# Dynamics of sustainability in Integrated Agriculture-Aquaculture systems in the Mekong Delta

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## Abstract

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In the Mekong Delta (MD), intensification and modernization of crop, fish and livestock production causes concern about sustainable use of natural resources. The objectives of this research were to understand the driving forces for changes in farming practices, and to quantify and evaluate agro-ecological attributes, nutrient balances, and environmental impacts in Integrated Agriculture-Aquaculture (IAA) systems. Three districts differing in cropping patterns and intensity of fish culture were selected for this study: a rice-based and high input fish system (R-HF) in O Mon district, a rice-based and medium input fish system (R-MF) in Tam Binh district, and an orchard-based and low input fish system (O-LF) in Cai Be district. Two surveys (2002 and 2004), covering 90 households, were carried out to analyse drivers for changes in IAA systems. Another survey was conducted at the end of the study to evaluate the awareness of farmers on sustainability issues. One extra survey (2005) was conducted to analyse the impact of the Avian Influenza (AI) outbreak on livelihoods. Eleven farms were selected for detailed monitoring of inputs, outputs and internal bio-resource flows of rice, fruits, vegetables, pigs, poultry, and fish over a period of two years (2002-2004). The agro-ecological attributes of the selected farms were quantified using ECOPATH. The adapted Nutmon (Nutmon-Asia) model was used to quantify soil nutrient balances. A detailed cradle-to-farm-gate life cycle assessment (LCA) was performed to assess the integral environmental impact of IAA farming. The policy of economic liberalization, introduction of modern rice varieties, increasing market demands, and natural disasters were main drivers for changes in IAA farming systems. Well-off farmers tended to intensify their farming practices, whereas the poorer farmers tended towards diversification to safeguard their livelihoods and avoid risks. The ECOPATH, Nutmon-Asia and LCA modeling approaches proved complementary in analysing agro-ecological performances, identifying ecological sustainability issues, and quantifying sustainability indicators at farm and farming system level. The 19 agro-ecological attributes, quantified by ECOPATH, were combined into four sustainability factors: Productivity-Efficiency, Diversity, Maturity, and Aquaculture Integration. Rice-based farms (R-HF and R-MF) were more efficient and productive than the orchard-based farms (O-LF) and recycled nitrogen more intensively within the farm. Productivity-Efficiency was directly related to sustainability of farms. A high farm output in relation to external input use could be achieved both by farms with low external input use and by farms with a relatively high external input use. Soil nutrient balances are important indicators of nutrient use efficiency of farming systems. The Nutmon-Asia results showed that all farms in the three systems had positive nutrient balances of nitrogen, phosphorus and potassium. A negative potassium balance was found in the rice fields of all three systems. Improvements of the nutrient balances can start by lowering the quantity of fertilizers applied. LCA was used to quantify the use of resources and environmental emissions per kcal and kg farm product, and per farm. Land use and energy use per kcal farm product did not differ among the three systems. However, global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP) per kcal farm product were higher in O-LF than in R-HF and R-MF, mainly due to the low calorie content of the two main products, fruits and vegetables, and the small fish yield in O-LF. One kg of fish produced in O-LF farms showed a higher land use, energy use, GWP, EP, and AP than the average kg of fish produced in the other two systems. Overall, rice and pigs were the main contributors to the environmental impact of food production in the MD. Excessive and inefficient use of fertilizers, and $CH_4$ emission from the paddy fields contributed most to the environmental impact in rice production, whereas the use of external feeds contributed most to the impact in pigs. The IAA farmers profited from their flexibility and diversity in farming activities during the period of the AI outbreaks. Farmers were more concerned about social than economic and ecological sustainability issues. The O-LF system scored less on some of the ecological sustainability issues and the O-LF farmers were also less aware of the importance of these issues. Intensification of farming practices will continue. For enhancing nutrient recycling on the farms, emphasis should be on maintaining traditional sustainable farm practices, such as re-use of crop and animal wastes within the farm and integrating fish ponds and using of pond sediment as crop fertilizer. Research, development and extension services should pay attention to strategies for increasing resilience of IAA systems in the MD, by focusing on reducing external farm inputs and improving farm nutrient management. In the MD the demands for animal protein will increase. Stimulation of aquaculture seems more appropriate than stimulation of pig and poultry production, seeing that the environmental impacts per kg protein for fish were lower than for pigs and poultry.

**Key words:** Mekong Delta; IAA; ECOPATH; Nutmon; LCA; environmental impact; sustainability

# Contents

# Chapter 1

# General Introduction

## 1.1 Integrated Agriculture-Aquaculture farming systems

In developing countries, populations, incomes and urbanization are all increasing. As a consequence consumption of animal foods is growing fast. By 2020 developing countries will be producing 60% of the world's meat and 52% of the world's milk (Delgado *et al.*, 2001). Aquatic food is an alternative animal protein source. It offers an excellent source of high quality, easily digestible protein. Aquaculture provides over 50% of total aquatic food production. Developing countries provide more than 90% of the global aquaculture production. In these countries, aquaculture plays an important role in the diets and livelihoods of many of the poor people (Van der Mheen, 2002; Roos *et al.*, 2007).

Aquaculture can be integrated into many different farming systems via the use of multipurpose farm ponds and other water sources. Mathias (1998) defined integrated fish farming as integrated agriculture-aquaculture (IAA). It is based on fish culture in ponds which are closely integrated into the energy and nutrient pathways of conventional farming. Integrated farming systems with fish are often less risky than stand-alone fish farms because, if managed efficiently, they benefit from synergisms among enterprises (Pullin, 1998; Prein *et al.*, 1998). The majority of rural households are smallholder farmers. Potential benefits from integrating aquaculture in smallholder farming systems include: enhanced rural employment and income through additional or off-season production; improved food security; increased availability of high-value protein food; decreased economic risk through diversification; improved water availability and nutrient recycling; environmental benefits through better on-farm natural resource management (Williams, 1997; Dalsgaard and Prein, 1999; FAO, 2000; Prein, 2002). The ponds can accept many forms of agricultural waste, including livestock manure and human excreta, and convert these wastes into high-grade fish protein. The pond sediment acts as a trap for excess nutrients, and prevents those nutrients from flowing into drainage waters. The sediment can be used to fertilize vegetable crops (Muendo, 2006) or grasses which are fed to livestock (Mathias, 1998), and restore soil fertility (Alibes, 2001).

IAA systems represent one potential avenue towards sustainable forms of smallholder farming (Dalsgaard and Christensen, 1997; Dalsgaard and Oficial, 1998; Dalsgaard and Prein, 1999; Christensen *et al.*, 2000). Sustainable smallholder farming is indicative of the concern that in future current farming practices might endanger the continuity of farming systems. This concern expresses environmental, economic and societal demands on farming systems. The increase in food demands, changing consumer preferences and degrading resources in farming will continue to pose new challenges (Dixon *et al.*, 2001). Intensification is a major strategy in meeting the increasing demands of animal products. The effects of intensification of farming activities on the environment are potentially worrisome (Delgado *et al.*, 2001). The use of compound feeds is the major tool in intensification of aquaculture. It also involves different species of fish and higher stocking densities. IAA systems in general are labelled semi-intensive as opposed to extensive systems relying exclusively on natural feed without intentional inputs, and intensive systems depending on nutritionally complete feeds (and fertilizers) (Edwards, 1993). As aquaculture continues to expand and intensify its impact on the environment is likely to increase (Edwards, 1993). As farming systems intensify, the relative importance of the various sub-systems may also change. The benefits of integration may be lost when intensification continues. This stresses the need to explore ecologically balanced development pathways for IAA systems.

## 1.2 Integrated Agriculture-Aquaculture systems in the Mekong Delta

In Asia, a wide range of IAA systems are practised in e.g., Bangladesh, China, India, Indonesia, Malaysia, Thailand and Vietnam (Pullin and Shehadeh, 1980; Little and Muir, 1987; Edwards, 1993; Mathias *et al.*, 1998; Luu, 1999; Prein, 2002). Vietnam, in particular the Mekong Delta (MD), has agro-ecological conditions that favour IAA systems. IAA farming is promoted to improve nutritional standards and incomes of smallholder households and to reduce the dependence on rice (Luu *et al*., 2002).

The MD is geologically young (Holocene age, about 10,000 years), and its exploitation only started about 300 years ago. Rice-based farming systems are characteristic of the MD. It is the rice bowl of Vietnam. Land use patterns vary from region to region due to the variations in landform, and soil and water conditions. Natural levees, alluvial sediments and artificial dikes along the rivers and canals provide space for dwelling in the upper flood-plain, where houses, orchards and paddy fields are distributed (Tanaka, 1995). The canal network has been essential in land use development in the MD. In the early stages three main canals were dug to mark the border between Vietnam and Cambodia, to strengthen the national defence and to exploit the land for settlement and rice cultivation. During the colonial period, canals were excavated for transportation of goods, and to irrigate and to wash away salt, so, that the land could be used for rice. Later, canals were dug to start new settlements and to improve the transport infrastructure. After the revolution (1975) canal digging continued for irrigation, flood control and again improving waterway transport (Xuan and Matsui, 1998).

Normally, farmers implement a system of ditches with their fruit orchards surrounded by a lateral ditch and a connection to the adjacent rice fields (Prein, 2002). The ditches in orchards, which are the result of excavations to raise the land above the flood level of the rainy season, are used for irrigation and for freshwater fish culture. Rice is the primary source of food and income for farmers. Traditionally, fish and other animals are used for home food consumption. Multiple cropping (e.g., cash crops in rotation with rice) is practiced mainly in the higher parts and tide-affected flood plains (Tanaka, 1995).

In the early 1970’s high-yielding rice varieties were introduced in the MD and they brought about a noticeable change in traditional rice culture. The widespread adoption of modern seed-fertilizer technology and use of agro-chemicals allowed farmers to grow two or three rice crops per year in the irrigated lowlands and to obtain higher yields per crop relative to traditional rice varieties. As a result, rice production in the MD increased substantially (Pingali and Xuan, 1992). For a long time market-oriented crops (e.g., fruit trees, cash crops) were not allowed to occupy rice lands, under the "food self-sufficiency" policy, even if such land was not suitable for rice (Xuan, 1994). This has changed after the Doi Moi (reform) economic policy in 1986. Since then, Vietnam has renovated its agricultural sector. In the MD, agricultural investments have resulted in modernization of the crop, livestock, forestry and fishery sectors. These changes motivated farmers to become more market-oriented. Together with efforts of intensification of rice cultivation (Berg, 2002), commercial crops like cash crops and fruit trees, livestock and fish have integrated gradually in farming (Tanaka, 1995). At present many variations in terms of crops, livestock and fish combinations and degrees of components integration can be found in the MD (Sanh *et al*., 1998; Yasunobu *et al*., 2000).

The MD accounts for about 18% of the gross domestic product (GDP), 90% of the rice exports and nearly 70% of the aquaculture products' export value (GSO, 2007). The GDP of the MD increased by 11.5% per year in the period 2000-2005 (Vietnamnet, 2006). The rapid socio-economic changes in the MD result from increases in agricultural and aquaculture production (AusAID 2004), for example, MD aquaculture production contributed approximately 52% in 2000 and 59% in 2008 to the total aquaculture products of the whole country (GSO, 2009). The main drivers for this fast growth were shrimp culture in the coastal areas and intensive *Pangasius* culture inland (Nhan, 2007).

Thus, within the past three decades, the farms in the MD have been transformed from self-sufficient farms producing mainly rice for home consumption and for the market to IAA farms, producing and marketing a large variety of products (Tanaka, 1995; Nhan *et al*., 2003). The greater liberalization and diversification of rural markets have improved opportunities for poor people both as producers and as consumers. Additionally, the MD is also prone to natural disasters (e.g., flooding), which leads to an uncertain existence for the poor (AusAID, 2004). Understanding the changes in farming can help to promote innovations for the sustainable development of IAA farming in the delta.

## 1.3 The study areas

The MD of Vietnam is located between longitudes 104°30’ to 106°47 E and latitudes 8°32’ to 11°02 N. Except for some minor hilly areas, the MD is flat and low-lying. The average altitude of the delta is about 2 meters above sea level. Comprising twelve provinces and one city, the total land area of the MD is 4,060,230 ha (12% of the national area) with a population of 17.695 million (in 2008) accounting for 21% of the national population. The population density is 436 persons per $km^2$, as much as 1.7

times of that of the nation (260 persons per km$^2$). About 72% of the population lives in rural areas (GSO, 2009).

The MD (Figure 1.1) has a tropical monsoon climate with an average annual air temperature of 27.2$^o$C, an average annual rainfall of 1511 mm, average annual number of sunshine hours of 2394, and an average relative humidity of 83% (CSO, 2005; GSO, 2009). Soils in the MD are alluvial soils (1,160,000 ha), acid sulphate soils (1,882,236 ha), temporarily and permanently saline soils (786,329 ha), grey soils (148,000 ha) and sand ridge soils (49,700 ha) (Phong, 1986). Based on agro-ecological characteristics such as rainfall, temperature, soil, topography, cropping system and water resources, the MD can be divided into seven major agro-ecological zones. They are Fresh Water Alluvial Zone, Plain of Reeds, Long Xuyen-Ha Tien Quadrangle, Trans-Bassac Depression, Coastal zone, Ca Mau Peninsula, and Hills and Mountains (Sanh *et al.*, 1998).

In 2008, the agricultural land in the MD comprised 2.56 million ha which is 27% of the agricultural land of the whole country. In the period 2000 to 2008 rice occupied 60%, annual upland crops 7%, fruit trees 9%, and aquaculture 24% of the agricultural land (Figure 1.2), in which the area used for aquaculture increased with 14%. In 2008, corresponding to each group of livestock, the number of cattle, pigs, poultry, and buffaloes contributed 11%, 14%, 19%, and 1.4%, respectively to the number of these livestock species in the whole country (Figure 1.3).

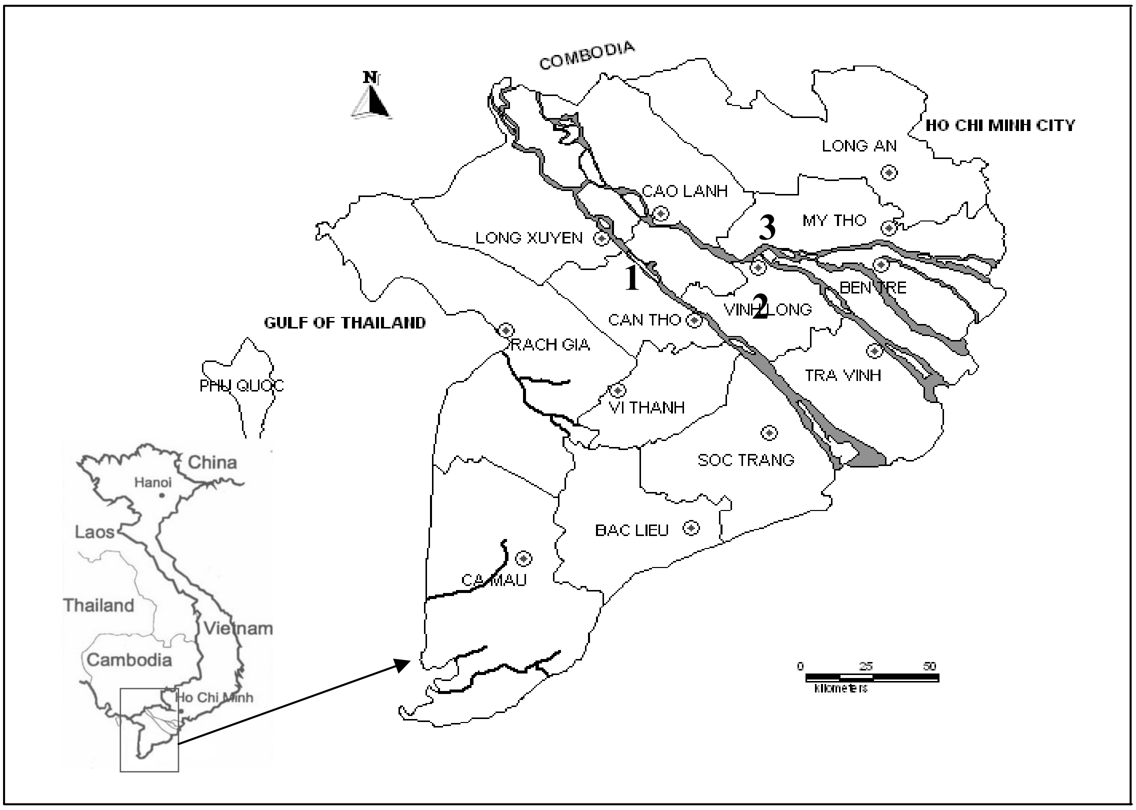

**Figure 1.1** Mekong Delta map with the three study sites. **1**: R-HF (rice-based and high input fish system); **2**: R-MF (rice-based and medium input fish system); and **3**: O-LF (orchard-based and low input fish system)

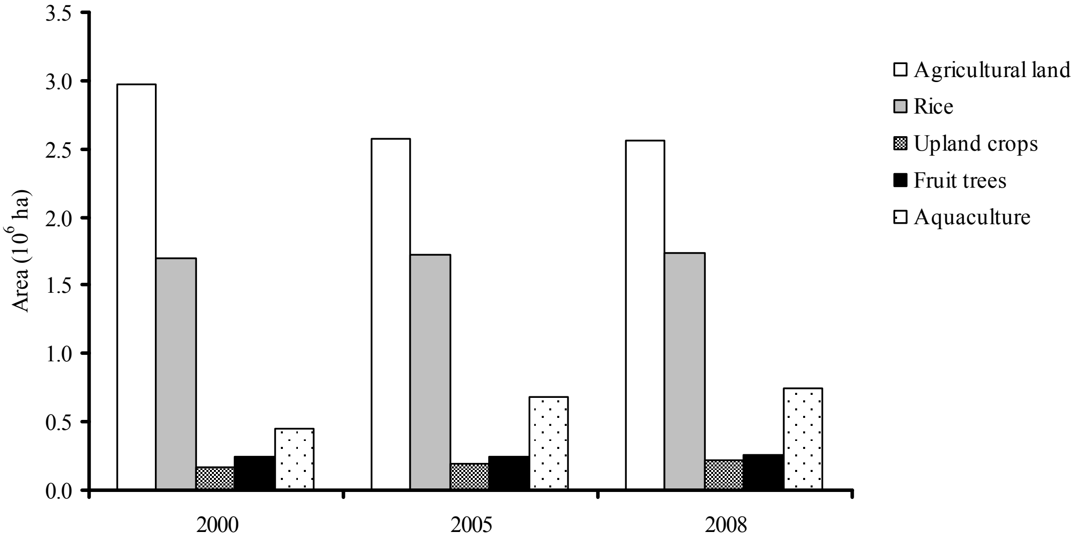

**Figure 1.2** Changes in land use in the MD from 2000 to 2008 (GSO, 2009)

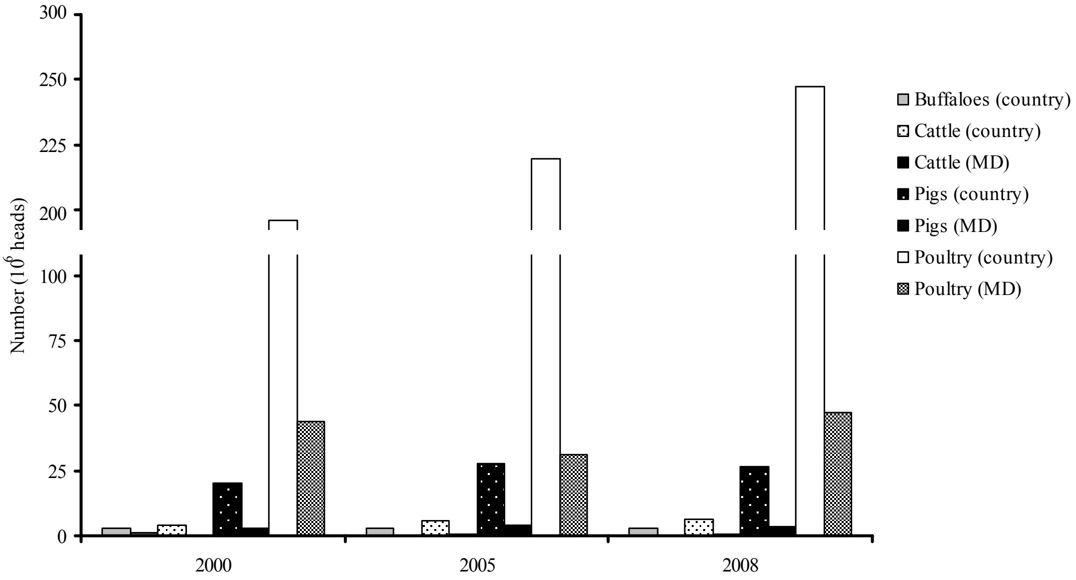

**Figure 1.3** Number of livestock in the MD and the whole country from 2000 to 2008 (GSO, 2009)

In 2002, the districts O Mon, Tam Binh, and Cai Be in Can Tho City, Vinh Long, and Tien Giang provinces, respectively, were chosen as the study sites (Figure 1.1) based on an expert consultation and a Participatory Community Appraisal (Pretty and Hine, 1999). These districts (1) are all located in the freshwater alluvial zone; (2) have distinctly different agro-ecological characteristics; (3) have high potential for improvement in agriculture and aquaculture; and (4) are easily accessible and not subject to severe flooding (WES Programme, 1997). The three districts differ in cropping patterns and intensity of fish culture: rice-based and high input fish system (R-HF) in O Mon district, rice-based and medium input fish system (R-MF) in Tam Binh district, and orchard-based and low input fish system (O-LF) in Cai Be district. The R-

HF and R-MF systems are located in low-lying flat land and less fertile soils with soil textures of clay to silty clay. Rice is the dominant crop in these two systems. The R-HF system is located close to Can Tho City and has relatively good access to urban markets, wheras the R-MF system is in a rural area. The O-LF system is located in higher-lying flat land with fertile alluvial soils, having silt clay texture. This area is a rural area with intensive fruit production.

