I would like to express my sincere gratitude to:

Ten cooperating farmers, who wholeheartedly participated in the study over the three-year period. This thesis would not have been successful without your great contribution. My colleagues, Mr. Nguyen Thanh Binh, Tran Duong Xuan Vinh, Huynh Cam Linh, Cao Quoc Nam and Nguyen Van Nhat at the Mekong Delta Development Research Institute (MDI, Can Tho University), spent many long days with me in the laboratory and the field, going from farmer to farmer and barefoot-jumping into ponds to sample, continuously encouraging me along this long and tiring road. This thesis would not be possible without your untiring efforts.

My promotor, Prof. Dr. Johan A.J. Verreth, and co-promotor, Dr. Marc C.J. Verdegem, gave me much appreciated guidance and dedicated advice on scientific matters. I am especially indebted to your bright ideas, patience, encouragement and motivation. The initial proposals would not be realized and the practical results would not be processed into scientific publications without your great supports. I learned a lot from you and am proud of being your student.

My teachers Le Thanh Duong, the former deputy director and principal investigator of Pond-Live project in Vietnam, and Dr. Tran Thanh Be, the director of MDI, strongly supported me to carry out the study, to write papers and to complete this thesis, and encouraged me during hard days of the PhD study. I am grateful to your invaluable supports and encouragement. My teacher Le Thanh Phong and colleagues Mr. Loi, Kiet and Hoang, who worked on the INREF-Pond - Pond-Live's sister project – for spending hard days in the field with me and sharing data and good ideas to form this thesis.

Mr. Roel Bosma (AFI, Wageningen University), who gave me a lot of professional, administrative and logistic assistance, and friendly hours during my stay in The Netherlands. Many thanks to Dr. Ana Milstein (Fish and Aquaculture Research Station, Israel), Dr. Leo A.J. Nagelkerke (AFI) and Dr. Nico Vromant (VVOB, Belgium) for your helpful statistical instructions and advice. Dr. Ana Milstein also gave me critical comments and did useful editings on manuscripts of papers included in this thesis. I am grateful to Dr. David Little (Stirling University, UK), Dr. Anne van Dam (UNESCO-IHE, Delft) and Dr. Jetse Stoorvogel (Soil Research Centre, Wageningen University) for your excellent ideas, helping me to realise the study.

I received a lot of great help and encouragement, directly or indirectly, from staff at MDI (Can Tho University) and at AFI (Wageningen University) during my study. Mrs. Helene van Paridon, Lies van Beek and Gera van Dikken gave me great assistance with administrative supports. Anh Chi Thanh Thuy, Co Chu Minh, Chi Huong and Vietnamese students in the Netherlands shared my loneliness during my stays in The Netherlands. PhD students at AFI, Patricia, Titu, Iyob, Mohammad, Paula and Harrison gave me special regards, shared good ideas and provided laughing times when I was in the Netherlands.

My parents, who devoted all their best efforts to my opportunity for this higher study and stimulated my interest in agriculture, rural poverty and environment. My wife, for all the endless patience and loving help during the study, and my son, for helping me to realize that there is much more in life than work and research.

This study was funded by European Commission (INCO Pond-Live, ICA4-2000-20034) and Wageningen University and Research Centre (INREF-Pond). Aquaculture and Fisheries Group and Mekong Delta Development Research Institute were partners facilitating the study.

Training and Supervision Plan		**Graduate School WIAS**
Name	DANG KIEU NHAN	
Group	Aquaculture and Fisheries	
Daily supervisor	Dr. M.C.J.Verdegem	
Supervisor	Prof. Dr. J.A.J. Verreth	
Period	March 2002 until March 2007	
Submitted	August 2007	

The Basic Package	Year	ECTS
WIAS Introduction Course	2006	
Course on philosophy of science and/or ethics	2006	
Subtotal Basic Package		**3**
Scientific Exposure (conferences, seminars and presentations)		
International conferences		
Tropentag in Gottingen and Hohenheim, Germany	2003, 2005	
World Aquaculture 2005, Bali, Indonesia	2005	
7th Asian Fisheries Forum	2004	
Symposium “Fishponds in farming systems”, Can Tho, Vietnam	2006	
Workshops		
Pond-live annual meetings	2003-2006	
Presentations		
Oral and poster presentations in Tropentags, Germany	2003, 2005	
Oral presentations in World Aquaculture 2005, Bali, Indonesia (2)	2005	
Oral presentation in 7th Asian Fisheries Forum	2004	
Pond-live annual meetings	2003-2006	
Oral presentation in Symposium “Fishponds in FS”, Can Tho, Vietnam	2006	
Subtotal		**16**
In-Depth Studies		
Underpinning of Biology	2003	
Multi-criteria analysis for agricultural decisions	2005	
Quantitative Research Methodology	2005	
Subtotal		**7**
Professional Skills Support Courses	year	
WIAS Course Techniques for Scientific Writing	2003	
Time Planning and Project Management	2005	
Subtotal		**3**
Research Skills Training		
Preparing own PhD research proposal	2002	
Subtotal		**6**
Supervising theses		
Msc thesis (Vo Van Ha): Optimization of water levels in concurrent rice-fish farming system	2003	
Bsc thesis (Nguyen Cong Uan): Economic returns of IAA-systems	2006	
Subtotal		**3**
Education and Training Total (minimum 30 ECTS)		**38**

Curriculum vitae

Dang Kieu Nhan was born on December 04, 1969 in Long An, Vietnam. He obtained his BSc in Agronomy at Can Tho University in 1990. From September 1990 till September 1997 he worked as an assistant researcher at the Mekong Delta Farming System Research and Development Institute (Can Tho University). In September 1999, he received an MSc in Water Resources Engineering (IUPWARE) at the Catholic University of Leuven and the Free University of Brussels in Belgium. Since then, he worked at the Mekong Delta Development Research Institute (Can Tho University). In 2002 he started his Sandwich PhD program at Wageningen University.

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List of publications

Peer-reviewed articles

Nhan, D.K., Milstein, A., Verdegem, M.C.J., Verreth, J.A.V., 2006. Food inputs, water quality and nutrient accumulation in integrated pond systems: a multivariate approach. *Aquaculture* 261, 160-173.

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Nhan, D.K., Duong, L.T., Thanh, D.N., Phong, L.T., Bosma, R.H., Verdegem, M.J.C., 2005. Is integrated aquaculture a livelihood option for poor farmers in the freshwater areas of Vietnamese Mekong Delta? Paper presented at WAS 2005, May 9-13, 2005, Bali, Indonesia (Abstract).

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