In the R-HF system, fish farming is mainly in the form of monoculture, in particular *Pangasius* catfish for export. In the R-MF and O-LF systems fish are mainly in the form of poly-culture (e.g., tilapia, kissing gourami, giant gourami, silver barb, common carp, and silver carp). Fish in these two systems are produced mainly for domestic sale and household consumption. Fish yield in the R-HF system is high (10 to 40 tons $ha^{-1}$ $y^{-1}$) compared to the R-MF system (2 to 10 tons $ha^{-1}$ $y^{-1}$) and to the O-LF system (1 to 2 tons $ha^{-1}$ $y^{-1}$). The differences in intensity of fish culture between the three farming systems can be explained by differences in the use of feed inputs. In the R-HF fish system, fish are grown in ponds adjacent to the homestead. Fish are fed mainly with pelleted feed, some by-products from a fish-processing factory, and manure and human excreta. In the R-MF system, fish are fed with pig and poultry manure, human excreta, crop residues, and some pelleted feed at fingerling stage. In the O-LF system, fish are fed with crop residues from the farm, farm manure, and human excreta. Farmers grow fish in trenches between rows of fruit trees. Multivariate analyses, based on feed inputs and water exchange rates of fish ponds confirmed the existence of significant differences between the three areas (Nhan, 2007).

In the three areas, poultry is raised for both household consumption and sale. Pigs are commonly kept as a security source of money for households. Sale of piglets is an income source. Small and large ruminants are rarely kept because of high costs of buying stock. Grazing of large ruminants is not possible because of lack of grazing land, whereas housing them requires considerable labour for collecting feeds.

## 1.4 Objectives

The overall objectives of the thesis are (1) to identify driving forces for changes of IAA systems; (2) to quantify and evaluate agro-ecological characteristics of IAA systems; (3) to estimate nutrient balances of IAA farms and use them as an indicator for farm sustainability; and (4) to assess the environmental impact of farming processes via cradle to farm-gate life cycle assessment of products produced in IAA farms. We hypothesized that understanding of IAA systems in terms of driving forces for changes in farming practices, agro-ecological characteristics, nutrient balances, and environmental impact can help to explore sustainable development options for IAA systems in the MD.

## 1.5 Rationale of the research methodologies

IAA systems are a prominent example of complex agro-ecosystems. An ecosystem is a natural unit consisting of all plants, animals and micro-organisms in an area functioning together with all the non-living physical factors of the environment (Christopherson and Robert, 1997). An agro-ecosystem is an ecosystem transformed for the purpose of agriculture (Soemarwoto and Conway, 1992). An output from one subsystem in an agro-ecosystem which otherwise might have been wasted becomes an input into another subsystem resulting in a greater efficiency of output of desired products (Little and Muir, 1987; Edwards, 1998).

In IAA farms crop-animal integration follows the trophic level structure (i.e., the feeding position in a food chain) of natural ecosystems. These follow the regular food chain and nutrient transfer processes. The intensification of IAA farming might disturb these processes. It has a negative impact on the environment because of pollution in terms of N and P. Edwards (1993) concluded that intensive fish ponds were 26-44 times more polluting in terms of N, and 12-15 times in terms of P than semi-intensive fish ponds.

In agro-ecosystems there is a complex relationship between environmental, economical, and societal demands. To understand this relationship participatory research approaches are applied (Cramb and Purcell, 2001). In such approaches, communities become directly involved in assessing their own problems and arriving at a consensus of action that needs to be taken (Lelo *et al*., 1995). In each of the three districts two hamlets were selected (in 2002), and a participatory community appraisal (PCA) (Pretty and Hine, 1999) was carried out to collect general information on agricultural production and socio-economic conditions of the households. After the PCA, a structured survey was done randomly on 90 IAA farms to collect information on farming patterns, land use and production characteristics. The survey was repeated (in 2004) in order to study changes in IAA farm activities. In each district a meeting with farmers was organized to answer their questions on know-how techniques in farming. At the end of the field research period, in each district meetings were organized to discuss the outcomes of the research.

Eleven of the survey farms were chosen for detailed monitoring of inputs, outputs and internal bio-resource flows. These farms were selected based on a combination of farm characteristics representing the three IAA farming systems and practical considerations, such as accessibility and willingness of farmers to participate in the research.

IAA farms are often characterised by the cultivation and utilization of a wide range of species with different levels of integration and intensification. Judging a productive performance of a subsystem, a farm or a farming system on the basis of main farm yields may underestimate its real contribution to the performance of the agro-ecological system, and ignoring agro-ecological system complexity leads to inadequate understanding of the ecological impact of farming. Quantitative approaches are needed to assess the productive performance and ecological performance of complex agro-ecological systems (Dalsgaard and Oficial, 1997). In integrated farming systems research, the ECOPATH software (ICLARM, 1995) is used extensively to quantify ecological sustainability of agro-ecosystems with aquatic components (Christensen *et al*., 2000). For this study we used ECOPATH to quantify sustainability attributes and to compare IAA-systems with different forms of aquaculture intensification.

Crop-animal integration determines the pattern of nutrient cycling, as well as the flow of materials in the agro-ecological system (Sajise, 1998). A major benefit of integrating aquaculture in farming could be an improvement in nutrient use efficiency. Soil degradation is one of the ecological concerns that threatens sustainability of farming systems (Devendra and Thomas, 2002), especially in developing countries where harsh climates, fragile soils, and resource constraints make it difficult for small-scale farmers to invest in soil fertility management, erosion control, and restoration of degraded soils and terrain (Lal, 2001). In IAA farming systems pond sediment acts as a trap for excess nutrients, and prevents those nutrients from flowing into drainage waters. Nutrient-balance exercises can serve as instruments to provide indicators for the sustainability of agro-ecological systems and may be helpful in devising more sustainable nutrient management strategies (Roy *et al*., 2003; Bassanino *et al*., 2007). To understand nutrient budgets and nutrient balances in the IAA farms Nutrient Monitoring (Nutmon) was applied (De Jager *et al*., 1998; Vlaming *et al*., 2001). Nutmon integrates the assessment of stocks and flows of the macro-nutrients nitrogen, phosphorus and potassium at farm and activity levels (e.g., crops, livestock). It does include all nutrient pathways through direct measuring or via transfer functions which estimate the ‘hard-to-quantify’ flows due to atmospheric deposition, nitrogen fixation, gaseous losses, leaching and erosion. From nutrient flows in ECOPATH a nutrient balance of a farm can be derived by application of input-output accounting (Dalsgaard and Oficial, 1998). However, this is performed outside the ECOPATH routines, whereas Nutmon automatically calculates farm nutrient balances.

Originally, Nutmon was developed for African farming systems (Stoorvogel and Smaling 1990; Smaling *et al*., 1993). Contrary to the African systems, farming systems in the MD are characterised by relatively high inputs, multiple cropping, and presence of fish ponds. To apply Nutmon in the MD conditions we intend to adapt some of its hard-to-quantify nutrient flows by application of reference values from studies on paddy and upland soils in Asian countries.

Nutrient balances do not cover all aspects of the environmental impact of farming processes; the environmental impact as a result of the production and transport of farm inputs, and greenhouse gas emissions are not included. In recent years, Life Cycle Analysis (LCA) has been considered as a method for evaluating environmental loading of farming. LCA is defined as a technique for assessing the environmental aspects and potential impacts associated with a product (ISO International Standard 14040, 1997). LCA can give an integral environmental impact of a cradle to farm-gate life cycle of a farm product (Svoboda, 1995; Thomassen and De Boer, 2005; Thomassen *et al*., 2008). In this thesis, LCA was used to quantify and evaluate the integral environmental impact of IAA farming systems with different levels of aquaculture integration, and to identify hotspots in the environmental impact in IAA farming systems in the MD.

The different methodologies will be compared in terms of feasibility and suitability of their use in studying changes and ecological impact of IAA farming.

## 1.6 Thesis outline

Chapter 2 deals with the current status of IAA systems in the MD. It is based on information obtained from a participatory community appraisal and two structured surveys. The driving factors for changes in farm activities in the three selected IAA-systems were identified. Based on data collected from the participatory community appraisal on-farm monitoring was carried out. Chapter 3 evaluates agro-ecological performances of farms with different farming typologies for IAA systems, based on different fish input levels and dominant crop types, in the three districts in the MD. The ECOPATH model was used to quantify a range of agro-ecological attributes. In Chapter 4 Nutmon was adapted for SE Asia integrated farming systems. Reasons for adapting Nutmon are discussed. The adapted Nutmon model was used to quantify the balances of macro-nutrients in the IAA-farms in the three farming systems. Chapter 5 deals with the integral environmental impact of farming for IAA farms in the three farming systems in the MD, using LCA. For each farm, a detailed cradle-to-farm-gate life cycle assessment, including on- and off-farm resource use and emissions, was performed to compare the integral environmental impact per kilocal of farm product, kg of farm product, and per farm. Hotspots in environmental impact were identified for the three systems. The Discussion (Chapter 6) compares the different methodologies in terms of their use, their potential in evaluating ecological sustainability of integrated farming systems, and their potential to explore improvement options. Added to this, sustainable development of IAA systems is discussed.

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# Chapter 2

# Integrated Agriculture-Aquaculture Systems in the Mekong Delta, Vietnam: an analysis of recent trends

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## Abstract

In order to explain the trends in the development and farm attributes of Integrated Agriculture-Aquaculture (IAA) systems in the Mekong Delta of Vietnam, a participatory community appraisal and two surveys are carried out in three districts with contrasting fish culture input systems. The first survey, undertaken in December 2002, covers 90 households; the second, held December 2004, covers 80 households. The factors driving changes in the farming systems are the introduction of modern rice varieties, the policy of economic liberalization, market demand, and natural disasters. The principal components of IAA systems in the Mekong Delta which the study examines are the land use intensity, market access, farm diversity, farm inputs, and household income. The study finds that the hard-to-change farm characteristics are the land use intensities of rice, orchard and cash crops. In contrast, the easy-to-change farm characteristics are the number of farm components, the land use intensity of fish ponds, on-farm family labor, off-farm and non-farm income, and farm inputs. The main drivers of the changes over the two years are market demand and a poultry disease outbreak (Avian Influenza). Well-off farmers with good farming practices and enough capital tend to intensify their farming practices, while the poorer farmers tend towards diversification in order to safeguard their livelihood and avoid risks.

**Key words:** Mekong Delta; IAA; diversification; intensification; spezialization

## 2.1 Introduction

Interactions between crops and livestock are considered crucial to the sustainable development of agriculture in Asia (Devendra and Thomas, 2002). Three development pathways for farming systems can be distinguished, namely: (1) extensification, i.e., extending the cultivated area while maintaining or reducing input levels per unit area; (2) intensification, i.e., increasing production per unit area through more intensive production practices in land use and technology; and (3) diversification, i.e., changing farm practices and products to align them better with social, environmental and economic contexts (Erenstein, 2006; Barghouti *et al.*, 2004). One form of diversified agriculture mainly practiced in Bangladesh, China, India, Indonesia, Malaysia, Thailand and Vietnam is smallholder Integrated Agriculture-Aquaculture (Edwards *et al.*, 1988; Pullin and Shehadeh, 1980; Little and Muir, 1987). Prein (2002) defined this system as "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".

In Vietnam, the Integrated Agriculture-Aquaculture (IAA) systems are widespread in the Mekong Delta (MD). In this region the IAA systems are commonly practiced in the freshwater farming systems (WES Programme, 1997). The IAA farms contain one or more ponds or ditches in which to raise fish. In the MD, three main IAA production systems can be identified on the basis of the intensity of the fish culture: high-input fish culture and rice as main farm components, medium-input fish culture and rice as main farm components, and low-input fish culture and fruit trees as main farm components. The fish culture classification is based on the sources of fish feed. In the low-input fish culture, fish are fed with crop residues from the farm, farm manure, and night soil. In the medium-input fish culture, fish are fed with pig and poultry manure, night soil, crop residues, and some pelleted feed (e.g., at the fingerling stage). In the high-input fish culture, the main feeds for fish are pelleted feed, some by-products from a fish-processing factory, and manure and night soil.

In the area with high-input fish culture, the gross outputs of crops, livestock and aquaculture contribute 66, 15 and 18% to the total agricultural gross outputs of the district, respectively. In areas with medium-input fish culture these figures are 77, 19 and 4% of the total agricultural gross output of the district, respectively; and in the low-input fish culture, 78, 13 and 9%, respectively. Three districts in the MD (POND-Live, 2004) are selected for this study. Employment in the agricultural sector (mainly farming) is 36, 65 and 44% of the total population in the districts with high, medium and low input fish systems, respectively (O Mon Statistical Yearbook, 2004; Tam Binh Statistical Yearbook, 2004; Cai Be Statistical Yearbook, 2003).

In recent years there have been rapid socioeconomic changes in the MD, with increases in agricultural and aquaculture production (AusAID, 2004). Given that multi-component IAA farming systems are easily affected by economic and environmental changes (Prein, 2002), our study sets out to elucidate recent trends in IAA farming systems and to ascertain which farm attributes account for the dynamics of different IAA farming systems. It is hoped that the findings would be useful when identifying feasible innovations for the IAA farming systems in the MD. An IAA farm is here defined as the combination of the agriculture and aquaculture components and the household. An IAA farming system represents farms with a relatively similar typology.

## 2.2 Materials and Methods

The MD, covering about four million hectares, extends over 13 provinces. It can be divided into seven agro-ecological zones based on rainfall, temperature, soil, topography, cropping system, and water resources (Sanh *et al.*, 1998). The districts of O Mon, Tam Binh and Cai Be (see Chapter 1) in Can Tho City, Vinh Long, and Tien Giang provinces, respectively are chosen as the survey sites because these districts (1) have distinctly different agro-ecological characteristics, and freshwater farming systems; (2) have high potential for improvement in agriculture and aquaculture; and (3) are easily accessible and not subject to severe flooding (WES Programme, 1997). The three districts differ in the intensity of fish culture: orchard-based and low-input fish (O-LF) in Cai Be, rice-based and medium-input fish (R-MF) in Tam Binh, and rice-based and high-input fish (R-HF) in O Mon (see Table 2.1 for details). In each district, two hamlets were selected in 2002 and a participatory community appraisal (PCA) (Pretty and Hine, 1999) was used to collect general information on the agricultural production and socioeconomic conditions of their households. In addition, in each hamlet three knowledgeable farmers ranked independently the wealth of the farm households which numbered 743 in O Mon, 693 in Tam Binh, and 773 in Cai Be. Thirteen farmers in O Mon, 17 in Tam Binh, and 20 in Cai Be were interviewed for the detailed PCA. The PCA included timelines, transect maps, bio-resource flows and production activities. The timelines began in 1972. After the PCA, a baseline survey was done in December 2002 on randomly selected farms: 30 in O Mon, 29 in Tam Binh, and 31 in Cai Be. A structured questionnaire was used to collect information on farming patterns, land use and production characteristics. When the survey was repeated in December 2004, ten farmers had stopped farming or had moved from the village, so the households re-surveyed were 28 in O Mon, 23 in Tam Binh, and 29 in Cai Be. This time they were also asked about changes in farm activities.

Five farm components were considered: rice, orchard, cash crops, livestock, and fish pond. The farm area (in ha) included agricultural land and compound. The land use intensity (LUI) was calculated as the ratio (expressed as percentage) of the area used for each individual farm component in terms of the total agricultural area of the farm. The gross margins were calculated as the farm gross returns minus the farm variable costs (farm inputs); the net farm income was calculated as the gross margins minus the fixed farm costs. The household income was the sum of net farm income plus off-farm and non-farm income (Udo *et al.*, 1992). Household expenditure and consumption were excluded from the calculations. The crop inputs were fertilizers, pesticides, seeds, and land preparation costs. The outputs were staple food crops (rice), cash crops (water melon, mushroom, pulses, maize, sesame), and fruits (mango, longan, citrus, banana, coconut). The inputs for the poultry, pigs or fish components were rice, broken rice, rice bran, vegetables, concentrates, veterinary medicines, and stock purchases. The on-farm family labour was measured in full-time equivalents. Off-farm and non-farm income was reported per household member. The annual fixed farm costs were the depreciation of equipment, land maintenance fees, and taxes. The economic data for 2002 were adjusted to take account of the average annual inflation rate of 5.1% (Viet, 2004).

**Table 2.1** Characteristics of three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam

| Characteristics | Farming system types[1] | | |
|---|---|---|---|
| | R-HF | R-MF | O-LF |
| Soil conditions | Low-lying land, less fertile soil | Low-lying land, less fertile soil | Near rivers, high-lying land, fertile alluvial soil |
| Flood depth | 0.5 to ≥ 1 m | 0.5 to 1 m | 0.3 to 0.5 m |
| Major source of income | Rice, fish | Rice | Orchard |
| Fish production | - Mainly for sale, medium to major source of income<br>- Mainly monoculture of *Pangasius* catfish or climbing perch | - For domestic consumption and sale, medium source of income<br>- Poly-culture[2] | - Mainly for domestic consumption, minor source of income<br>- Poly-culture[2] |
| Fish yield | 10 - 40 tons $ha^{-1}$ $y^{-1}$ | 2 - 10 tons $ha^{-1}$ $y^{-1}$ | 1 - 2 tons $ha^{-1}$ $y^{-1}$ |
| Sources of Fish feed | Pig pen wastes, crop residues, vegetables, weeds/grasses, crabs, golden snail, waste products from fishery processing industry, pelleted feed | Mainly pig pen wastes, poultry manure, crop residues, vegetables, weeds/grasses, crabs, golden snail, pelleted feed | Small and irregular quantity of pig pen wastes, crop residues, vegetables, weeds/grasses |
| Animal husbandry | - Chickens, ducks for both food and sale<br>- Pigs as security; breeding (major) and fattening pigs for sale<br>- Rarely large or small ruminants | - Chickens, ducks for both food and sale<br>- Pigs as security; breeding and fattening pigs mainly for sale<br>- Rarely large or small ruminants | - Chickens, ducks for family food<br>- Pigs as security; breeding and fattening pigs mainly for sale<br>- Rarely large or small ruminants |
| Sub-components ranked in order of importance | 1. Fish pond<br>2. Rice<br>3. Livestock<br>4. Orchard | 1. Rice<br>2. Orchard<br>3. Livestock<br>4. Fish pond | 1. Orchard<br>2. Rice<br>3. Livestock<br>4. Fish pond |

[1] R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

[2] tilapia, kissing gourami, giant gourami, silver barb, common carp, silver carp, *Pangasius* catfish

*Statistical analysis*

One-way ANOVA (Analysis of variance) and T-tests were applied to examine the variability and changes in farm management in the three fish input systems. Annual mean values of selected variables were linked in a factor analysis using the principal component method, to identify the relationships between the variables of interest in the three systems. Correlation coefficients of less than 0.5 were suppressed. Varimax rotation with Kaiser Normalization was used to facilitate interpretation of the principal components (Leech *et al*., 2005).

## 2.3 Results

Based on data gathered from the two surveys, this study applied the ANOVA and factor analysis on several factors relating to the farm characteristics, farm activities, and household economy. The results are presented below in terms of the main events that influenced agricultural development; the ranking of wealth among the three input systems; patterns of farm settlements, activities and bio-resource flows; the changes in the farm activities and economic characteristics of the households; and of the principal components that would explain the variance.

### *2.3.1 Timeline*

Figure 2.1 shows an example of a timeline of around 30 years in one of the survey sites in the Mekong Delta, in which the main events are the Vietnamese revolution of 1975, the introduction of modern rice cultivars, the start of the Doi Moi economic reform policy, natural disasters, market fluctuations, and the reduction of agricultural taxes. The modern rice varieties, introduced in 1968, gave farmers the opportunity to grow two or three crops per year, from 1972 onwards. The increased rice production contributed to food security, and also impacted on animal production, because extra feed became available e.g., for more intensive pig production; this started around 1983.

In 1976, all provinces in southern Vietnam were urged to move gradually toward collectivization (Pingali and Xuan, 1992). Land was redistributed in an attempt to implement the cooperative movement (CM), and was contracted to families or production teams to meet production targets. Under the centrally planned economic system, the emphasis was on creating large production units: cooperatives at the village, inter-village, or commune level. Farm households could use services provided by the cooperatives (Harms, 1996).

The most important event in the 1980s was the Doi Moi economic reform policy. It marked the transition from a centrally planned economy to a market-oriented one. The cooperative movement was abandoned in 1990 as part of this policy. Farmers were supported financially via the Rural Credit Programme (RCP) and Poverty Alleviation Programme (PAP) and received technical advice from the local extension network. Encouraged by the high economic returns from fruit trees (e.g., mango, longan, and citrus) in the 1990s, the gardening development program encouraged the O-LF farmers,

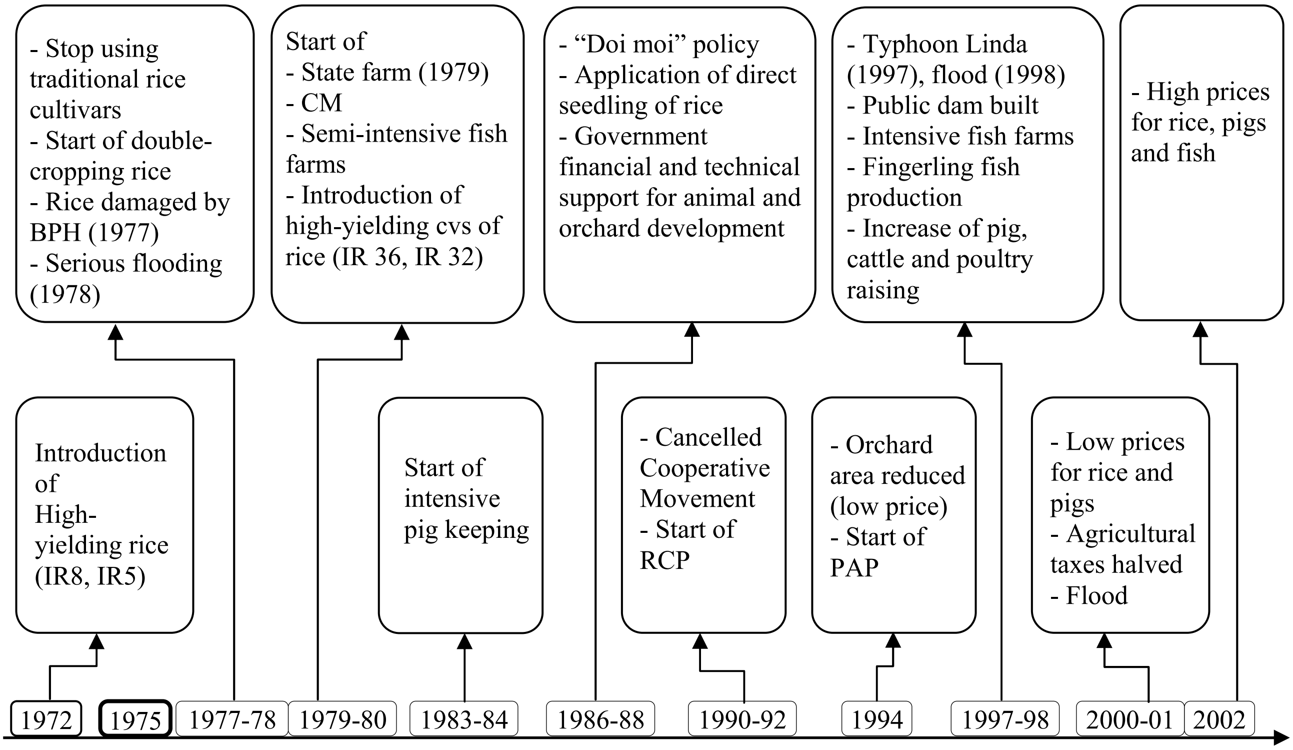

**Figure 2.1** Timeline in O Mon. In the other two districts, the main events are similar but the chronology of technology may differ (The abbreviations used above and their meanings are: BPH - Brown Plant Hopper, CM - Cooperative Movement, RCP - Rural Credit Programme, and PAP - Poverty Alleviation Programme)

whose lands had fertile soils, to develop orchards. Like all other land uses, fruit orchards have been flooded annually by the Mekong River. One way to control flooding has been to build a dike around villages and orchards. This has become popular in all fruit-producing areas of the MD. Farmers have regularly been faced with market price fluctuations (e.g., low fruit prices, which resulted in less land planted to fruit trees in 1994), and the loss of produce due to insect attack, storms or floods (e.g., the Brown Plant Hopper (BPH) outbreak in 1977, typhoon Linda in 1997, or the floods of 1978, 1998 and 2002). To encourage farm activities, the government halved agricultural taxes in 2000-2001.

### *2.3.2 Wealth*

The farmers' criteria for ranking wealth in the three input systems were similar. The people classified as "rich" generally had fewer than four children, all of whom went to school. They usually owned more than one hectare of land and their farming activities commonly consisted of pig husbandry, fish hatchery, or an intensive orchard. The moderately wealthy people owned around 0.3 to 1 hectare of land. Their children all went to primary school, but rarely went on to high school. The families had a stable livelihood with no debts; they also earned their income through off-farm and non-farm activities. The poor farm households normally had more than four children, not all of whom attended school. They had little or no land to farm and lived in small palm-thatched houses. The poorest were unskilled farmers working as hired labourers, who had debts and were classified as poor by local authorities. Ranking by wealth revealed that in the R-HF system there were twice as many rich people and more poor people than in the R-MF and O-LF systems (Figure 2.2).

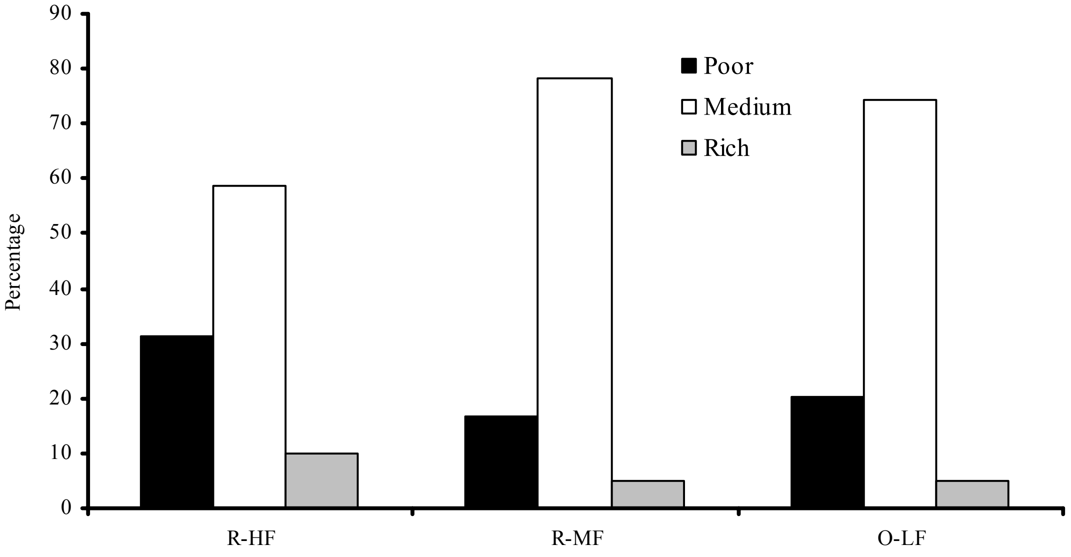

**Figure 2.2** Ranking of wealth in the rice-based and high input fish (R-HF), rice-based and medium input fish (R-MF), and orchard-based and low input fish (O-LF) systems in the Mekong Delta

### *2.3.3 Farm transect, farm activities and farm bio-resource flows*

The farm transects reflect the patterns of settlement. Commonly, farmers live near a river or canal in order to access water and transport facilities. There is usually an orchard behind the house, on raised beds of a well-drained soil. Animals are kept in the yard around the house or in the orchard. A pond is constructed near the house to provide water and for rearing fish. Fish are also reared in ditches between the raised beds of the orchard. Adjoining the orchard is a paddy field on land subject to annual flooding. The three fish input systems have similar soil types (young alluvial clays) but rice fields in the R-HF system have problems of acid sulfate soil. The R-MF system is on lower-lying land, has acid sulfate soils, and is also flooded most deeply (up to one meter in the wet season). Farms in the south of Cai Be district (O-LF system) are higher-lying and their soil is fertile, recently-deposited alluvium from the Mekong River. The main water sources for the three input systems are the rivers and main canals; water flows under gravity, via inlet sluices.

Annual rice production varies from one to three cropping seasons, with yields of 4 to 6 tons per ha per crop. In places with irrigation, cash crops such as chili pepper, beans, cabbage, tomato, cucumber, and watermelon could replace rice as the dry season crop. Though fruit trees (citrus, longan, and mango) are commonly grown in the three systems, the most intensive orchards are in the O-LF system: these are mono-crop orchards with high investments (e.g., high rate of fertilizer and chemical application). In the other two systems, the orchards are extensive or semi-intensive. In the R-HF system, mono-fish culture (mainly catfish for export) is common, while the R-MF and O-LF systems have a mixture of species (e.g., common carp, silver barb, kissing gourami, tilapia, and catfish). Poultry are kept in the farmyard or orchard, mainly for family consumption. Pigs are kept in pens and sold at the market. Other animals such as rabbits are raised incidentally, depending on seasonal market demand. Large ruminants are rarely kept because of the high purchasing cost and cumbersome marketing.

The farm components in IAA farms could be linked through bio-resource flows. Traditionally, rice is the main source of food and provides cash income for the family and feed for the animals. Rice straw is used to mulch beds of vegetables and orchards, or to produce mushrooms. Weeds from the orchard and wastes from vegetables and fruits serve as other feed sources for pigs, poultry, and fish. Commonly, a catfish pond hosts a latrine supplying human excreta. Pig manure could be used to fertilize the fish pond or the orchard. The manure from chickens and ducks is a source of organic fertilizer for fruit trees when the poultry are free-ranging, or for fish when they are penned above the pond. The orchard trees are mulched with the enriched mud from the pond bottom and the decomposed rice straw left after mushroom cultivation. In addition, the pond is used to supply water for fruit trees and for pigs and poultry, and to produce water spinach, snails, or crabs. In this way, almost all waste and excreta are recycled on the farm.

### *2.3.4 Changes of farming activities and economic characteristics of households*

In the two survey years the farm size (5-6 persons), the farm's cultivated area (1.14 - 1.23 ha in 2002 and 0.87-1.14 ha in 2004), and the LUIs of cash crops and fish pond were similar in the three systems (Table 2.2). The slight change in mean distance from the farm to district market in the R-MF farms in 2004 was caused by the change in sample size. The maximum number of farm components was five: rice, orchard, cash crop, livestock, and fish pond. Almost all the farms had at least two components, and just under half of the farms (49% in 2002 and 44% in 2004) had four components. In 2002, the R-HF farms had a significantly lower number of farm components than the R-MF and O-LF farms, but by 2004 this difference had disappeared. The number of farm components had significantly decreased in 2004 compared to 2002 (Table 2.3). In both 2002 and 2004 the LUI of rice was significantly higher in the R-HF and R-MF farms than in the O-LF farms, while the LUI of orchard was significantly higher in the O-LF farms compared to the R-MF and R-HF farms. Between 2002 and 2004 the LUIs of rice, orchard, and cash crops were quite stable in the three systems (Figure 2.3). However, the LUI of fish ponds increased significantly: from 7% to 11% ($P<0.05$). In both 2002 and 2004 the number of chickens and ducks reared in the R-MF farms was significantly higher than in the O-LF and R-HF farms ($P<0.05$). The numbers of pigs reared were similar between the three systems, and hardly changed between 2002 and 2004 (Figure 2.4).

**Table 2.2** Farm characteristics and land use intensity in the three input fish systems in 2002 and 2004 (standard error in parentheses)

| Variables | Farming system types[1] | | | |
|---|---|---|---|---|
| | R-HF | R-MF | O-LF | CV[2] |
| **2002** | | | | |
| Distance to district market (km) | 7.0$^b$ (0.5) | 15.0$^a$ (1.2) | 14.0$^a$ (0.5) | 32 |
| Farm's components (n) | 3.4$^b$ (0.2) | 4.2$^a$ (0.1) | 4.0$^a$ (0.1) | 21 |
| Farm size (ha) | 1.23 (0.16) | 1.15 (0.15) | 1.24 (0.12) | 59 |
| LUI[3] of rice (%) | 69.0$^a$ (6.3) | 66.0$^a$ (4.9) | 38.0$^b$ (6.7) | 52 |
| LUI of orchard (%) | 23.0$^b$ (5.4) | 23.0$^b$ (4.6) | 47.0$^a$ (5.6) | 84 |
| LUI of cash crops (%) | 3.0 (1.7) | 2.0 (1.2) | 8.0 (3.6) | 268 |
| LUI of fish pond (%) | 5.0 (1.4) | 9.0 (1.6) | 7.0 (1.6) | 109 |
| **2004** | | | | |
| Distance to district market (km) | 7.0$^c$ (0.5) | 17.0$^a$ (1.1) | 14.0$^b$ (0.4) | 27 |
| Farm's components (n) | 3.3 (0.2) | 3.5 (0.2) | 3.1 (0.2) | 29 |
| Farm size (ha) | 1.10 (0.14) | 1.14 (0.15) | 0.87 (0.10) | 64 |
| LUI of rice (%) | 74.0$^a$ (6.9) | 68.0$^a$ (5.3) | 32.0$^b$ (6.7) | 58 |
| LUI of orchard (%) | 16.0$^b$ (4.7) | 17.0$^b$ (3.1) | 51.0$^a$ (5.4) | 81 |
| LUI of cash crops (%) | 1.0 (0.5) | 4.0 (4.1) | 3.0 (2.5) | 545 |
| LUI of fish pond (%) | 9.0 (3.4) | 10.0 (1.7) | 14.0 (2.4) | 119 |

[1] R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

[2] Coefficient of variation in percentage

[3] Land use intensity

Different superscripts ($^{a,b}$) denote significant differences between means within rows (P<0.05)

**Table 2.3** Changes in household characteristics and household economy between 2002 and 2004 (standard error in parentheses)

| Variables | Survey | Overall mean | Change[1] | CV[2] |
|---|---|---|---|---|
| Farms' components (n) | 2002 | 3.9$^{**}$ (0.1) | | 22 |
| | 2004 | 3.3 (0.1) | -15 | 30 |
| LUI[3] of fish pond (%) | 2002 | 6.9 (0.9) | | 110 |
| | 2004 | 11.3$^{*}$ (1.5) | 64 | 120 |
| On-farm family labour (day) | 2002 | 103.0 (8.0) | | 67 |
| | 2004 | 202.0$^{**}$ (25.0) | 96 | 109 |
| Variable costs (million VND) | 2002 | 11.97 (1.32) | | 95 |
| | 2004 | 25.12$^{**}$ (3.24) | 110 | 113 |
| Gross returns (million VND) | 2002 | 25.45 (2.34) | | 79 |
| | 2004 | 43.71$^{**}$ (4.04) | 72 | 81 |
| Off- and non-farm income (million VND) | 2002 | 6.05 (1.16) | | 166 |
| | 2004 | 10.05$^{*}$ (1.19) | 66 | 104 |
| Household income (million VND) | 2002 | 19.16 (2.20) | | 99 |
| | 2004 | 28.26$^{**}$ (2.93) | 48 | 91 |

[1] Relative change in percent

[2] Coefficient of variation in percent

[3] Land use intensity

$^{*}$ P<0.05, $^{**}$ P<0.01

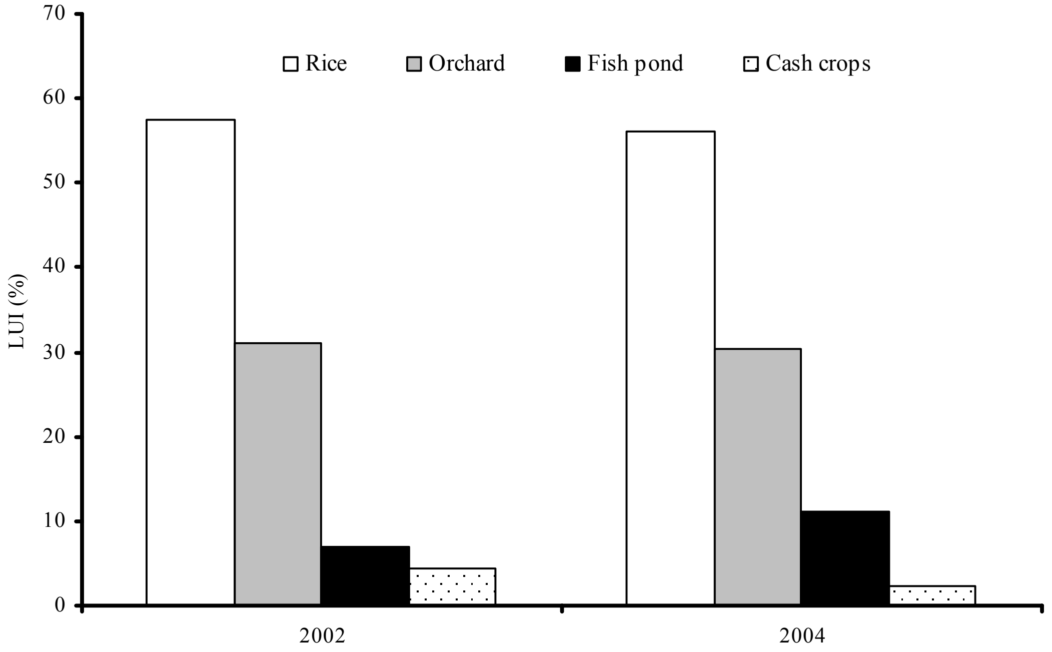

**Figure 2.3** Changes in LUIs (Land use intensity) of farm components in the three input fish systems (2002 to 2004)

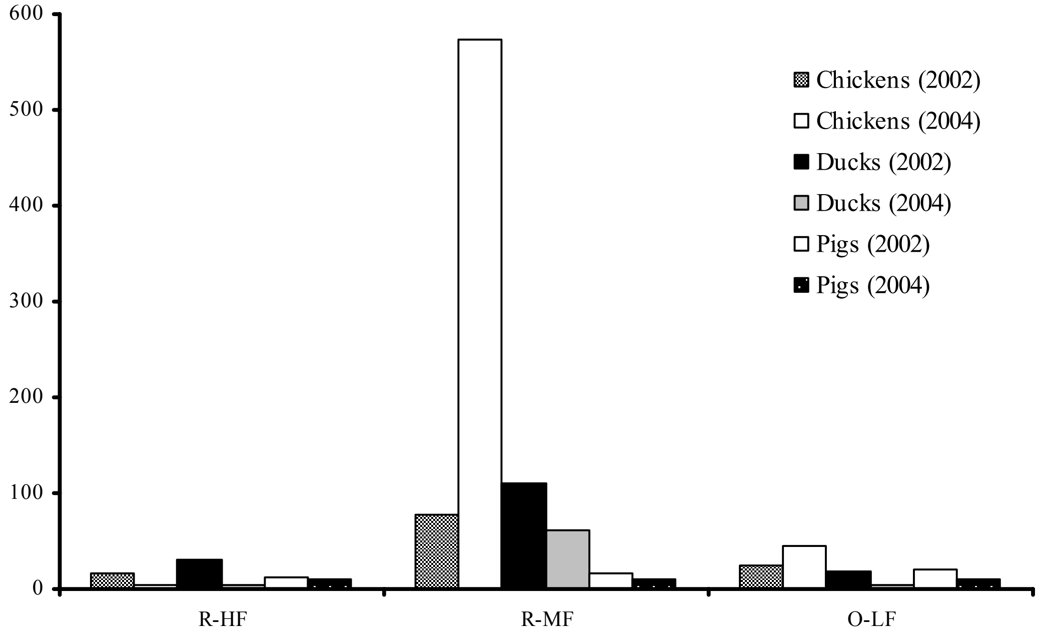

**Figure 2.4** Number of livestock in the rice-based and high-input fish (R-HF), rice-based and medium-input fish (R-MF), and orchard-based and low-input fish (O-LF) systems in 2002 and 2004

In 2002 and 2004 no significant differences were observed between the farms in the three systems in terms of farm gross returns, variable costs, gross margins, general charges, and net farm income (Table 2.4). However, off-farm and non-farm incomes were significantly ($P<0.05$) lower in the R-MF farms than in the O-LF and R-HF farms

**Table 2.4** Household economic parameters[1] in the three input fish systems in 2002 and 2004 (standard error in parentheses)

| Variables | Farming system types[2] | | | |
|---|---|---|---|---|
| | R-HF | R-MF | O-LF | CV[3] |
| **2002** | | | | |
| On-farm family labour (day) | 99 (14.1) | 100 (15.2) | 110 (12.9) | 68 |
| Variable costs | 12.76 (2.31) | 12.95 (2.27) | 10.24 (2.31) | 95 |
| Fixed costs | 0.44 (0.09) | 0.38 (0.06) | 0.31 (0.05) | 90 |
| Gross returns | 30.58 (5.58) | 22.14 (2.66) | 23.50 (3.17) | 79 |
| Gross margins | 17.82 (3.65) | 9.19 (1.67) | 13.27 (2.20) | 98 |
| Net farm income | 17.38 (3.62) | 8.81 (1.67) | 12.96 (2.20) | 101 |
| Off- and non-farm income | 6.69 (2.15) | 6.04 (2.19) | 5.42 (1.78) | 168 |
| Household income | 24.07 (5.03) | 14.85 (2.79) | 18.38 (3.07) | 98 |
| **2004** | | | | |
| On-farm family labour (day) | 134 (17.1) | 272 (72.6) | 211 (32.2) | 107 |
| Variable costs | 24.99 (5.52) | 33.19 (8.27) | 19.12 (3.07) | 112 |
| Fixed costs | 0.47 (0.08) | 0.43 (0.08) | 0.25 (0.05) | 96 |
| Gross returns | 44.64 (6.84) | 47.06 (8.86) | 40.34 (5.92) | 82 |
| Gross margins | 19.65 (2.83) | 13.87 (6.51) | 21.22 (3.96) | 121 |
| Net farm income | 19.18 (2.82) | 13.44 (6.47) | 20.97 (3.95) | 123 |
| Off- and non-farm income | $10.68^{a}$ (1.47) | $3.77^{b}$ (0.89) | $14.24^{a}$ (2.51) | 96 |
| Household income | $29.87^{ab}$ (2.81) | $17.21^{b}$ (6.56) | $35.21^{a}$ (5.10) | 88 |

[1] Million VND $y^{-1}$

[2] Coefficient of variation in percentage

[3] R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

Different superscripts ($^{a,b}$) denote significant differences between means within rows ($P<0.05$)

in 2004. Household income was significantly ($P<0.05$) lower in the R-MF farms than in the O-LF farms in 2004. On-farm family labour was similar in all systems in 2002, but was significantly higher ($P<0.05$) in the R-MF farms in 2004. This corresponds to an important rise in number of chickens (e.g., 6 farms had 150 to 6000 chickens per farm in 2004) in this area (see also Figure 2.4). The on-farm family labour and the variable costs increased significantly ($P<0.05$) in 2004, but despite this the farm gross returns were higher. Together with a significant increase in off-farm and non-farm income, this contributed to a significantly higher ($P<0.05$) household income (Table 2.4). The most important contributors to the gross margins were rice, orchard, and fish pond. The negative contribution of poultry was caused by the outbreaks of Avian Influenza (AI) in 2003 and 2004 (Figure 2.5).

### *2.3.5 Principal components explaining the types of IAA systems*

Nineteen average values of the main farm characteristics for 2002 and 2004 were used in the factor analysis, extracting seven principal components that explain 81% of the total variance (Table 2.5). All variables have high loadings (correlation coefficients greater than 0.5) indicating that a significant percentage of the variance of each variable is explained by these seven principal components. More than half of the variables

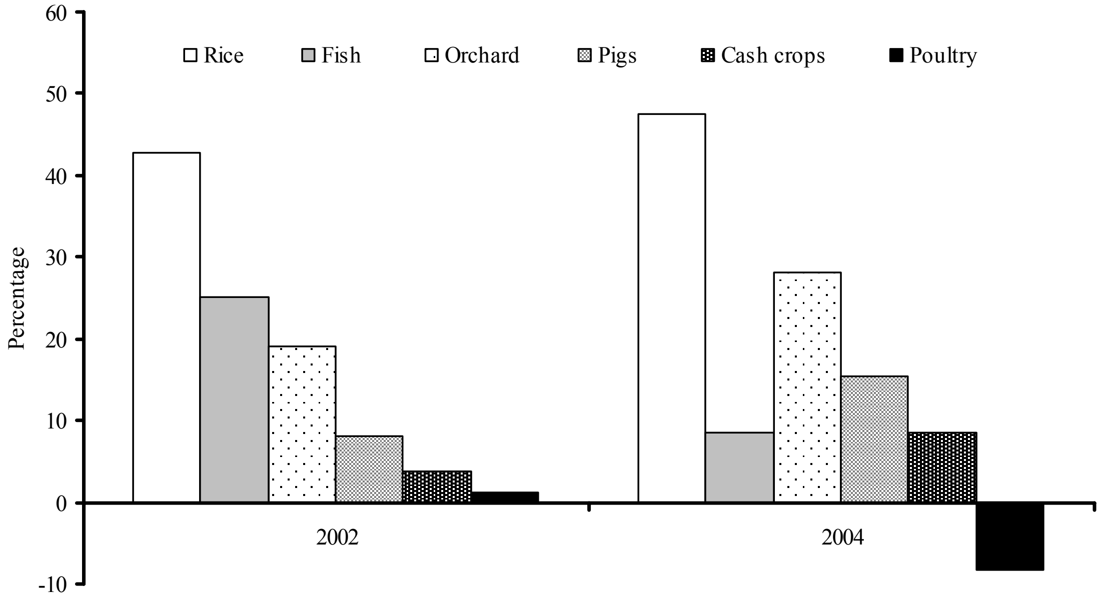

**Figure 2.5** Average contribution of the farm components to the gross margins in 2002 and 2004

**Table 2.5** Rotated component matrix and correlation coefficients based on baseline surveys for 2002 and 2004

| No. | Variables | Components | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | Net farm income | 0.972 | | | | | | |
| 2 | Gross margins | 0.969 | | | | | | |
| 3 | Household income | 0.924 | | | | | | |
| 4 | Variable costs | | 0.848 | | | | | |
| 5 | Gross returns | 0.626 | 0.702 | | | | | |
| 6 | On-farm family labour | | 0.629 | | | | | |
| 7 | Farm size | 0.517 | 0.626 | | | | | |
| 8 | Cultivated area | 0.517 | 0.626 | | | | | |
| 9 | Fixed costs | | 0.583 | | | | | |
| 10 | LUI[1] of rice | | | -0.958 | | | | |
| 11 | LUI of orchard | | | 0.936 | | | | |
| 12 | LUI of fish pond | | | 0.732 | | | | |
| 13 | Off- and non-farm income | | | | 0.791 | | | |
| 14 | Family size | | | | 0.772 | | | |
| 15 | School years of HH[2] | | | | | 0.821 | | |
| 16 | Years of residence of HH | | | | | -0.538 | | |
| 17 | Distance[3] | | | | | | 0.836 | |
| 18 | Farm components | | | | | | 0.552 | |
| 19 | LUI of cash crops | | | | | | | 0.938 |
| | Eigenvalue | 5.4 | 2.8 | 2.0 | 1.6 | 1.2 | 1.1 | 1.1 |
| | % of variance | 28.5 | 14.8 | 10.7 | 8.7 | 6.6 | 5.9 | 5.6 |

[1] Land use intensity

[2] Household head

[3] from district market

carried high loadings in the first three principal components, explaining 54% of the total variance. The first principal component was strongly related to household income, the second to farm investment, the third to the LUI of the farm. The last four principal components related to household demography, farm diversity and market access.

## 2.4 Discussion

We now proceed to ferret out the implications of the study's findings presented above. The discussion below includes how forces such as new technological developments or environmental disasters or government policies impact on the farming system. Also tackled are the motivations that propel farmers to adopting either diversification or intensification to cope with the changing farm resources and market opportunities. The key roles of on-farm strategies, relative to non-farm or off-farm income, in sustaining improvements to their livelihoods are looked into, as well.

### *2.4.1 Diversification and intensification*

The farming systems in the MD are determined by agro-ecological conditions, tradition and related government policy. They are rice-based, with fruits as the secondary crop. Most farmers prioritize rice cultivation, not only for food security but also to increase income. In the past, traditional rice cultivars with a low yield and a long growth cycle were grown, but the introduction of modern high-yielding rice varieties with a short growth cycle has enhanced production. In areas with irrigation, cropping systems have switched from one cropping season of 6–8 months to two consecutive rice crops per year of four months each (Pingali and Xuan, 1992). Other crops such as beans, maize or watermelon are sometimes grown as an alternative to the irrigated rice crop, to supply food or cash to the household. The rapid and widespread adoption of new rice varieties and technology (e.g., fertilizer application, insect pest control) had caused an overproduction of rice (e.g., rice export in 1990s) and a sharp decline of market prices (IFPRI, 1995). This motivated farmers to develop other farm components and to use rice products to feed pigs, poultry or fish.

The Doi Moi economic reform policy has been a major force driving diversification. Government-controlled collectivized systems using production contracts have changed to systems with individual farm management, and oriented to the open market (Anh *et al.*, 2003). Government services provided the farmers with new farm technology, and new animal breeds and cultivars. Credit and other extension activities were provided for those who engaged in fruit tree production, and no agricultural taxes were charged for the first three-year period. Since 1990 the area under fruit trees has greatly increased. After a few years, (Figure 2.1), a fall in the market fruit prices due to surpluses and an unstable export market slowed down farmers' investments in orchards. Farmers were also encouraged to raise hybrid pigs and to use concentrates to shorten the fattening period (e.g., 4–5 months' cycle instead of 6 or 8 months' cycle) and to produce leaner animals. The intensification of poultry started later and local breeds have remained more popular because they are easy to sell in the local market, are resistant to common diseases, and are less demanding with regard to feed.

Between 2002 and 2004, the household characteristics and land areas in the three systems remained fairly similar (Table 2.4) but there were many internal changes in the systems, especially in land use and farm economy (Table 2.3). One change was a decrease in the number of farm components: this may have been due to fluctuations in market demand and falling farm product prices. Rice fields and orchards are likely always to be present on the farms; they represent "hard-to-change" farm components. They make major contributions to the farm income (Figure 2.5). Cash crops are often cultivated between rice crops in the same fields, or in a separate permanent vegetable plot. The LUI of cash crops was small and did not change in the two years, but it was different between the three input systems possibly because traditional cultural practices differ in the different agro-ecological zones: e.g., in the O-LF system, watermelon is commonly grown to supply markets during the traditional Tet holiday.

Livestock and fish are easy-to-change farm components. Livestock keeping does not require much land area, as crop wastes or grasses/weeds are used as feed. Animal wastes can substantially reduce farmers' input costs for fish feed or for fertilizer. In 2003 the first outbreak of AI in Vietnam occurred; it lasted till March 2004. This outbreak did not greatly affect the surveyed farms; therefore after the first AI some farmers intensified their chicken production, hoping that they could benefit from the collapse of industrial chicken production. However, their chicken production collapsed too, as there was a second outbreak of AI at the end of 2004. The intensification of chicken production needed more on-farm family labour (Table 2.3). The shortage of poultry meat that followed from the AI outbreak increased the demand for pork and fish. Consequently, an increase in the LUI of fish pond was recorded (Table 2.3). Pig production did not increase, due to a fall in market price, the high cost of hybrid piglets, and the continuing rise in the price of rice bran (Bosma *et al*., 2006).

The significant increase in off-farm and non-farm income in the O-LF and R-HF farms in 2004 compared to 2002 meant that more family members were working as hired labourers outside the farm. This reflected the increased opportunities offered by the labour market in these areas. In the R-MF farms the high on-farm family labour in 2004, mainly caused by the labour demands of increasing the poultry flock, affected the figures for labour used for off-farm and non-farm activities. The level of investments differed between the systems (Table 2.4). On top of the increase in costs of gasoline (21%) and fertilizer (22%) in 2003 (Incombank, 2003), the variable costs increased between 2002 and 2004 by 110% (Table 2.3), which is evidence of farm intensification. The significant increase of household income in 2004 was the result both of an increase in the farm gross margins due to higher gross returns, and of higher off-farm and non-farm income.

Generally, it can be said that the well-off farmers with good farming skills and enough capital tend to intensify their farming systems, while the poorer farmers tend to move towards diversification, in order to safeguard their living and avoid risks. The gap between the poor and the rich in the R-HF (e.g., 21%) and O-LF (e.g., 15%) farms (Figure 2.2) indicates that the rich are successful in farming because they have sufficient financial resources to intensify their farming and to assure long-term commitment to farming. Shortage of cash means that the poor are not buffered against risk: crop failure or animal disease means they lose money and may have to stop farming and become hired labourers for rich farmers, or move to the town to work in the service sectors. The high percentage of moderately wealthy households in the R-MF farms (78% of all households) indicates that more diversified farming leads to a trend towards higher incomes for these households. In addition, the job opportunities related to market access and urbanization (as in the R-HF and R-MF areas) can cause farmers to abandon agriculture: This can increase the disparity in household wealth.

### *2.4.2 Determinant attributes of IAA systems*

The principal components reflect two main attributes of the IAA farms: the diversified farm resources and household economy.

Pond aquaculture is only a minor component in the IAA systems but integrating aquaculture with fruit, rice, and livestock can help to improve the use made of local natural resources and to increase the contribution of inland aquaculture to total agricultural production. The O-LF system is near the Mekong River, where the higher-lying land and fertile soil have favoured the development of intensive fruit production combined with a low-input and low-output fish system (Table 2.1). The use of large quantities of chemicals (e.g., fertilizers, pesticides, chemical control of fruit-tree flowering) and the reduced solar radiation due to shading by fruit trees may affect the fish growth in the narrow orchard ditches (Nhan *et al*., 2006).

In the R-MF farms, no single farm component like the fruit trees in the O-LF farms or fish in the R-HF area is dominant: in other words, the R-MF farms show the widest variety of farm components. A government program to encourage horticulture has resulted in many orchards being established in the 1990s on land where rice had been grown. This contributed to the development of fish ponds in ditches between the raised beds for the fruit trees. However, fruit yields here are low because of the combination of the low-lying land at risk of flooding, the high groundwater, and the acidic soils.

Most fishes in the R-HF area are commercially produced and of export quality. Intensive fish farming requires high capital investment, specialized labour and technical know-how. It is especially suitable for farmers with sufficient land and cash to be able to construct a large fish pond. The trading tactic of “buy first, pay later” (i.e., a farmer buys feed but only pays for it after harvesting the fish) of local feed agencies encourages farmers to engage in fish culture. For farmers who have little land or insufficient capital to rear fish for export, an alternative way of generating income is to produce fingerlings.

Changes of LUI and income diversification are common farmer responses to changing farm resource and market opportunities (Dixon and Gulliver, 2001). Off-farm and non-farm activities generate an important part of many household incomes on the farms (32 to 36%). The expected decrease in family size in the long term makes it likely that the on-farm intensification, diversification, and changes/choices of LUI will prove to be more important livelihood household strategies than off-farm and non-farm activities.

A main difference between the three research areas is market access. It affects the potential for sales of farm produce and access to external inputs, extension services, and opportunities for non-farm income. The relationship between the market access of remote farms and the farms' diversity (number of farm components) suggests that remote farms recycle their internal resources better between farm components (Bosma *et al*., 2006). This is illustrated by the higher number of farm components in the R-MF farms (Table 2.2) and its higher values for ecological sustainability indicators (Phong *et al*., 2006).

Holling (1995) and Luu (1999) have concluded that diversification can be a key strategy to meet the increasing demand for farm products. The sustainable livelihood of IAA farmers in the MD may also depend more on farm diversification than specialization, as the diversified IAA systems can help to spread risks from market fluctuation or natural disasters. In farm diversification, individual farm components can be intensified to compensate for the income losses of other farm components. The intensification of the pig and fish components in IAA farms in the MD during the AI crisis is a good example (Phong *et al*., 2007). This can be considered as a "hard diversification" versus a "soft diversification" (Scottish Executive, 2003) when farming practices and investments are spread over all farm components. The execution of these strategies across the IAA farms will depend on agricultural policies and extension support.

## 2.5 Conclusions

Over 30 years the rice-based systems in the MD have developed into integrated agriculture-aquaculture systems. The main forces driving changes in the farming systems were the introduction of modern rice varieties, economic liberalization policy, market demand, availability of production technologies, and natural disasters. These forces drove farm diversification. A "hard diversification" could help insure against risks from natural disasters. Agro-ecological conditions, level of technology support by public extension services, and access to credit accounted for the differences found between the three districts. The main attributes of the IAA farms were the diversified farm resources and household economy. Hard-to-change farm characteristics were the LUI of orchard and rice or other cash crops. Easy-to-change farm characteristics were the number of farm components, the LUI of fish pond, on-farm family labour, off-farm and non-farm income, and farm inputs. The main drivers of change over the two years have been market demand and a natural disaster (Avian Influenza). Over the 30 years, the IAA systems have proved to be dynamic, demonstrating a trend from specialization (or monoculture) with extensive farming towards diversification and intensification. Farmers have responded to threats and opportunities by increasing their inputs to improve their income. Off-farm and non-farm income have made an important contribution to household income; however, for farm development, ways of sustaining improvements to the household's livelihood are on-farm diversification and intensification, and changing the LUI of a particular activity. Farms in the R-MF area were more diversified than the O-LF and R-HF farms. Overall, it can be concluded that well-off farmers with good farming skills and enough capital tended to specialize and intensify their farming practices, while the poorer farmers tended towards diversification in order to safeguard their livelihood and avoid risks.

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# Chapter 3

# An agro-ecological evaluation of aquaculture integration into farming systems of the Mekong Delta

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## Abstract

This study compared ecological sustainability of Integrated Agriculture-Aquaculture (IAA) systems with different forms and intensity of aquaculture integration in the Mekong Delta of Vietnam: orchard-based and low-input fish (O-LF); rice-based and medium-input fish (R-MF); and rice-based and high-input fish (R-HF) farming systems. We monitored eleven IAA-farms from September 2002 to September 2004. ECOPATH models, based on nitrogen flows, produced 19 agro-ecological system attributes that were reduced to four factors by factor analysis (Productivity-Efficiency; Diversity; Maturity; Aquaculture Integration), explaining 76.8 % of total variance. In general, R-HF farms scored higher on Productivity-Efficiency, R-MF on Diversity, and O-LF farms on Maturity than the other systems. Within all three farm systems, variability among farms was high, caused by differences in land use, financial and crop disease constraints, market possibilities, and family conditions. The ponds and ditches served as a trap to capture nutrients and re-distribute them to other parts of the farms. Despite the differences in intensity of fish keeping between the three systems, the fish ponds in the rice-based systems and fish in ditches in the orchard-based system contributed to the same extent to the nutrient supply of other components. Differences in nutrient efficiency among the farming systems were caused primarily by the inefficient orchard and rice components on the O-LF farms. Fertilizers were often applied in excess. Nutrient use efficiency should be improved through proper application of fertilizers and promotion of the traditional integration practices.

**Key words:** ECOPATH; Integrated Agriculture-Aquaculture; Mekong Delta; Sustainability

## 3.1 Introduction

Southeast Asia has a long tradition of integrated farming with fish, crops, and livestock to sustain the livelihoods of farming families. In the Mekong Delta of Vietnam (MD), these farming systems have changed from self-sufficient systems, producing mainly rice with some fish and livestock for home consumption to more market-oriented integrated agriculture-aquaculture (IAA) systems. Driving forces for these changes were economic liberalization since 1986, a big flood in 1997, and market demands (Phong *et al*., 2008). The Vietnamese government is promoting diversification of agriculture and intensification of aquaculture to reduce dependence on rice and to increase the contribution of fish to economic development (Luu, 1999). Fish also has an added nutritional benefit for the farmers by providing a more balanced diet. Pond aquaculture, therefore, is developing quickly.

In the MD different forms of aquaculture integration in IAA-systems can be found, ranging from systems with traditional subsistence aquaculture that depend on recycling of crop and animal wastes, to systems with external, artificial feed inputs producing for the domestic and export market. Potential benefits of integration are not only a more even distribution of opportunities to generate cash, but also a more efficient and ecologically sustainable use of resources as wastes from one farm component are used as input into another (Prein, 2002). The environmental benefits of integration might be lost when aquacultural production systems are intensified, as intensive fish production based on external inputs produces higher emissions to soil, water and air than more extensive, integrated fish production (Edwards, 1993; Nhan *et al*., 2006; MARD-DAQ, 2009). Ecological constraints resulting from intensification of fish production likely will affect the sustainability of agro-ecosystems in the MD.

For practical purposes, ecological sustainability in agricultural systems is often interpreted as a combination of a high efficiency of nutrient use and low discharges of nutrients and agrochemicals into the environment, internal cycling of nutrients, stable high yields over a long period of time, no depletion of nutrients and organic matter in the soil, and maintaining diversity (Altieri, 2002; Estellès *et al*., 2002). For comparison of different systems and for policy analysis and planning purposes, a better understanding and quantitative estimation of these "common sense" characteristics of ecological sustainability is needed. One of the quantitative methods used to evaluate ecological sustainability of farming systems is ECOPATH, which was developed originally for aquatic ecosystems and fisheries but can also be used in an integrated farm context (Christensen and Pauly, 1992; 1993; Lightfoot *et al*., 1993; Dalsgaard *et al*., 1995; Dalsgaard and Oficial, 1997; 1998). It provides a well-documented framework to quantify properties related to ecological sustainability of complex (agro-) ecosystems.

The overall objective of this study was to analyze the ecological sustainability of IAA farming systems in the MD. Specific objectives were: (1) to construct ECOPATH models based on nitrogen flows and calculate sustainability indicators for each farm; (2)

to use these indicators to assess ecological performances of IAA farming systems with different forms and intensity of aquaculture integration.

## 3.2 Materials and methods

### *3.2.1 Study sites*

The MD is located between longitudes 104°30’ and 17° E and latitudes 8°30’ and 11°N. Except for some minor hilly areas, the MD is a flat and low-lying area of almost 4 million ha with a population of about 17.4 million (in 2006). Based on agro-ecological characteristics such as rainfall, temperature, soil, topography, cropping system, and water resources, the MD can be divided into seven agro-ecological zones. We chose the freshwater alluvial zone as the area (see Chapter 1) appropriate to study IAA farming systems (WES Programme, 1997).

In early 2002, expert consultation and participatory community appraisal identified three districts representing the three main IAA systems, based on the dominant type of crop and the form and intensity of aquaculture integration (Nhan *et al.*, 2006; Phong *et al.*, 2008). These three districts were O Mon with rice-based and high-input fish farms (R-HF system), Tam Binh with rice-based and medium-input fish farms (R-MF system) and Cai Be with orchard-based and low-input fish farms (O-LF system).

Rivers and canals were the main water sources for the IAA systems in the three districts, but they differed in soil conditions, flood depth, farm activities, and fish culture (see Phong *et al.*, 2008 for details). The rice based systems were found in peri-urban areas with less fertile soils differing in market access, whereas the orchard based system was found in a rural area with fertile soils. The fish component can be distinguished based on feed inputs, species, and fish management. In R-HF farms, fish were fed mainly with pelleted feed, some by-products from the fish-processing industry, and pig manure and human excreta; in R-MF farms, fish were fed with pig and poultry manure, human excreta, crop residues, and some pelleted feed at fingerling stage; and in O-LF farms, fish were fed with crop residues from the farm, pig manure, and human excreta. In the R-HF system fish farming is mainly monoculture of catfish for export, whereas in the other two systems it is poly-culture for domestic markets and home consumption. In R-HF and R-MF farms, fish were raised in ponds, whereas in O-LF farms; fish were raised mainly in ditches between the orchard beds. A baseline survey on land use and agricultural production for 90 IAA farms in 2002 and for 80 IAA farms in 2004 and multivariate analyses confirmed the classification of the three areas (Nhan *et al.*, 2006; Phong *et al.*, 2008).

We selected 11 case-study farms: three in O Mon (R-HF system), four in Tam Binh (R-MF system), and four in Cai Be (O-LF system). Selection was based on a combination of farm characteristics and practical considerations, such as accessibility and willingness of farmers to participate. Only a small number of farms could be selected because of the high intensity of data collection.

### *3.2.2 Farm monitoring*

The 11 farms were monitored daily for two years (Year 1: September 2002 to August 2003; year 2: September 2003 to August 2004). Farmers mapped the bio-resource flows on their farm and recorded their daily farm activities in note books. A land use map of each farm was drawn by consulting with farmers about their land use types (homestead, orchard, rice field, vegetable field, and fish pond). The number of species of fruit trees, rice, vegetables, weeds/grasses, livestock, fish, and plankton were counted. Weed and grass species were classified as one group. Similarly, phytoplankton (identified in the field as *Cyanophyta, Euglenophyta, Chlorophyta, Bacillariophyta*) and zooplankton (identified as *Protozoa, Rotifera, Cladocera, Copepoda, nauplius*) were each classified as one group. Soil was sampled at the beginning, middle, and end of the monitoring period to a depth of 20 cm in rice fields, vegetable fields, and fish ponds; and to 50 cm in homesteads and orchards. In each land use type, five mixed soil samples were collected according to a pentagonal pattern for analysis of soil nitrogen and texture. Farm inputs, outputs, on-farm resource flows, household consumption and household wastes were recorded daily by farmers, with support from field researchers of Can Tho University, Can Tho.

### *3.2.3 ECOPATH modeling approach*

In an ECOPATH model an ecosystem is represented by a limited number of functional groups ("boxes") that are linked through trophic relationships ("flows"). ECOPATH was developed for aquatic ecosystems and fisheries with predators, preys, plankton, and detritus (Christensen and Pauly, 1992; 1993). In the context of integrated farms, the boxes represent crops, trees, weeds, grasses, livestock, phytoplankton, and fish. Several soil detritus boxes (Figure 3.1) can be included in the model according to the farm's land use and soil types. Detritus in an aquatic system is equivalent to the organic matter in the farm soil. The flows represent bio-materials flowing into, out of, and between soil, crop and animal boxes. A linear equation defines each box, balancing the production of that box with the flows for which that production is used:

Production = harvest + flow to other groups + export out of the system + biomass accumulation + mortality

By re-arranging the equation and defining it for each box in the model (see e.g., Christensen & Pauly, 1992 for the derivation), a system of linear equations results which allows description of each box with a limited number of "ECOPATH parameters": biomass (B), biomass accumulation (ΔB), production (P), consumption (Q), production/biomass ratio (PB), consumption/biomass ratio (QB), harvest (H), ecotrophic efficiency (EE), and resource flows to other boxes. EE is the proportion of production of each box that is harvested, exported or consumed by other boxes in the system. The model must be balanced so that inflows and outflows of all boxes are accounted for. This is done by solving the linear equations for one missing parameter while the values of the other parameters are based on quantitative input data. In this study, the missing parameter was EE and the other parameters were calculated based on the results of farm monitoring. A balanced model thus has EE values between 0 and 1 for each box. The exception is detritus, for which EE > 1 means that more N is extracted from the soil than added through fertilization or decomposition (soil depletion).

The trophic relations between boxes are defined in a matrix that gives the diet composition of each box in terms of the flows from other boxes or import into the system. After accounting for all harvest, biomass accumulation, export flows and flows to other boxes, the remaining production ("mortality" in the equation) is channeled to a detritus/soil box, assuming that all flows are in equilibrium during the period studied. Because accumulation in the boxes can be accounted for, the model is not necessarily a steady-state model (Christensen *et al.*, 2005).

Flows can be expressed in terms of biomass, energy, or nutrients. For this study, we chose nitrogen (N) as the model currency, because N is an important nutrient determining production of crops and animals. Moreover, N efficiency of farm systems is an important sustainability indicator which can be compared to other ECOPATH farm models expressed in N (Dalsgaard and Oficial, 1997).

After defining a balanced model for a production unit during a specified period, agro-ecosystem attributes are quantified. These attributes include measures for efficiency, system productivity, nutrient throughput and cycling, nutrient balance, biomass, production/biomass and biomass/system throughput ratios, and diversity (Dalsgaard *et al.*, 1995; Dalsgaard and Oficial, 1997; Christensen *et al.*, 2005).

### *3.2.4 Estimation of ECOPATH parameters and quantification of agro-ecological system attributes*

For each farm, boxes were defined based on farm observations, interviews with farmers, and their resource flow drawings. Four soil detritus boxes were defined according to land use types of the farms (rice, orchard, vegetables, and fish pond). For each box, values of the ECOPATH parameters were calculated based on farm monitoring and data from literature, and entered into ECOPATH 3.0 (ICLARM, 1995).

To estimate ECOPATH parameters, the N content of purchased inorganic fertilizers and concentrates was obtained from the suppliers. Other farm inputs and outputs were converted into N on a dry matter (DM) basis (FAO, 1972; FNRI, 1990). Nutrient values for human excreta were derived from Suong and Dung (2000), and values for manure of pigs, poultry, goats, and rabbits were from Can (1982) and Yem *et al.* (2001). Values of DM and N for weeds and grasses were from Dung (1996). Biomass of phytoplankton and zooplankton were calculated from the average N content of pond water on each farm (Nhan *et al.*, 2006). The production of phytoplankton was based on integrated rice–fish systems (Lightfoot *et al.*, 1993; Ruddle and Christensen, 1993). The quantity of soil N was calculated, using total N, bulk density, soil depth, and farm area, for each land use type (kg N $ha^{-1}$) of farms. The biological nitrogen fixation (BNF) of wetland rice fields was based on Roger and Ladha (1992), and the daily BNF of the fish ponds was estimated as 24 mg N $m^{-2}$ (Acosta-Nassar *et al.,* 1994). The input of N from atmospheric deposition and irrigation water was based on App *et al*. (1984). Losses of N from leaching, soil erosion, drainage of water, and gaseous emission of the ponds were assumed to be negligible (Dalsgaard and Oficial, 1998).

Because farm activities varied within farms between Years 1 and 2, ECOPATH calculations were carried out for each of the two years on each farm (6 calculations for R-HF, 8 for R-MF, and 8 for O-LF). Annual flows of the boxes were expressed in kg N per ha of total farm area. Based on the ECOPATH model for each farm, the agro-ecological attributes were quantified.

Factor analysis was used to reduce the 19 agro-ecological attributes to a smaller number of factors and look for underlying patterns related to sustainability. We used SPSS 13 (SPSS, 2004) with the principal component method (Field, 2002) and varimax rotation with Kaiser Normalization (Kaiser, 1960) to facilitate interpretation of the factors (Leech *et al*., 2005). This type of rotation produces factors that have high correlations with one small set of attributes, and little or no correlation with the remaining attributes. Factor loadings of 0.5 and higher were used for interpretation.

One-way ANOVA was used to assess differences in agro-ecological attributes and factor scores among R-HF, R-MF and O-LF systems. Differences between means were based on Duncan's multiple range test in SPSS 13 (SPSS, 2004).

## 3.3 Results

### *3.3.1 Land use and components of monitored farms*

Land use and numbers of animals are in Table 3.1. R-HF farms (2.9 ha) were on average five times larger than O-LF farms (0.64 ha) and R-MF farms (1.16 ha) were two times larger than O-LF farms. Main components of R-HF farms were rice (71% of farm area) and fish (17%), whereas main components of O-LF farms were orchard (69% of farm area) and fish (17%). R-MF farms had a mix of rice (41% of farm area), orchard (34%) and fish (13%). Vegetables were commonly grown in the R-MF farms (3% of farm area), but were less common in R-HF farms and rotated with rice in O-LF farms. The number of pigs per farm ranged from 7 in O-LF farms to 16 in the R-MF farms, whereas the number of poultry ranged from 56 in O-LF farms to 196 in R-HF farms.

### *3.3.2 ECOPATH models*

Each ECOPATH farm model can be visualized in a diagram showing all boxes and flows. As an example, Figure 3.1 shows the model for R-MF farm 1 in Year 2. The farm included a homestead with pigsty and poultry pen surrounded by fish ponds, a fruit orchard and vegetable field, and a rice field at some distance. The rice field provided food and cash for the family and feed for the animals. Other feed sources for pigs, poultry and fish were weeds, and vegetable and fruit wastes. After the fish harvest, the pond supplied enriched mud to the orchard, water to the fruit trees, and feed (such as water spinach, snails, or crabs) to pigs and poultry. The pig manure and human excreta

**Table 3.1** Land use of farm components and animals in three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam. Percentage of land use in parentheses

| Component and animals | Unit | Farming system type[1] | | | | | |
|---|---|---|---|---|---|---|---|
| | | R-HF | | R-MF | | O-LF | |
| Number of farms | | 3 | | 4 | | 4 | |
| Farm size | ha | 2.9 | (100) | 1.16 | (100) | 0.64 | (100) |
| Orchard | ha | 0.33 | (11) | 0.4 | (34) | 0.44 | (69) |
| Rice field | ha | 2.05 | (71) | 0.48 | (41) | 0.08 | (13) |
| Ponds/ditches | ha | 0.48 | (17) | 0.15 | (13) | 0.11 | (17) |
| Vegetables | ha | 0.02 | (1) | 0.04 | (3) | - | |
| Pigs | no. | 10 | | 16 | | 7 | |
| Poultry | no. | 196 | | 145 | | 56 | |

(-): vegetables rotated with rice in same field

[1]: R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

were used to feed fish. Boxes are plotted so that the horizontal axis of symmetry is aligned with the trophic level of the box, and are sized to the logarithm of the biomass of each box. Lines (see Legend) represent the N-flows connecting boxes: “Connector” links the N-flows between boxes, “Harvest” indicates N-harvest of boxes; and “Import” represents the external N-flows, such as inorganic fertilizers, atmospheric deposition, irrigation water, and BNF (Figure 3.1). The resulting figures of each farm display the values of all input parameters except for biomass accumulation within boxes. The trophic levels are calculated by ECOPATH, based on the nutrient consumption of boxes relative to soil detritus and primary producers. In an N-based model, trophic Level 1 is assigned to soil detritus, 2 to vegetation, and 3 to animals.

Mean values of ECOPATH parameters are in Table 3.2 for each farming system type. In each year, orchard (O-LF farms), and orchard and rice field (R-MF and R-HF farms) were the main contributors to the total biomass. Weeds and grasses also contributed to a high biomass in the O-LF farms. Biomass of pigs did not vary much between the three systems, except that it was small in the R-HF farms in Year 2. Biomass of chickens and ducks was relatively low in the R-HF farms in Year 1, but was not different among the three systems in Year 2, except for a high value for ducks in the R-MF farms in Year 2. The biomass of geese, goats, and rabbits was small because these animals were not common. The R-HF and R-MF farms had the highest fish biomass in both years. The EEs of pigs, poultry, and fish were generally high reflecting the complete harvesting and use of these groups within the farms. The EEs of the plant groups were much lower. The PB ratios of the boxes did not differ much among the years, but the difference in PB ratio among the three systems reflected differences in farming activities and productivity. The PB ratio was highest in R-MF and lowest in O-LF farms, because of different fertilizer application levels and different types of annual crops in the respective systems.

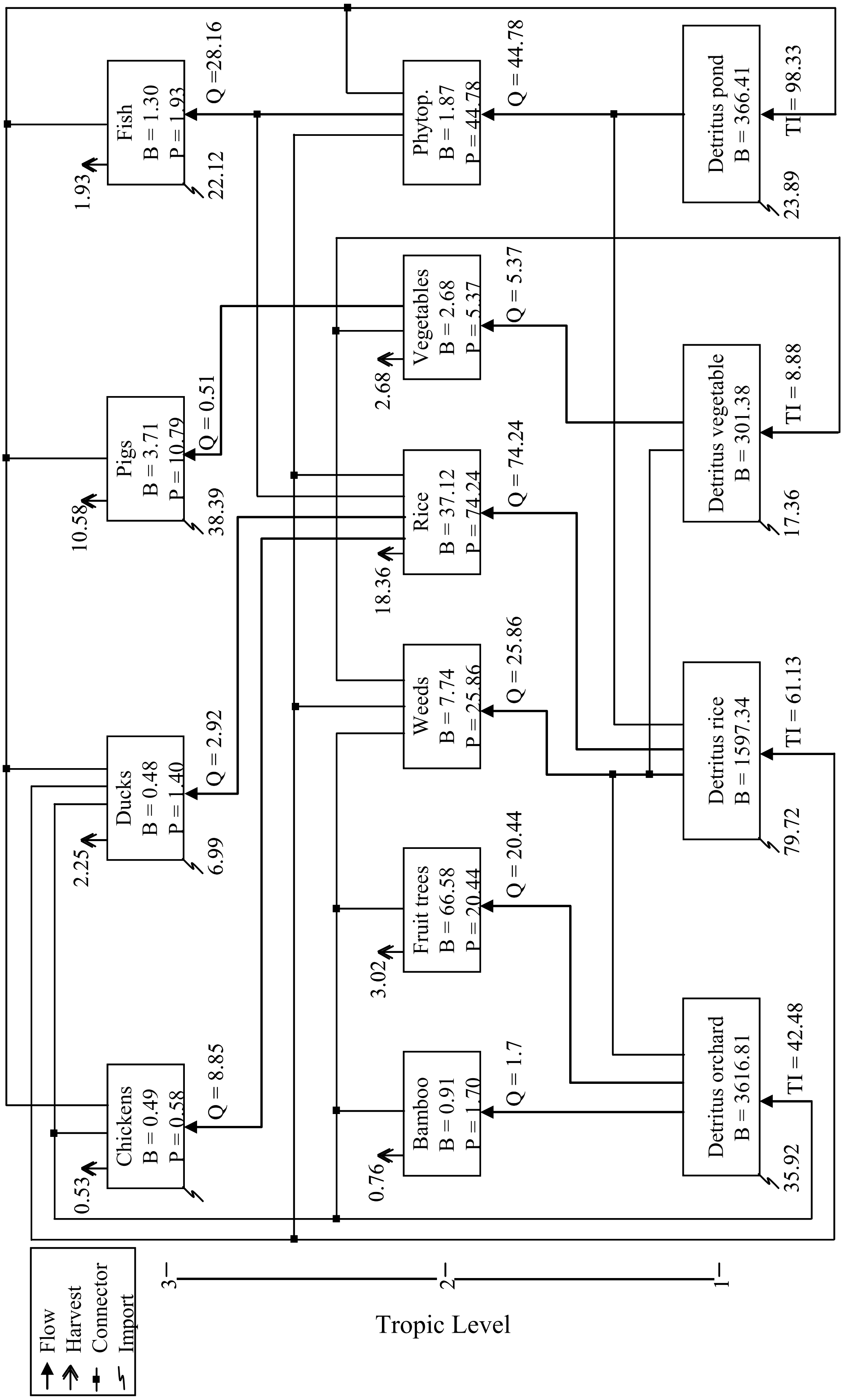

**Figure 3.1** Ecopath flow (kg N ha$^{-1}$ y$^{-1}$) diagram of one rice-based and medium input fish farm (R-MF farm) in the second year (B: biomass, P: production, Q: consumption, TI: internal flow to detritus)

**Table 3.2** Mean values of calculated ECOPATH parameters of three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam, over two years (September 2002-September 2004)

| Farming system[1]: | R-HF | | | | R-MF | | | | O-LF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year 1 (2002-2003) | B[2] | PB | QB | EE | B | PB | QB | EE | B | PB | QB | EE |
| Rice | 37.9 | 1.33 | 1.33 | 0.32 | 46.20 | 2.00 | 2.00 | 0.45 | 2.92 | 0.50 | 0.50 | 0.15 |
| Orchard | 28.27 | 1.92 | 1.92 | 0.28 | 43.82 | 0.32 | 0.32 | 0.29 | 63.65 | 0.29 | 0.29 | 0.55 |
| Vegetables | 0.5 | 0.67 | 0.67 | 0.17 | 2.93 | 2.00 | 2.00 | 0.80 | 3.96 | 0.50 | 0.50 | 0.02 |
| Bamboo | 1.65 | 0.16 | 0.16 | 0.48 | 3.18 | 0.15 | 0.15 | 0.00 | 0.45 | 0.04 | 0.04 | 0.00 |
| Weeds/Grasses | 2.26 | 5.38 | 5.38 | 0.13 | 3.43 | 3.81 | 3.81 | 0.10 | 11.00 | 5.25 | 5.25 | 0.05 |
| Phytoplankton | 4.73 | 24 | 24 | 0.16 | 8.46 | 24 | 24.00 | 0.10 | 2.83 | 24.00 | 24.00 | 0.15 |
| Pigs | 6.97 | 1.08 | 10.72 | 0.67 | 4.74 | 2.99 | 15.99 | 0.94 | 5.26 | 2.45 | 10.83 | 0.87 |
| Chickens | 0.23 | 4.32 | 33.44 | 0.83 | 0.51 | 4.61 | 59.20 | 0.75 | 0.66 | 2.66 | 23.79 | 0.38 |
| Ducks | 0.17 | 6.99 | 69.72 | 1 | 0.51 | 6.56 | 237.89 | 0.79 | 0.31 | 1.94 | 23.07 | 0.91 |
| Geese | -[3] | - | - | - | - | - | - | - | 0.02 | 0.22 | 13.39 | 0.14 |
| Goats/Rabbits | 0.004 | 0.28 | 3.16 | 0.17 | 0.002 | 3.62 | 26.07 | 0.12 | 0.04 | 0.04 | 2.12 | 0.02 |
| Fish | 2.13 | 1.3 | 15 | 0.99 | 1.63 | 1.72 | 15.00 | 1.00 | 0.92 | 1.27 | 15.00 | 0.90 |
| Year 2 (2003-2004) | | | | | | | | | | | | |
| Rice | 40.56 | 1.33 | 1.33 | 0.35 | 35.59 | 1.5 | 1.50 | 0.34 | 7.82 | 0.50 | 0.50 | 0.15 |
| Orchard | 32.08 | 1.35 | 1.35 | 0.44 | 46.92 | 0.33 | 0.33 | 0.47 | 78.49 | 0.35 | 0.35 | 0.46 |
| Vegetables | - | - | - | - | 3.52 | 2 | 2.00 | 0.71 | 0.65 | 0.50 | 0.50 | 0.18 |
| Bamboo | 1.69 | 0.1 | 0.1 | 0.39 | 3.12 | 0.68 | 0.68 | 0.17 | 0.50 | 0.08 | 0.08 | 0.11 |
| Weeds/Grasses | 2.62 | 5.06 | 5.06 | 0.02 | 4.8 | 3.34 | 3.34 | 0.01 | 9.55 | 4.40 | 4.40 | 0.05 |
| Phytoplankton | 2.51 | 24 | 24 | 0.05 | 3.89 | 24 | 24.00 | 0.39 | 2.03 | 24.00 | 24.00 | 0.33 |
| Pigs | 0.18 | 0.34 | 2.66 | 0.33 | 5.56 | 2.94 | 11.42 | 1.00 | 7.93 | 2.10 | 7.06 | 0.90 |
| Chickens | 0.24 | 3.15 | 24.3 | 0.84 | 0.38 | 1.27 | 37.26 | 0.90 | 0.24 | 2.09 | 16.41 | 0.79 |
| Ducks | 0.18 | 3.49 | 30.45 | 0.74 | 0.71 | 2.25 | 20.31 | 0.87 | 0.29 | 2.51 | 35.44 | 0.60 |
| Geese | - | - | - | - | - | - | - | - | 0.02 | 0.08 | 6.73 | 0.00 |
| Goats/Rabbits | - | - | - | - | - | - | - | - | 0.07 | 0.02 | 3.61 | 0.12 |
| Fish | 1.32 | 2.33 | 15 | 1 | 2.12 | 1.75 | 15.00 | 0.99 | 1.12 | 1.23 | 15.00 | 1.00 |

[1] : R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard based and low-input fish system

[2] B: annual biomass in kg N $ha^{-1}$; PB: annual production to biomass ratio; QB: annual consumption to biomass ratio; and EE: Ecotrophic Efficiency. B, PB and QB were based on farm monitoring data and served as ECOPATH input, and EE was calculated by ECOPATH (see text for further explanation)

[3] - : not applicable

Table 3.3 shows the agro-ecological system attributes by farming system type. Functional agricultural diversity was highest ($P<0.05$) in R-MF farms. The Net system yield and the Sum of all production were higher ($P<0.05$) in R-MF farms than in O-LF farms. The BT ratio was lower ($P<0.05$) in R-HF farms than in O-LF farms. This difference resulted from the high Total system throughput of the rice-based systems

**Table 3.3** Mean values* of selected agro-ecological attributes of three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam, over two years (September 2002 - September 2004) (standard error in parentheses)

| No. | Attribute | Farming system type** | | | |
|---|---|---|---|---|---|
| | | Unit | R-HF | R-MF | O-LF |
| 1 | Actual efficiency[1] | % | 21 (5) | 20 (2) | 11 (2) |
| 2 | Apparent efficiency[2] | % | 31 (9) | 27 (3) | 14 (3) |
| 3 | System harvest index[3] | d.l.*** | 0.21 (0.03) | 0.21 (0.02) | 0.14 (0.03) |
| 4 | Functional agricultural diversity[4] | d.l. | $0.91^{b}$ (0.08) | $1.37^{a}$ (0.04) | $0.94^{b}$ (0.17) |
| 5 | Annual net system yield[5] | kg N ha$^{-1}$ | $50^{ab}$ (11) | $51^{a}$ (8) | $22^{b}$ (4) |
| 6 | Annual net system production[6] | kg N ha$^{-1}$ | 139 (31) | 134 (18) | 97 (8) |
| 7 | Annual sum of all production[7] | kg N ha$^{-1}$ | $226^{ab}$ (25) | $282^{a}$ (40) | $156^{b}$ (13) |
| 8 | Annual total system throughput[8] | kg N ha$^{-1}$ | 789 (91) | 916 (105) | 620 (72) |
| 9 | Annual total system biomass[9] | kg N ha$^{-1}$ | 83 (4) | 111 (11) | 100 (10) |
| 10 | Nutrient cycling index[10] | % | 43 (2) | 49 (4) | 43 (6) |
| 11 | Biomass/Total system throughput (BT ratio)[11] | d.l. | $0.11^{b}$ (0.01) | $0.12^{ab}$ (0.01) | $0.18^{a}$ (0.03) |
| 12 | Production/Biomass (PB ratio)[12] | d.l. | 1.63 (0.32) | 1.18 (0.09) | 1.05 (0.15) |
| 13 | Animal gross efficiency (animal GE)[13] | d.l. | 0.14 (0.02) | 0.11 (0.01) | 0.12 (0.01) |
| 14 | Ecotrophic Efficiency (EE) of plants[14] | d.l. | 0.36 (0.04) | 0.36 (0.02) | 0.31 (0.04) |
| 15 | EE of animals[14] | d.l. | $0.92^{a}$ (0.04) | $0.90^{a}$ (0.04) | $0.75^{b}$ (0.04) |
| 16 | EE of rice detritus[15] | d.l. | $0.38^{ab}$ 0.12) | $0.52^{a}$ (0.09) | $0.08^{b}$ (0.05) |
| 17 | EE of orchard detritus[15] | d.l. | 0.67 (0.15) | 0.60 (0.08) | 0.43 (0.11) |
| 18 | EE of vegetable detritus[15] | d.l. | 0.24 (0.24) | 0.19 (0.09) | – **** |
| 19 | EE of fish pond detritus[15] | d.l. | 0.43 (0.08) | 0.50 (0.07) | 0.48 (0.04) |

*: Values are means of 6 annual farm models for rice-based and high-input fish system , 8 for rice-based and medium-input fish system, and 8 for orchard-based and low-input fish system; **: R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system; ***: Dimensionless; ****: Vegetables rotated with rice in same field, so no separate value

[a,b]: Different superscripts denote significant differences between means within rows ($P<0.05$)

Explanation of attributes – [1]: Ratio of total farm exports and imports in feeds, fertilizers, BNF, wet and dry atmospheric deposition and irrigation water inflow; [2]: Ratio of total farm exports and imports in feeds and fertilizers; [3]: Ratio of net system yield (harvest) and sum of all production; [4]: Shannon index: $H' = -\sum pi \, Ln(pi)$ (Magurran, 1988), where pi is the group biomass proportion; [5]: Net N harvests exported from whole farm; [6]: Total plant and animal production; [7]: Sum of all materials produced by farm, whether harvested, added to the stocks, or returned to soil for decomposition; [8]: Sum of all imports, consumption, returns to detritus, harvests and exports; [9]: Total average standing biomass above ground of all farm groups/stocks; [10]: Finn's (1980) cycling index: fraction of total throughput that is recycled within farm system; [11]: Ratio of biomass and total system throughput; [12]: Ratio of primary production and total biomass; [13]: Gross feed conversion efficiency of animals ratio of production and consumption, usually varies from 0.1–0.3; [14]: Fraction of this group's production harvested or used by other groups in the system, varies from 0–1; [15]: Ratio of flows out of and flows into this soil type, varies from 0–1.

compared with the orchard-based system. The EE of animals was highest ($P<0.05$) in R-HF and R-MF farms, indicating a better utilization of animal biomass production in the rice-based systems than in the orchard-based system. Average EEs of rice, orchard, vegetables, and fish were below 1, indicating an accumulation of N in these soils. No EE of vegetable detritus was estimated for O-LF farms because vegetables in this system were rotated with rice. The EE of rice detritus in R-MF farms was higher ($P<0.05$) than in O-LF farms, suggesting more accumulation of soil N in the fruit-based system. The EEs of fish pond detritus reflect the recycling of nitrogen from pond sediments, but no significant differences between farming systems were found.

O-LF farms tended ($P<0.06$) to have lower Apparent and Actual efficiencies than the rice-based systems, due to its low Net system yield and high rates of fertilizer use. O-LF farms had the highest inputs of inorganic fertilizer (159 kg N $ha^{-1}$ farm area vs 100 kg N $ha^{-1}$ in R-MF and 103 kg N $ha^{-1}$ in R-HF) and highest yield of fruits (5263 kg $ha^{-1}$ vs 1147 kg $ha^{-1}$ in R-MF and 1295 kg $ha^{-1}$ in R-HF) and vegetables (3002 kg $ha^{-1}$ vs 1431 kg $ha^{-1}$ in R-MF and 23 kg $ha^{-1}$ in R-HF). Because of the low N content and dry matter in these products, the resulting Actual and Apparent efficiencies for O-LF farms were about half that of the other two systems. The relatively high PB ratio in R-HF farms reflected the small annual Total system biomass compared with R-MF and O-LF farms.

### *3.3.3 Factor analysis of agro-ecological attributes on farms*

Four factors (F1, F2, F3, and F4) explained 76.8% of the total variance in the 19 agro-ecological attributes (Table 3.4). The remaining factors each explained 6% or less of the total variance and were not considered in the analysis. The four important factors were “Productivity-Efficiency” (F1), “Diversity” (F2), “Maturity” (F3), and “Aquaculture Integration” (F4).

Productivity-Efficiency explained 35.7% of the total variance, and was related positively to Actual efficiency, Apparent efficiency, PB ratio, Net system production, Animal GE, EE of orchard detritus, Net system yield, System harvest index, and EE of rice detritus. Productivity-Efficiency is associated with efficiency of nutrient use, high productivity and yields, and high utilization of nutrients from orchard and rice soil in farms that have a high production relative to their biomass.

Diversity explained 18.1% of the total variance, and was related strongly and positively to Total system throughput, Sum of all production and Functional agricultural diversity; and also positively (but less strongly) to Net system yield and EE of rice detritus. Diversity was related negatively to the BT ratio (the BT ratio is a measure of maturity).

Maturity explained 12.8% of the total variance, and was related positively to Total system biomass and BT ratio, and negatively to EE of plants. Maturity represents systems with high total biomass but low utilization of plant biomass. In ecology, such systems are called "mature" because they are at the last stage of ecological succession with low productivity and high biomass density.

Aquaculture Integration explained 10.2% of the total variance, and was related

**Table 3.4** Factors and correlation coefficients based on selected agro-ecological attributes for three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam

| No. | Attribute | Factors | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| 1 | Actual efficiency | 0.919 | | | |
| 2 | Apparent efficiency | 0.904 | | | |
| 3 | System harvest index | 0.719 | | | |
| 4 | Functional agricultural diversity | | 0.778 | | |
| 5 | Annual net system yield | 0.721 | 0.602 | | |
| 6 | Annual net system production | 0.805 | | | |
| 7 | Annual sum of all production | | 0.848 | | |
| 8 | Annual total system throughput | | 0.965 | | |
| 9 | Annual total system biomass | | | 0.828 | |
| 10 | Nutrient cycling index | | | | 0.933 |
| 11 | Biomass/Total system throughput (BT ratio) | | -0.656 | 0.652 | |
| 12 | Production/Biomass (PB ratio) | 0.815 | | | |
| 13 | Animal gross efficiency (animal GE) | 0.781 | | | |
| 14 | Ecotrophic Efficiency (EE) of plants | | | -0.707 | |
| 15 | EE of animals | | | | |
| 16 | EE of rice detritus | 0.619 | 0.590 | | |
| 17 | EE of orchard detritus | 0.769 | | | |
| 18 | EE of vegetable detritus | | | | |
| 19 | EE of fish pond detritus | | | | 0.771 |
| | Eigenvalues | 6.8 | 3.4 | 2.4 | 1.9 |
| | % of variance | 35.7 | 18.0 | 12.8 | 10.2 |

Factor 1: Productivity-Efficiency; Factor 2: Diversity; Factor 3: Maturity; Factor 4: Aquaculture Integration

positively to the Nutrient cycling index and EE of pond soil detritus. Aquaculture Integration is associated with the role of the pond sediment in the cycling of nutrients through the system. Many farmers in the MD use pumps to distribute the nutrient-rich sludge from the fish ponds to the orchards or vegetable gardens. This recycling of nutrients that have accumulated in the fish ponds is represented by Aquaculture Integration.

Table 3.5 presents the mean factor scores for the three systems. The R-HF farms scored relatively high on Productivity-Efficiency. The R-MF farms scored relatively high on Diversity; the difference in Diversity between the R-MF system and the O-LF system was significant ($P<0.05$). The O-LF farms scored relatively high on Maturity. The R-MF farms scored relatively high on Aquaculture Integration. The differences among the three systems for Productivity-Efficiency, Maturity and Aquaculture Integration were not significant, due to the high variability within each farming system and the small number of observations.

The factor scores are based on the loadings of all attributes on the factor and represent the degree to which each farm scores high on the agro-ecological attributes that have high loadings on a factor. A negative score means that the attributes with negative

**Table 3.5** Mean factor scores of four factors for three farming systems with different forms of aquaculture integration in the Mekong Delta, Vietnam (standard error in parentheses)

| Factor | Farming system type[1] | | |
|---|---|---|---|
| | R-HF | R-MF | O-LF |
| F1: Productivity-Efficiency | 0.547 (0.617) | 0.097 (0.221) | -0.508 (0.228) |
| F2: Diversity | -0.150$^{ab}$ (0.279) | 0.691$^{a}$ (0.348) | -0.578$^{b}$ (0.306) |
| F3: Maturity | -0.474 (0.218) | -0.053 (0.392) | 0.409 (0.384) |
| F4: Aquaculture Integration | -0.161 (0.311) | 0.344 (0.390) | -0.223 (0.379) |

[1]: R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

$^{a,b}$ Different superscripts denote significant differences between means within rows ($P<0.05$)

loadings on that factor were more important than the attributes with positive scores. Since factor scores are standardized to have a mean of 0 and a standard deviation of 1, they have no absolute meaning but rather indicate the position of an individual farm relative to the other farms in the sample.

The significant difference in Diversity between R-MF and O-LF farms is highlighted when the factor scores for each farm in Year 1 and 2 are plotted (Figure 3.2): mainly positive Diversity scores for R-MF farms and mainly negative Diversity scores for O-LF farms. The factor scores show the strong variability within and between individual farms. This variation is due to different farming practices. Some farmers (the three R-HF farms) kept pigs or grew vegetables in Year 1 but not in Year 2. One farmer (R-MF farm 4) leased out rice land in Year 2, because of financial constraints. Some farmers (R-HF farm 1, R-MF farm 2, and O-LF farm 3) decided not to fertilize their orchards when fruit prices were low. In O-LF farm 4, the vegetable yield (mainly watermelon) was lower in Year 2 than in Year 1 because of disease problems.

The R-HF system is the most intensive farming system. This is reflected in the high Productivity-Efficiency scores for R-HF farms 1 and 2. R-HF farm 3, however, had negative scores for Production-Efficiency and most of the other factors. The farmer was working as an extension agent and spent relatively little time on his farm, especially in Year 2 when his wife fell seriously ill. As a result, this farm had a very low Apparent efficiency of only 6% against 23% for all farms.

A high Apparent efficiency (a high farm output in relation to external input use) was achieved both by farms with low external input use and by farms with a relatively high external input use. An example of the first was O-LF farm 3, the only O-LF farm with two positive scores on Production-Efficiency. It had positive scores for Maturity and Aquaculture Integration, but scored negatively on Diversity. This farm had a small farm area (0.53 ha) mainly used for producing fruits (74% of farm area). Inorganic fertilizer use (44 and 0 kg N $ha^{-1}$ in Year 1 and 2, respectively) was very small. No fertilizers were applied to fruit trees in Year 2 because of a market problem. External feed use (19 kg N $farm^{-1}$) was low but in line with the average feed use (14 kg N $farm^{-1}$) in O-LF farms. The average fertilizer use was 122 kg N $ha^{-1}$ for all farms. The average feed use

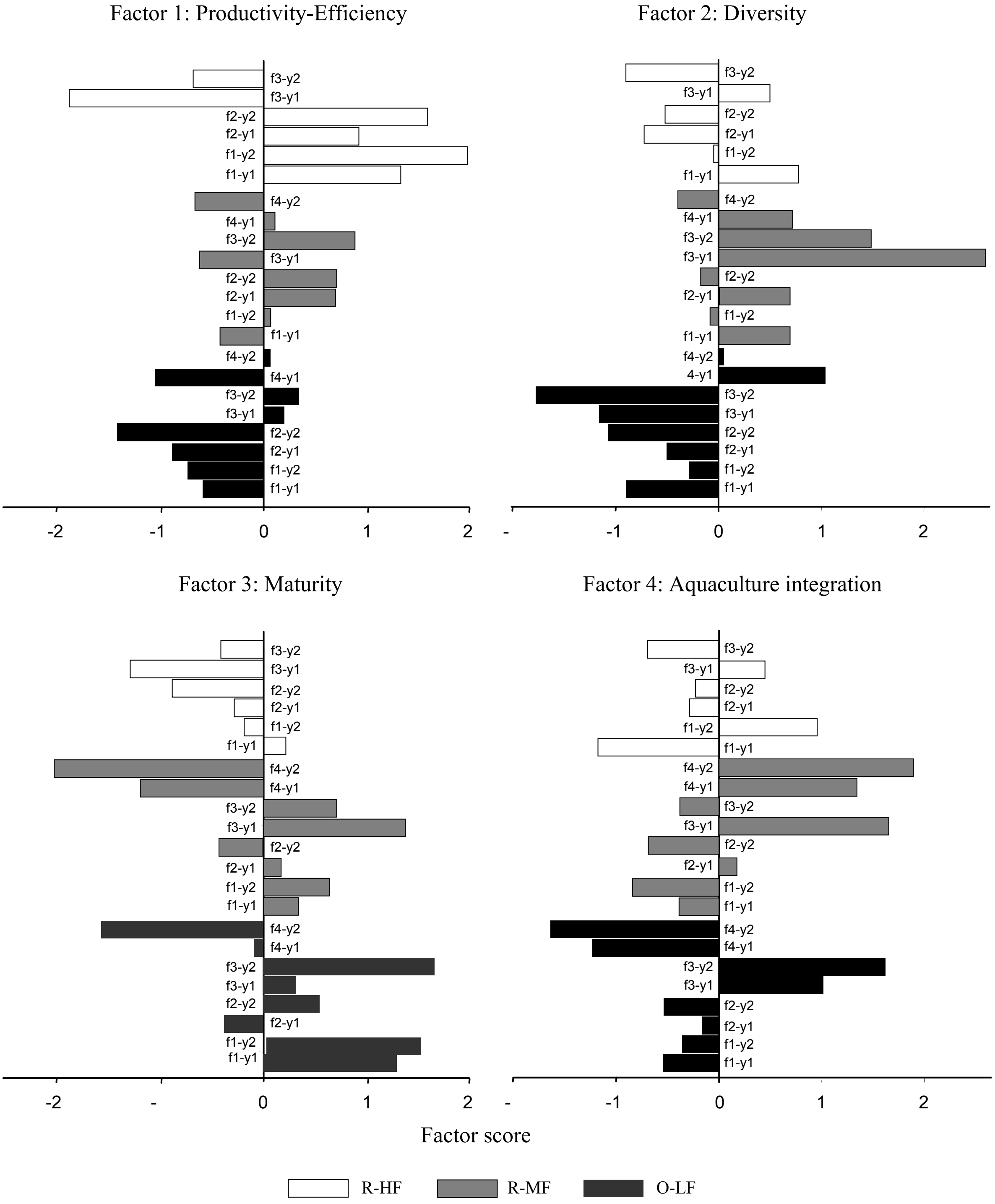

**Figure 3.2** Factor scores from four factors (F1, 2, 3, and 4) for three farming systems with different forms of aquaculture integration in the Mekong delta, Vietnam in years 1 and 2 (e.g., f1-y1: score of Factor 1, year 1). R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

was 105 kg N per farm. The total farm harvest of O-LF farm 3 consisted mainly of fruits (38%) and pigs (46%). Its average Apparent efficiency was 27%.

R-HF farm 1 had the highest average Apparent efficiency: 41%. This was a large farm (5.3 ha) with mainly rice (80% of the farm area). It had a large number of pigs (99) in

Year 1 but no pigs in Year 2 because of a piglet supply shortage. Inorganic fertilizer use (162 kg N $ha^{-1}$ in Year 1 and 120 kg N in Year 2, and external feed use (767 kg N $farm^{-1}$ in Year 1 and 22 kg N in Year 2) were higher than the average for R-HF in Year 1. Its total farm harvest consisted mainly of rice (75%), pigs (12%), and fish (11%) and it had a negative score on Aquaculture Integration. In Year 1, pig manure was abundantly available and could not all be used for feeding fish.

## 3.4 Discussion

### *3.4.1 ECOPATH modeling*

The ECOPATH farm models provided a rigorous framework to analyze and compare, on basis of N flows, agro-ecological performances of the complex smallholder farms in the Mekong Delta. The resulting agro-ecological system attributes measured a range of ecological sustainability characteristics that are highly relevant for the MD: from common to composite measures of farm productivity, efficient management of resources, and health of agro-ecosystems. However, discharges of agrochemicals into the environment, an important issue in rice production in the MD (Berg, 2002), are not covered by ECOPATH.

Model results were comparable to those obtained by Dalsgaard and Oficial (1997) in their ECOPATH analysis of four farms in the Philippines. Compared with two diversified and integrated rice farms in their study, the efficiency of nutrient use in our farms was generally lower, whereas nutrient throughput and total production in our farms were higher. Different farming practices (e.g., double rice or triple rice crops per year) might have led to these differences.

### *3.4.2 Ecological sustainability of IAA systems*

Factor analysis reduced the 19 ecological attributes to four factors that covered four dimensions of ecological sustainability. Productivity-Efficiency was responsible for about one-third of the variation between farms. It was related to high production and efficiency, both needed for sustainable farming systems: farms scoring high on Productivity-Efficiency had a high production that was achieved with relatively low discharges of nutrients to the environment (compared to the other farms), and had a relative low biomass. In general, the rice-based farms used nitrogen more efficiently and productively than the O-LF farms because of their large rice, fruits, and pigs harvest in relation to total farm inputs, with the exception R-HF farm 3 with the absent farmer.

Diversity was responsible for close to 20 percent of the variation between farms. It is related to the number of flows and boxes and the yield of a farm. The R-MF system was the most diverse system, which is shown by the significantly higher Diversity in R-MF than in O-LF farms and the significantly higher Functional agricultural diversity, which is based on the biomass of the different guilds on the farms, in the R-MF system compared to the other two systems. Diversity is often used to interpret an ecosystem's well-being (Magurran, 1988). More diverse agro-ecosystems are assumed to be more stable and resilient to fluctuations in market prices and environmental extremes such as drought and pest attacks, and consequently more sustainable (Conway, 1987; Dalsgaard *et al*., 1995), but this was not supported by our dataset. R-MF farms scored relatively high on Diversity but showed large changes in scores on Productivity-Efficiency between the two years (Figure 3.2).

Similarly, Maturity has been suggested as an indicator of an eco-system's sustainability. When ecosystems mature, biomass production rates slow down and maintenance costs increase (Odum, 1969, Christensen, 1995). A tendency towards high farm production therefore seems contrary to a tendency towards maturity. This is reflected in an increasing BT ratio as systems mature. In general, O-LF farms scored higher on Maturity than the rice-based farms because fruit trees have a high biomass but low productivity compared with rice and vegetables. O-LF farms tended to have more negative scores for Diversity and Production-Efficiency. Maturity per se, consequently, seems to be incompatible with other sustainability characteristics of IAA farms.

Aquaculture Integration was responsible for only 10 percent of the variation between farms. Integration of aquaculture in the MD is achieved by using wastes from crops, animals, and the homestead as inputs for the fish, and by using mud from the pond or ditches to fertilize vegetable plots and orchards. So, the pond/ditch serves as a trap to capture nutrients and re-distribute them to other parts of the farms. The EEs of the fish pond detritus in the three systems indicated that the ponds and ditches contributed to the same extent to the nutrient supply of other components in the respective systems, despite the differences in fish feed inputs and fish management among the three systems. The land use of the fish component was about the same in the three systems, but in terms of farm income fish contributed much more in the R-HF system (27% of farm income) than in the R-MF (12%) and O-LF systems (6%) (Phong *et al*., 2008). The Aquaculture Integration factor tended to be higher in the R-MF system than in the other two systems. The low water exchange rate in the R-MF system resulted in more natural feed for fish. R-HF farmers used high water exchange to reduce the effects of their high feed inputs on water quality.

The factors produced by factor analysis are by definition un-correlated. This suggests that productivity and efficiency, united in Factor 1, were strongly linked in the farms studied but were unrelated to the other factors. The most productive and efficient farms were therefore not necessarily more or less diverse, mature or integrated with their aquaculture component. Of all the factors, Productivity-Efficiency is most obviously related to sustainability of farms. It reflects their productive capacity and their success in converting farm resources and inputs into harvestable products. Diversity and Maturity represent the role of farms in mimicking natural ecosystems but are less clearly linked to sustainability of farms.

### *3.4.3 Implications for farming practices*

There was strong variability within and between individual farms in the respective factors, which was often due to differences in farming practices caused by financial constraints, crop diseases, changes in input and output markets, and personal conditions. The efficiency attributes (EE values for the crop and fish components, and Actual and Apparent efficiencies) show that all farms experienced nitrogen surpluses. The key to nutrient use efficiency on the IAA farms studied is the management of their rice and orchard components rather than the management of the aquaculture component. The O-LF farms dedicated a large part of the farm area to orchards (69%) with much lower average EE values (0.43) than orchards on the rice-based farms. Moreover, the O-LF farms showed very low EE values for rice detritus, indicating that large amounts of nitrogen accumulated in these soils. The R-MF system scored highest on EE for rice soil detritus.

Despite the relatively high inherent soil fertility in the MD, farmers often apply fertilizers in excess (Phong *et al.*, 2009). Five of the 11 farms used very large amounts of fertilizers (232 to 357 kg N $ha^{-1}$). Improvements in nutrient use efficiency could be achieved by reducing the use of external fertilizer inputs. The leaf colour chart method for fertilizer N management and site-specific nutrient management (Buresh *et al.*, 2005; IRRI, 2007) can contribute to optimal nutrient applications in irrigated rice. Rice by-products can also help in improving nutrient efficiency, e.g., by using rice straw to mulch vegetable fields (Sanh *et al.*, 1998; Xuan and Matsui, 1998). In some farms, however, rice straw was burnt because of redundancy and lack of storage space (Dobermann and Fairhurst, 2000).

For enhancing nutrient recycling on the farms, emphasis should be on maintaining traditional sustainable farm practices, such as re-use of crop and animal wastes within the farm and use of pond/ditch sediment as crop fertilizer, by periodically pumping pond mud to vegetable and tree beds. These practices can lead to more sustainable systems with high nutrient efficiency, low nutrient accumulation in the soil, and low discharges of nutrients into the environment. In fish farming low water exchange rates of ponds should be considered as an important practice for high nutrient accumulation in the sediments and high phytoplankton and zooplankton biomass production (Nhan *et al.*, 2006).

In terms of policy recommendations, results of this study do not provide a justification for characterizing any one of the three IAA systems as more ecologically sustainable than the others. Intensification of fish production, as witnessed in the R-HF farms, did not result in poorer ecological performances of the farms. In R-HF farms fish was still an integrated component in the farming system. However, if further intensification of fish production means de-coupling of aquaculture from the rest of the farm and using more external feeds for fish, there is a severe risk for environmental contamination (MARD-DAQ, 2009). Policy should aim for supporting environmentally friendly farming practices in all types of IAA systems, rather than promoting any one of these systems.

## 3.5 Conclusions

ECOPATH models based on nitrogen flows of IAA farms produced 19 agro-ecological system attributes that were reduced to four factors that represented four dimensions of sustainability of these farms: Productivity-Efficiency; Diversity; Maturity; and Aquaculture Integration. Based on these attributes and factors, rice-based farms (R-HF and R-MF) were more efficient and productive than the orchard-based farms (O-LF) and recycled nitrogen more intensively within the farm. The R-MF system was the most diverse. The O-LF system was the least productive and diverse, but the Maturity factor was relatively highest here. Productivity-Efficiency is directly related to sustainability of farms, whereas Diversity and Maturity are related to the role of farms as ecosystems. Fish farming differed strongly between the three farming systems, however, the Ecotrophic Efficiencies (EE) of fish pond detritus indicated that the ponds and ditches contributed to the same extent to the nutrient supply of other components. Within all three farm systems, variability among farms was high, which was due to differences in farming practices. A high farm output in relation to external input use could be achieved both by farms with low external input use and by farms with a relatively high external input use. None of the IAA farms experienced nitrogen depletion. The very low EE values for rice detritus in O-LF farms and vegetable detritus in the rice-based farms indicated that large amounts of nitrogen accumulated in these soils. On many of the farms improved nutrient use efficiency could be achieved through appropriate fertilizer application techniques, integrating farm components for enhancing use of internal nutrient flows, applying traditional farm practices such as recycling of pond/ditch soil, reincorporating crop residues, and re-using animal wastes.

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# Chapter 4

# Modeling the soil nutrient balance of Integrated Agriculture-Aquaculture Systems in the Mekong Delta, Vietnam

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## Abstract

This study quantifies soil nutrient balances of Integrated Agriculture-Aquaculture Systems in the Mekong Delta of Vietnam. Eleven farms were monitored to collect data on farm activities and nutrient inputs and outputs to compute these balances of rice-based and high input fish system in O Mon district (R-HF); rice-based and medium input fish system in Tam Binh district (R-MF); and orchard-based and low input fish system in Cai Be district (O-LF). For the estimation, the Nutmon model has been adapted to the specific conditions in these integrated systems in Asia (Nutmon-Asia). New regression models of leaching and gaseous losses of nitrogen were applied to fields used for upland crops and paddy rice. For nitrogen fixation in paddy soils, wet atmospheric deposition, and irrigation water reference values were used. The results showed that farms in all three systems have nitrogen, phosphorus and potassium surpluses (84 kg N, 73 kg P, and 69 kg K $ha^{-1}$ $y^{-1}$). The O-LF system had the smallest nitrogen surplus while the smallest surplus of phosphorus and potassium was seen in the R-HF system. High surpluses of phosphorus and potassium were found in vegetable fields, whereas a negative potassium balance was found in the rice fields of all three systems. The positive farm nutrient balances indicate that it is likely that soil fertility will be maintained although there is a risk for environmental contamination.

**Key words:** Integrated agriculture-aquaculture; Mekong Delta; Nutmon; nutrient balance; fish ponds

## 4.1 Introduction

In the Mekong Delta of Vietnam (MD) the development of integrated agriculture-aquaculture (IAA) farms has been driven by food security, economic liberalization, market demands, and natural disasters (e.g., flooding). These IAA farms combine paddy rice, vegetable fields, orchards, livestock, and fish ponds. Recently, management on these farms intensified in terms of input use and production (Phong *et al.*, 2008). Because of diversification and integration it is claimed that IAA systems use resources (e.g., land and soil nutrients) efficiently with minimal emissions (Gooley and Gavine, 2003). Such claims, however, have rarely been supported by quantitative evidence.

Soil nutrient balances can be used as an indicator to determine nutrient use efficiency of farming systems (Van der Pol, 1992; Stoorvogel, 2007; Cobo *et al.* 2010)). Different tools that quantify the nutrient balances have been discussed in literature (Roy *et al.*, 2003). This study uses Nutmon (Smaling and Fresco, 1993) which has proven to be a powerful tool for assessing soil nutrient balances (Lynam *et al.,* 1998). The concept of Nutmon is based on an analysis of nutrient inputs and outputs. Nutrient flows like fertilizers, feeds, and farm products are monitored and measured. Other flows like nitrogen fixation, leaching, and erosion are more difficult to measure and are estimated by means of regression models. Nutmon is originally developed for African farming systems (Stoorvogel and Smaling, 1990; Smaling *et al.*, 1993; Smaling and Fresco, 1993; De Jager *et al.*, 1998; Van den Bosch *et al.,* 1998; Vlaming *et al.,* 2001) where numerous studies have been carried out in Kenya (De Jager *et al.,* 1998; Van den Bosch *et al.,* 1998; Gachimbi *et al.,* 2002; Muendo, 2006), Ethiopia (Abegaz, 2005), Uganda and Burkina Faso (Agwe *et al.,* 2007). These studies in Sub-Saharan Africa reveal, almost unequivocally, alarming nutrient depletion rates (Stoorvogel, 2007). These nutrient balances can serve as indicators for the magnitude of losses of nutrients and help to identify the causes for such losses. Recently Nutmon has been applied in Asia including India (Surendran *et al.,* 2005; Surendran and Murugappan, 2006), China, Vietnam (Vlaming *et al.,* 2001; Howeler, 2001; Lam *et al.,* 2005; Khai *et al.,* 2007; Dang, 2005), and Thailand (Wijnhoud, 2007). However, since the regression models in Nutmon have been developed for African conditions, studies outside Africa base their assessment on the flows that can be easily measured or monitored leaving out important, more difficult-to-measure nutrient flows like leaching, gaseous losses, and erosion. The resulting so-called partial balances are rather awkward to interpret as positive and neutral balances do not necessarily correspond to sustainable farming systems.

The question that remains is whether the methodology that was designed for the low external input African farming systems can be adapted for other agro-ecosystems and still yields a reasonable estimate of the full nutrient balance. Various difficulties can be encountered in applying Nutmon to South-East Asia or more specifically to IAA systems in the MD. The systems are, contrary to the African systems, intensive with high inputs, multiple cropping, and with high use of irrigation water. In addition, fish ponds are a common component of IAA systems in the MD. A pond can trap run-off water and its sediments can subsequently be used as an on-farm crop fertilizer and improve on-farm nutrient retention and utilization efficiencies (Muendo 2006). Those differences in farm management call for an adjustment of the estimation of some of the hard-to-quantify flows. This study aims to (i) adapt Nutmon to South-East Asia to quantify the nutrient balances in IAA farms in the MD, and (ii) evaluate the sustainability of IAA farming systems in the MD with respect to soil nutrient balances.

## 4.2 Materials and methods

### *4.2.1 Study sites and farm selection*

The MD covers approximately 3.9 million ha and is located between 104$^o$26’ to 106$^o$47’ eastern longitude and 8$^o$33’ and 11$^o$02’ northern latitude. Except for some minor hilly areas, the MD is flat and low-lying with an average altitude of about 2 meters above sea level (Hoa, 2003). The MD has a tropical monsoon climate with an average annual temperature of 27.2$^o$C. There are two distinct seasons: (i) the rainy season with southwestern winds from May to November, and (ii) the dry season with northeastern winds from December to April. Average annual rainfall varies between 1200 and 2400 mm of which about 90% occurs in the wet season. With many natural streams and a dense network of man-made canals, the MD has complex hydraulics. Prolonged heavy rains, combined with water from the huge upstream catchments of the Mekong river, result in flooding (usually from August to November) of the delta with an average flooding depth of 0.8m - 1.5 m (Nga, 2004). Acid sulphate soils occur widely throughout the MD, but prevail in the back swamps and make up a total of 45% of the MD (White, 2002).

Eleven representative IAA farms were selected from a large rapid rural appraisal (Phong *et al.,* 2008). The farms were located in three fresh water districts in the MD: (i) in O Mon district (R-HF) (105$^o$36’ E; 10$^o$07’ N) having a rice based system with high input (mainly pelleted food) fish ponds, (ii) in Tam Binh district (R-MF) (105$^o$53’ E; 10$^o$07’ N) having a rice-based system with medium input (farm residues, manure, and some pelleted food) fish ponds, and (iii) in Cai Be district (O-LF) (106$^o$00’ E; 10$^o$24’ N) having an orchard-based system with low input (farm residues and manure) fish ponds.

### *4.2.2 Farm monitoring*

Household characteristics, size of agricultural fields and fish ponds, farm activities, nutrient inputs and outputs of the farm components, internal resource use, herd and flock growth, livestock management, livestock manure, household consumption, and household waste were recorded from September 2002 to September 2004 in a dynamic survey. During the survey, farms were visited on a monthly basis to monitor farm inputs and farm outputs. During the entire survey farmers kept log books of all farm operations. Farmers registered the quantities of inputs and outputs using local units (e.g., bags). On separate occasions conversion factors between local units and weights were determined. Dry matter contents and nitrogen (N), phosphorus (P) and potassium

(K) concentrations of farm products and by-products were based on FAO (1972) and FNRI (1990). The nutrient concentrations in faeces of pigs, poultry, goats, and rabbits were based on studies by Yem *et al.,* (2001) and Can (1982) whereas the nutrient concentration in weeds and grass was based on Dung (1996). The nutrient values of inorganic fertilizers and purchased feed concentrates were recorded from their trade marks.

Soil samples were taken at the beginning, the middle and the end of monitored period to a depth of 20 cm in rice fields, vegetable fields and fish ponds, and to a depth of 50 cm in homestead and orchard beds. Five soil samples in each land use system on each farm were collected and analyzed for organic matter through the measurement of loss on ignition, total nitrogen using the Kjeldahl methodology, available phosphorus using Bray-2, and exchangeable potassium with a $BaCl_2$ 0.1N solution. Details on the methods are described in DHCT (2006). The data were aggregated to estimate soil nutrients stocks of the cropping systems in the three systems.

### *4.2.3 Nutmon*

Nutmon uses a conceptual model that distinguishes various compartments on the farm including farm section units (FSU), primary production units (PPU), secondary production units (SPU), redistribution units (RU), the household (HH), stocks (STOCK), and the external world (EXT) (see Van den Bosch *et al*., 1998 and De Jager *et al*., 1998 for a full description). Land resources are described by FSUs which are land units that are considered homogeneous with well described characteristics. PPUs are the basic units of analysis and are defined as cropping activities of one or more crops in well defined fields over a specific period. One FSU can contain one or more PPUs. The animals present on the farm are described as SPUs which are groups of animals of the same species under similar management conditions in relation to e.g., feeding, grazing, and confinement. Locations within the farm where nutrients are accumulated and frequently reallocated (such as animal houses, corrals, fish ponds, dung hills, compost pits, latrines) are called the RUs. The HH is characterized by consumer and labor units including their gender, age distribution, and education as well as capital stocks. The STOCK is the temporary storage of crop products and residues, as well as other inputs. Finally, EXT comprises everything outside the farm limits including e.g., markets and neighboring farms.

Nutrient flows between the various compartments are being monitored and modeled. Nutmon considers five nutrient inputs: IN1 (inorganic fertilizers and feed concentrates), IN2 (organic feeds and organic materials), IN3 (atmospheric deposition), IN4 (nitrogen fixation), and IN5 (sedimentation), and five outflows: OUT1 (crop and animal products), OUT2 (plant/crop residues and manure), OUT3 (leaching), OUT4 (gaseous losses), and OUT5 (erosion and overland flow). Nutmon quantifies the various nutrient flows in two different ways (Van den Bosch *et al.,* 1998). The so-called easy-to-quantify nutrient flows (IN1, IN2, OUT1, and OUT2) are directly assessed during a dynamic farm survey. Other hard-to-quantify flows (IN3, IN4, IN5, OUT3, OUT4, and

OUT5) are estimated with regression models based on a literature review. The full nutrient balance is assessed as the difference between all inputs and outputs. Many research programs use the partial balance based on the easy-to-quantify flows (IN1 + IN2 - OUT1 - OUT2). Although this avoids the sometimes tedious estimation of the difficult-to-quantify nutrient flows, the interpretation of the partial balance is rather difficult as major nutrient flows are lacking from the analysis.

### *4.2.4 The approach to adapt Nutmon to South-East Asia*

Although IAA farming systems in the MD do not compare with African farming systems, this does not inhibit the use of Nutmon and the calculation of partial balances. However, the estimation of the full soil nutrient balance requires the assessment of the difficult-to-quantify flows which are currently based on very specific African data. It was therefore necessary to adapt the regression models for the difficult-to-quantify flows on the basis of a literature review specific to the Mekong delta. We considered four alternative ways to assess the difficult-to-quantify nutrient flows: (i) regression models remained unchanged when their contribution to the nutrient balance was expected to be of minor importance or when results were considered to be realistic, (ii) an average value for a nutrient flow was applied when literature review reveals little variation, (iii) a new regression model was assessed when literature review reveals variation related to some measured parameters, and (iv) when literature review revealed variation but no logical pattern additional research was suggested. Through the above procedures Nutmon was adapted so that it provided reliable estimates for the MD.

### *4.2.5 Applying Nutmon to the IAA farming systems in the MD*

The adapted Nutmon model was applied to the farm data to asses the soil nutrient balances for the three IAA systems in the MD. Balances were estimated at the farm level, but also for the various primary production units. The nutrient balances were used to evaluate nutrient emissions of the IAA system and formed the basis for a discussion on nutrient use efficiency of the IAA systems.

## 4.3 Results

### *4.3.1 Farm components and production*

All farms had orchards (fruit trees), livestock (mainly pigs and poultry), and fish. The farms in the R-HF system focused on the production of rice and fish although some included orchards, livestock, and vegetables. The farms in the R-MF system focused on the production of rice but also included some fruit trees, vegetables, livestock, and fish. One farm in this system had leased out its rice field during the second year because of financial problems. The farms in the O-LF system focused on orchards. Three of the four farms combined orchards with livestock and fish; the fourth also included rice and vegetables. The main farm components were rice and fish in the R-HF system, rice in the R-MF system, and fruit trees in the O-LF system. Vegetables were more common in the R-MF system compared to the other two systems. Goats and rabbits were present on one farm of each system with very small numbers.

In this study, the IAA farms in the MD are characterized using the conceptual model of Nutmon. The IAA farms can be subdivided into three major Primary Production Units that coincide with three distinct Farm Section Units: the rice fields, orchards with fish ponds, and vegetable fields. Four Secondary Production Units can be identified i.e., pigs, poultry, goats/rabbits, and fish. The fish pond is the only major Redistribution Unit. The households did not keep a significant STOCK which was therefore ignored in the subsequent analysis. Table 4.1 shows the average area and yields of the main PPUs. The farms in the R-HF system were significantly larger than of the other two systems and also more land is dedicated to rice and fish ponds. Areas assigned to orchards were similar in the three systems, but fruit yields in the R-HF and O-LF systems were higher than in the R-MF system which had the highest rice yield. The lowest rice yield was in the O-LF system with only one farm cultivating rice on a small patch. In the R-HF and R-MF systems vegetables were cultivated in small areas with various crops over the two monitored years. In the O-LF system one farm rotated vegetables with rice. The production of pigs and poultry per farm was relatively high in the systems R-HF and R-MF compared to the O-LF system. The three systems have a similar area under fish pond (e.g., 17% in R-HF, 13% in R-MF, and 17% in O-LF), but their productions varied significantly ($P<0.05$) because of differences in intensity of fish farming.

**Table 4.1** Land use and annual yields of various farm components for the three systems in the MD (standard error between parentheses)

| Item | R-HF[**] | R-MF | O-LF | All farms |
|---|---|---|---|---|
| Number of farms | 3 | 4 | 4 | 11 |
| Land use | | | | |
| - Orchard (ha) | 0.33 (0.03) | 0.40 (0.05) | 0.44 (0.10) | 0.39 (0.04) |
| - Rice (ha) | $2.05^{a}$ (0.78) | $0.48^{b}$ (0.06) | $0.08^{b}$ (0.05) | 0.76 (0.27) |
| - Vegetables (ha) | 0.02 (0.01) | 0.04 (0.01) | - | 0.02 (0.01) |
| - Fish pond (ha) | $0.48^{a}$ (0.08) | $0.15^{b}$ (0.01) | $0.11^{b}$ (0.02) | 0.23 (0.04) |
| - Whole farm (ha) | $2.90^{a}$ (0.86) | $1.16^{b}$ (0.12) | $0.64^{b}$ (0.09) | 1.45 (0.30) |
| Crop production[*] | | | | |
| - Rice (kg $ha^{-1}$ $y^{-1}$) | $5510^{ab}$ (1776) | $10657^{a}$ (2273) | $1159^{b}$ (768) | 5799 (1298) |
| - Fruits (kg $ha^{-1}$ $y^{-1}$) | $6014^{a}$ (728) | $3206^{b}$ (638) | $7215^{a}$ (1135) | 5430 (621) |
| - Vegetables (kg $ha^{-1}$ $y^{-1}$) | 1188 (1188) | 7721 (3212) | 3949 (2741) | 4567 (1606) |
| Animal production | | | | |
| - Number of pigs | 10 (8) | 16 (3) | 7 (2) | 11 (3) |
| - Number of poultry | $196^{a}$ (43) | $145^{ab}$ (23) | $56^{b}$ (13) | 126 (19) |
| - Pig production (kg $y^{-1}$) | 2210 (2020) | 1118 (168) | 602 (196) | 1228 (541) |
| - Poultry production (kg $y^{-1}$) | 286 (75) | 297 (83) | 109 (37) | 226 (42) |
| - Goats/Rabbit production (kg $y^{-1}$) | 4 (4) | 5 (5) | 3 (3) | 4 (2) |
| - Fish production (kg $ha^{-1}$ $y^{-1}$) | $830^{a}$ (302) | $480^{ab}$ (98) | $200^{b}$ (45) | 474 (101) |

Different superscripts ($^{a,b}$) denote significant differences between means within rows ($P<0.05$)

[*] crop production is expressed per ha of crop area; (-) in rotation with rice

[**] R-HF: Rice-based and high input fish system; R-MF: Rice-based and medium input fish system; and O-LF: Orchard-based and low input fish system

Although management differences between the crops and farms do exist we observed intensive crop management with large quantities of mineral fertilizer of particularly nitrogen (>100 kg/ha) but also P (> 20 kg/ha) and K (>10 kg/ha). In addition, there was significant input of nutrients to the farms in the form of feed concentrates.

Despite the differences in crop management no major difference in soil properties can be observed (Table 4.2). Available P is an exception with significantly higher contents in the R-HF system. The topsoil properties are used to calculate the nutrient stocks of the major primary production units in the systems (Table 4.3). The nutrient stocks of the orchards are much larger than the stocks in the rice and vegetable systems because of differences in effective soil depth between the perennial trees and the annual crops (50 cm versus 30 cm), and probably also due to the lower nutrient uptake under the orchards in combination with litter deposition and minimal tillage.

**Table 4.2** Topsoil (0-20 depth) characteristics of the three systems in the MD

| Parameter | R-HF* | R-MF | O-LF |
|---|---|---|---|
| Soil pH | 5.1 | 4.6 | 4.3 |
| Soil organic matter (%) | 3.94 | 4.90 | 4.00 |
| N Total (%) | 0.20 | 0.20 | 0.17 |
| P Total (%) | 0.16 | 0.19 | 0.16 |
| K Total (%) | 1.36 | 1.48 | 1.35 |
| Available P (mg $100g^{-1}$) | 10.12 | 6.96 | 2.94 |
| Exchangeable K (meq $100g^{-1}$) | 0.26 | 0.26 | 0.24 |
| Soil bulk density (g $cm^{-3}$) | 1.08 | 1.02 | 0.93 |
| Sand (%) | 1.17 | 0.97 | 1.04 |
| Clay (%) | 55.78 | 50.69 | 53.55 |

* R-HF: Rice-based and high input fish system; R-MF: Rice-based and medium input fish system; and O-LF: Orchard-based and low input fish system

**Table 4.3** Average N, P and K soil stocks of Primary Production Units in the three systems in the MD (kg $ha^{-1}$) (standard error in parentheses)

| Nutrient | R-HF** | R-MF | O-LF | All farms |
|---|---|---|---|---|
| Orchard | | | | |
| N | 8405 (661) | 9357 (375) | 8647 (282) | 8839 (251) |
| P | 4641 (354) | 8619 (446) | 7361 (797) | 7077 (478) |
| K | 88947 (5964) | 95953 (4483) | 76992 (3669) | 87147 (3090) |
| Rice | | | | |
| N | 4943 (285) | 3947 (334) | 2421 (1213) | 4019 (332) |
| P | 3795 (241) | 4132 (559) | 2133 (958) | 3721 (375) |
| K | 24635 (2169) | 26960 (2049) | 19015 (9836) | 25022 (1835) |
| Vegetables | | | | |
| N | 3468* | 4821 (418) | - | 4551 (422) |
| P | 1881* | 4816 (542) | - | 4229 (722) |
| K | 38248* | 34464 (3062) | - | 35222 (2490) |
| Fish pond | | | | |
| N | 4359 (597) | 4102 (548) | 3194 (225) | 3842 (279) |
| P | 4254 (1288) | 3814 (301) | 2982 (215) | 3631 (371) |
| K | 27971 (616) | 30044 (1177) | 27101 (1265) | 28408 (682) |

*: only one farm; (-) in rotation with rice

** R-HF: Rice-based and high input fish system; R-MF: Rice-based and medium input fish system; and O-LF: Orchard-based and low input fish system

### *4.3.2 Adapting Nutmon to Asian conditions*

The estimation of the easy-to-quantify flows in Nutmon is universal and does not require any adaptations. The methods for the estimation of the difficult-to-quantify flows, however, require reconsideration. In this Section we present the procedures and adaptations per nutrient flow to make Nutmon suitable for Asian conditions.

*Atmospheric deposition (IN3)*

Atmospheric deposition includes both wet and dry deposition. Nutmon calculates wet deposition as a function of annual precipitation. In the literature nutrient inputs from wet deposition in Asia were estimated at 1.5 kg N (App *et al*., 1984), 0.25 kg P (Carbo *et al.,* 2005), and 8 kg K ha$^{-1}$ y$^{-1}$ (Hoa *et al.,* 2006). We will use these values as fixed inputs for the MD. Dry deposition in the humid parts of Africa was considered to be of minor importance. This is probably also true for the humid MD. Dry deposition is therefore ignored.

*Nitrogen fixation (IN4)*

There are three types of N fixation: (i) non-symbiotic N fixation through free-living bacteria occurring in almost all agricultural systems, (ii) symbiotic N fixation through symbiotic bacteria (Rhizobia) in systems with leguminous crops, and (iii) N fixation through Azolla and other algae in irrigated rice fields (Roy *et al.,* 2003). We assumed that the non-symbiotic N fixation in dry land agriculture in the MD is similar to African conditions. In the IAA farms in the MD very few leguminous crops are grown limiting the importance of symbiotic N-fixation. N fixation in irrigated systems should be included for rice fields in South-East Asia. According to Roger and Ladha (1992) N fixation in wetland rice fields can be estimated by various agents associating with the rice rhizosphere (1-7 kg N ha$^{-1}$ crop$^{-1}$), rice straw (2-4 kg N t$^{-1}$ straw), organic debris (1-31 kg N ha$^{-1}$ crop$^{-1}$), blue-green algae (0-80 kg N ha$^{-1}$ crop$^{-1}$), azolla (20-150 kg N ha$^{-1}$ crop$^{-1}$), and green manure legumes (20-260 kg N ha$^{-1}$ crop$^{-1}$). Those estimations were derived from separate measurements (Dalsgaard and Oficial, 1998). Total N fixation in a rice field has not yet been estimated by measuring simultaneously the activities of the various components in situ. As a result, it is not clear if N fixation agents are independent or related (Roger and Ladha, 1992). Roy *et al.* (2003) indicated that, although of the total N demand of low producing wetland rice (including naturally flooded and irrigated land) 80 percent can be supplied through N fixation, in most cases N fixation does not exceed 30 kg N ha$^{-1}$ y$^{-1}$. With the high production levels in the MD, 30 kg N ha$^{-1}$ y$^{-1}$ from biological nitrogen fixation was used as an input for rice fields in the IAA farms (Roy *et al.,* 2003).

*Sedimentation and irrigation (IN5)*

In the MD sedimentation takes place during the yearly flooding and mainly on low-laying rice fields. The sediment load depends on the source of flood water and is influenced by distance from rivers. At regional level the sedimentation from flooding can be an important source of nutrient inputs. However the studied IAA farms were surrounded with dikes to control flooding. Therefore, sediment input with the flood water is unimportant. In IAA farms, nutrients also accumulate in the pond including residues from fish feed and sediment accumulated via exchange of river/canal water. Nutrients in the fish pond sediment were estimated by monitored farm data. In the IAA farms fish pond sediment is considered as nutrient input for the orchard and vegetable fields, which is quantified as product of pond area and pond sediment divided by total orchard and vegetable area. We only considered nutrient inputs from irrigation water in the nutrient balance calculation. In IAA farms the fruit trees and vegetables are irrigated with a frequency of 3 days in the dry season (i.e., 6 months). Based on Nhan *et al.* (2006) and Hoa *et al.* (2006), irrigation water in IAA farms is estimated to contribute 1.8 kg N, 2.4 kg P, and 1.2 kg K $ha^{-1}$ $y^{-1}$. For one rice crop (i.e., 3 months) the irrigation water supplies 2.7 kg N, 3.6 kg P, and 1.8 kg K $ha^{-1}$.

*Leaching of N, P and K in paddy and upland soils (OUT3)*

Land preparation and intensive rice farming with large amounts of fertilizer on clayey paddy fields can influence the rates of leaching and gaseous losses. In Nutmon, Nitrogen leaching on dry land farming systems in Sub-Saharan Africa is based on soil texture and rainfall (Smaling *et al.,* 1993). Application of the African regression models will overestimate N leaching for paddy soils in South-East Asia. Various values of leaching and gaseous losses of N in paddy soils corresponding to their rates of N fertilizer application, soil types, and study locations were collected for Asian countries (Table 4.4). Leaching of N in these systems varied from 0.1 to 9% of applied N fertilizer (Figure 4.1a). Leaching values showed a weak relationship with N fertilizer rates ($r^2$=0.12). Therefore an average leaching rate of 6 kg N $ha^{-1}$ $y^{-1}$ is used in paddy soils.

Literature showed that N leaching amounted to 49% of the N fertilizer applied in soils with a rotation of annual upland crops (Table 4.4, Figure 4.1c). Leaching of N ($N_{leaching}$) is strongly related to the application of inorganic nitrogen fertilizer ($N_{fertilizer}$) yielding the following equation:

$$N_{leaching} = 0.37N_{fertilizer} + 20.7 \ (r^2 = 0.97)$$

Studies on N leaching in orchard soils are rare in South-East Asia. We propose to use the above equation for estimation of N leaching in upland soils in the MD. Leaching of K in upland soil with a rice-wheat rotation (Fan *et al.,* 2005) amounted to 3% of the K fertilizer applied. In the MD, K leaching was also estimated at about 3% (Table 4.4) of K fertilizer applied on acid sulfate soil (Hoa *et al.,* 2006). The adapted model uses this value.

In tropical soils, soil particles bind P tightly. For example small P leaching from 0.071 to 0.11 kg P $ha^{-1}$ $y^{-1}$ was calculated under rice and wheat rotation on Gleyi-stagnic Anthrosols, with an application of 60-300 kg P $ha^{-1}$ $y^{-1}$, using a large-scale lysimeter

**Table 4.4** Annual fertilizer rates, leaching values of N and K, and gaseous losses in paddy soils and upland soils in some Asian countries

| Items | Soil types/land uses | Leaching$^{(1)}$ | Fertilizer$^{(1)}$ | Locations | Sources |
|---|---|---|---|---|---|
| **Leaching of N** | | | | | |
| Paddy soil | Transplanted rice | 0.2 - 3.5 | 201-258 | Cauvery Delta, India | Pampolino *et al*., 2007 |
| | Transplanted and broadcasted | 0.9 - 1.2 | 225-249 | Nueva Ecija, Philippines | Pampolino *et al*.,2007 |
| | Broadcasted rice | 0.1 - 0.3 | 174-224 | Mekong Delta, Vietnam | Pampolino *et al*.,2007 |
| | Fluventic Haplaquepts | 9 -11.9 | 122-140 | Maryung-myun, Korea | Yoon *et al*., 2006 |
| | Inceptions | 0.7 | 120 | New Delhi, India | Bandyopadhyay and Sarkar, 2005 |
| | NA | 10.6 | 345 | Jiangsu, China | Ma *et al*., 1997 cited by Xing & Zhu, 2000 |
| | NA | 27 | 300 | Zhejiang, China | Wang *et al*., 1996 cited by Xing & Zhu, 2000 |
| Upland soil | Hillside, silty clay loam | 41-56 | 61 | Na Haew, Thailand | Pansak *et al*., 2005 |
| | Clayey soil. Maize inter-cropped with soybean, and sweet potato | 140 | 309 | Nongshi-tun, China | Liang *et al*., 2005 |
| | | 234 | 540 | Nongli-tun, China | Liang *et al*., 2005 |
| | | 178 | 461 | Patan-tun, China | Liang *et al*., 2005 |
| | | 121 | 297 | Waixain-tun, China | Liang *et al*., 2005 |
| **Leach. of K**: Paddy s. | Acid sulfate soil | 1-2 | 40-70 | Mekong Delta, Vietnam | Hoa *et al.,* 2006 |
| Upland soil | Fluvaquent, rice-wheat rotations | 3-4 | 125 | Chengdu Plain, China | Fan *et al*., 2005 |
| **Gaseous loss of N** | Soil types/land uses | Gaseous loss$^{(1)}$ | Fertilizer$^{(1)}$ | Locations | Sources |
| Paddy soil | Transplanted rice | 88-148 | 201-258 | Cauvery Delta, India | Pampolino *et al*., 2007 |
| | Transplanted and broadcasted | 102-139 | 225-249 | Nueva Ecija, Philippines | Pampolino *et al*., 2007 |
| | Broadcasted rice | 75-150 | 174-224 | Mekong Delta, Vietnam | Pampolino *et al*., 2007 |
| | Inceptisol | 21 | 120 | New Delhi, India | Bandyopadhyay and Sarkar, 2005 |
| | Tropaqualf | 71 | 150 | IRRI, Philippines | Belder *et al*., 2005 |
| | Tropaqualf | 52 | 150 | IRRI, Philippines | Belder *et al*., 2005 |
| Upland soil | Alluvial soil. Rice-barley | 24-43 | 64 | Ariake Bay, Japan | Shiratani *et al*., 2005 |
| | Clayey soil. Maize inter-cropped with soybean, and sweet potato | 166 | 309 | Nongshi-tun, China | Liang *et al.,* 2005 |
| | | 288 | 540 | Nongli-tun, China | Liang *et al*., 2005 |
| | | 237 | 461 | Patan-tun, China | Liang *et al*., 2005 |
| | | 159 | 297 | Waixain-tun, China | Liang *et al.,* 2005 |

(1) in kg ha$^{-1}$ y$^{-1}$; NA: not available

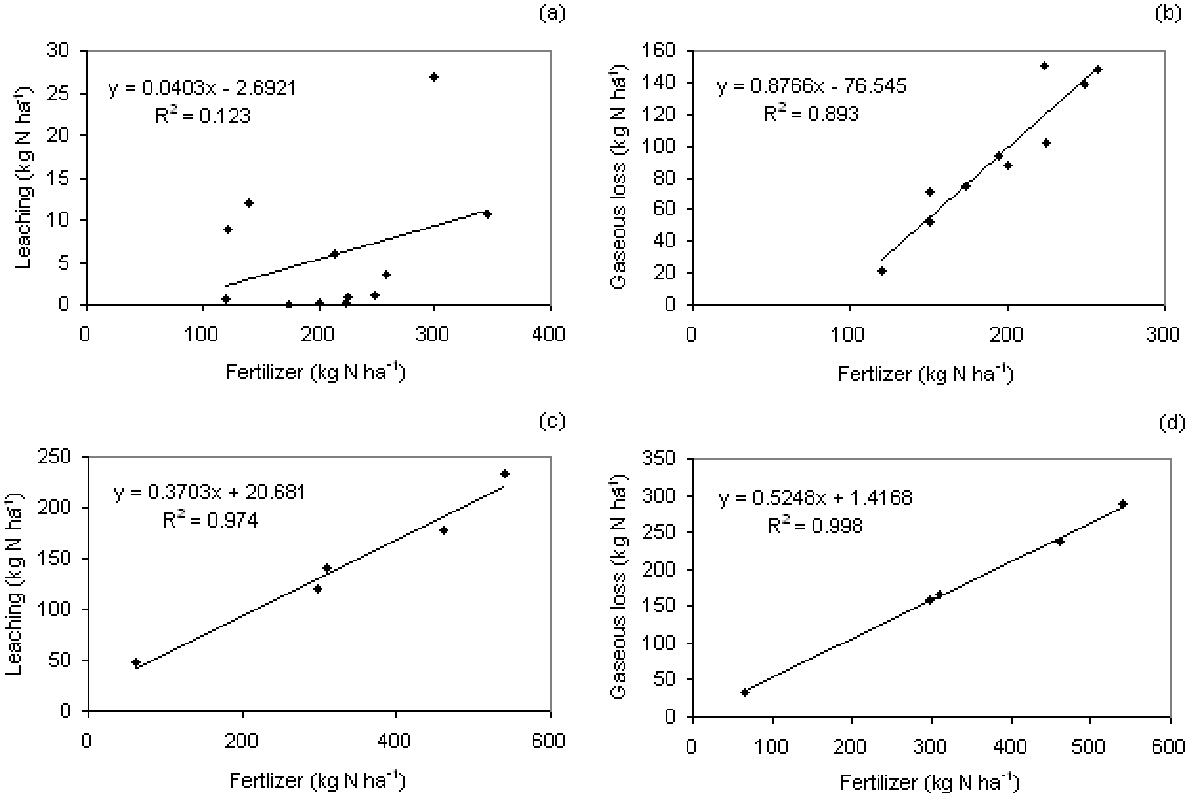

**Figure 4.1** Relationship of leaching of N and gaseous losses with rates of N fertilizer applied; (a) and (b): leaching and gaseous losses in paddy soils, respectively; (c) and (d): leaching and gaseous losses in upland soils, respectively

(Shan *et al.,* 2005). Cho *et al.* (2002) estimated that losses of P in the paddy soil through leaching were only 0.2% to 0.3% to the amount of P applied. Therefore, P leaching is considered unimportant (Roy *et al.,* 2003).

*Gaseous losses in paddy and upland soils (OUT4)*

Table 4.4 shows a range of experiments from Asian countries with measurements of gaseous N losses in paddy soils with varying rates of N fertilizer application, soil types, and study locations. Gaseous N is lost to the atmosphere by two processes: denitrification and volatilization. Denitrification losses are expected to be greatest in wet climates, on highly fertilized, clayey soils, and for crops that withdraw relatively small amounts of N. Ammonia volatilization plays a role mainly in alkaline environments (Roy et al. 2003) which are not present in the MD with an average soil pH of 4.7 (Table 2) and an average pH of pond water of 6.7 (Nhan et al. 2006). On average, gaseous losses amounted up to 48% of N fertilizer application (Figure 4.1b). Almost 90% of variation in gaseous losses ($N_{gaseous}$) can be explained by fertilizer rates. In Nutmon-Asia, we used a regression equation to estimate the gaseous losses in paddy soils:

$$N_{gaseous,\ paddy} = 0.88\ N_{fertilizer} - 76.5$$

Studies on gaseous losses of N in orchard soils are rare in South-East Asia. From literature we found a very strong relationship ($r^2 = 0.998$) between N fertilizer rates and gaseous losses in upland soil indicating a 53% loss. These gaseous losses can be predicted by equation (Figure 4.1d):

$$N_{gaseous,\ orchard} = 0.52\ N_{fertilizer} + 1.4$$

In addition burning crop residues causes almost complete N loss, P losses of about 25% and K losses of 20%. The amount of nutrients lost depends on the method used to burn the straw. In areas where harvesting has been mechanized, all the straw remains in the field and is rapidly burned in situ; therefore, losses of P and K are small (Dobermann and Fairhurst, 2000). Burning rice straw is practiced in the MD. In this study, burning of rice straw was observed and has been measured directly. Remaining rice straw was treated as an internal flow in the farms.

*Erosion (OUT5)*

Because all IAA farms in this study are located in completely flat areas we believe the erosion of the farm land is unimportant.

In summary, the hard-to-quantify flows were adjusted in Nutmon-Asia using methods as indicated in Table 4.5.

**Table 4.5** Nutrients inputs and outputs flows at farm level

| Flows | Description | Adapted value/Nutmon | | |
|---|---|---|---|---|
| | | N | P | K |
| Inputs | | | | |
| IN1 | Inorganic fertilizers, feed concentrates | Farm data | Farm data | Farm data |
| IN2 | Organic inputs | Farm data | Farm data | Farm data |
| IN3 | Atmospheric deposition | 1.5 kg N $ha^{-1}$ $y^{-1}$ | 0.25 kg P $ha^{-1}$ $y^{-1}$ | 8 kg K $ha^{-1}$ $y^{-1}$ |
| IN4 | Nitrogen fixation | | | |
| | - Rice | 30 kg N $ha^{-1}$ $y^{-1}$ | Nutmon | Nutmon |
| | - Other crops | Nutmon | Nutmon | Nutmon |
| IN5 | Irrigation | | | |
| | - Rice | 2.7 kg N $ha^{-1}$ $y^{-1}$ | 3.6 kg P $ha^{-1}$ $y^{-1}$ | 1.8 kg K $ha^{-1}$ $y^{-1}$ |
| | - Other crops | 1.8 kg N $ha^{-1}$ $y^{-1}$ | 2.4 kg P $ha^{-1}$ $y^{-1}$ | 1.2 kg K $ha^{-1}$ $y^{-1}$ |
| Outputs | | | | |
| OUT1 | Farm products | Farm data | Farm data | Farm data |
| OUT2 | Organic outputs | Farm data | Farm data | Farm data |
| OUT3 | Leaching | | | |
| | - Paddy soils | 6 kg $ha^{-1}$ $y^{-1}$ | Nutmon | Nutmon |
| | - Orchard soils | Regression model | Nutmon | 3% of applied K |
| OUT4 | Gaseous losses | | | |
| | - Paddy soils | Regression model | Nutmon | Nutmon |
| | - Orchard soils | Regression model | Nutmon | Nutmon |
| OUT5 | Erosion | 0 kg $ha^{-1}$ $y^{-1}$ | 0 kg $ha^{-1}$ $y^{-1}$ | 0 kg $ha^{-1}$ $y^{-1}$ |

### *4.3.3 Application of Nutmon-Asia to MD farming systems*

*Farm nutrient balances*

Table 4.6 shows positive nutrient balances for the IAA-farms in all three systems. Nutrient balances are dominated by the large inputs of nutrients through mineral fertilizer and feed. In the rice-based systems (R-HF) more nutrients leave the system through crop products compared to the R-MF and O-LF systems. A very small fraction of nutrient outputs leaves the system as crop products. Much more important is the output of nutrients through leaching and gaseous losses. N fixation was significantly higher in the rice based systems. The N, P and K from irrigation water were higher in the rice-based systems because of the importance of irrigation.

Nutrient outflows through animal products in the systems R-HF and O-LF were not much different. However, the outflow of N from animal products in the R-MF system was almost twice higher than in the R-HF system. There was no nutrient export of livestock manure from the farms. Manure from pigs was used as input to the ponds and manure from poultry was left in the orchards and farm yards because of free-ranging. The highest ($P<0.05$) leaching of N was in the O-LF system. This could result from the high amount of inorganic fertilizer applied, and strong leaching in the upland soil under orchards. The gaseous losses of N were also high in the O-LF system. Balances of P and K were similar due to small quantities of nutrients involved. The highest ($P<0.05$) surplus of K was also found in the O-LF system.

*Balances for the different cropping systems*

Table 4.7 compares partial and full nutrient balances of the main crops in the three systems. A positive partial and full balance of N and P was found for all crops except the N full balance of vegetables in the R-MF system. The partial and full balances of K for rice were negative in all three systems except the K full balance in the R-MF system. For orchards, the N partial balance was relatively high in the O-LF system as were the partial and full balance of K in the R-MF system. For vegetables, a negative N full balance was found in the R-MF system.

For all farms, total N input of rice was high (273 kg ha$^{-1}$) compared to vegetables (190 kg ha$^{-1}$), and orchards (123 kg ha$^{-1}$). However, the small full balance of N in rice fields resulted from a large amount of harvested rice grain (97 kg N ha$^{-1}$) and large gaseous losses of N (106 kg ha$^{-1}$). Furthermore, crop residues were removed from the fields (36 kg N ha$^{-1}$) as hygiene measure in crop rotation (e.g., the O-LF). The low P surplus of rice (Table 4.7) was caused by harvested grain and crop residue removal. Total K input for rice was high (136 kg ha$^{-1}$) whereas total K loss due to crop residue removal was quite high (129 kg ha$^{-1}$), which led to negative partial and full balances of K in rice (Table 4.7). The N full balance of orchards was mainly affected by weeds/grasses removed (20 kg ha$^{-1}$), N leaching (41 kg ha$^{-1}$), and gaseous loss (30 kg N ha$^{-1}$). The P full balance in the orchards was quite high (33 kg ha$^{-1}$) when compared to its total inputs

**Table 4.6** Mean (s.e.) values* of N, P and K flows and partial plus full nutrient balances of the IAA-farms (kg ha$^{-1}$ of farm area) in the three systems

| | N | | | | P | | | | K | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nutrient flows | R-HF** | R-MF | O-LF | all farms | R-HF | R-MF | O-LF | all farms | R-HF | R-MF | O-LF | all farms |
| IN1a: inorganic fertilizers | 104 (15) | 100 (17) | 159 (46) | 122 (18) | 31 (4) | 23 (4) | 48 (16) | 34 (6) | $13^b$ (4) | $15^b$ (4) | $46^a$ (14) | 26 (6) |
| IN1b: feed concentrates | 30 (12) | 43 (9) | 22 (7) | 32 (5) | 7 (3) | 11 (2) | 4 (1) | 7 (1) | 14 (5) | 21 (4) | 9 (2) | 14 (2) |
| IN2a: organic materials | 82 (38) | 48 (6) | 48 (11) | 57 (11) | 22 (9) | 37 (6) | 35 (9) | 32 (5) | $15^b$ (7) | $8^b$ (2) | $38^a$ (9) | 21 (5) |
| IN2b: organic fertilizers | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 0 (0) | 11 (11) | 4 (4) |
| OUT1a: crop products | $41^a$ (11) | $32^{ab}$ (6) | $10^b$ (4) | 26 (5) | $8^a$ (3) | $6^{ab}$ (1) | $1^b$ (1) | 5 (1) | 6 (2) | 5 (1) | 3 (1) | 4 (1) |
| OUT1b: animal products | 9 (3) | 17 (3) | 12 (3) | 13 (2) | 0.5 (0.2) | 1.0 (0.2) | 0.7 (0.2) | 0.7 (0.1) | 1.0 (0.3) | 1.8 (0.3) | 1.2 (0.3) | 1.4 (0.2) |
| OUT2: manure | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| **Partial balance** | 165 (49) | 142 (21) | 208 (47) | 172 (23) | 51 (11) | 63 (9) | 87 (20) | 69 (9) | $35^b$ (14) | $37^b$ (6) | $99^a$ (27) | 59 (12) |
| IN3: atm. deposition | 1.5 | 1.5 | 1.5 | 1.5 | 0.25 | 0.25 | 0.25 | 0.25 | 8 | 8 | 8 | 8 |
| IN4: nitrogen fixation | $17^a$ (4) | $12^{ab}$ (2) | $7^b$ (2) | 11 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| IN5: irrigation | $5^a$ (1) | $4^a$ (0) | $2^b$ (0.0) | 1.3 (0.1) | $7^a$ (1) | $5^a$ (0) | $3^b$ (0) | 5 (1) | $3^a$ (1) | $3^a$ (0) | $1^b$ (0) | 2 (0) |
| OUT3: leaching | $22^b$ (8) | $26^b$ (4) | $71^a$ (15) | 41 (8) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | $0.1^b$ (0.1) | $0.2^b$ (0.1) | $1.3^a$ (0.4) | 0.6 (0.2) |
| OUT4: gaseous loss | 45 (9) | 52 (13) | 87 (24) | 63 (11) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| **Full balance** | 121 (36) | 82 (14) | 60 (18) | 84 (13) | 58 (11) | 69 (9) | 89 (19) | 73 (8) | $46^b$ (13) | $48^b$ (6) | $107^a$ (27) | 69 (12) |

* Values are means of 6 annual models for the system R-HF, 8 for the system R-MF, and 8 for the system O-LF

** R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system; and O-LF: orchard-based and low-input fish system

Different superscripts ($^{a,b}$) denote significant differences between means within rows

Farm components and farming activities changes so strongly over the two years (e.g. one farm had rice and pigs in one year but not in the next, in another farm the period of operation of the fishpond changed strongly, farmers used different rice cultivars between crops) that for a simple explanation we treated the two subsequent years on the same farm as independent replicates

**Table 4.7** Nutrient balances[*] of crops (kg ha$^{-1}$ of field area) in the three systems (standard error between parentheses)

| | **N** | | | | **P** | | | | **K** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nutrient balance | R-HF[**] | R-MF | O-LF | Overall | R-HF | R-MF | O-LF | Overall | R-HF | R-MF | O-LF | Overall |
| Rice | | | | | | | | | | | | |
| Partial balance | 62 (25) | 105 (33) | 169 (16) | 102 (21) | 23 (8) | 16 (11) | 107 (22) | 32 (11) | -60 (25) | -4 (9) | -75 (43) | -32 (13) |
| Full balance | 32 (15) | 25 (13) | 32 (60) | 28 (11) | 34 (8) | 27 (12) | 111 (22) | 42 (11) | -47 (25) | 10 (9) | -65 (43) | -19 (13) |
| Orchard | | | | | | | | | | | | |
| Partial balance | 99 (39) | 53 (20) | 132 (32) | 94 (18) | 34 (13) | 18 (6) | 40 (9) | 30 (6) | 169 (96) | 13 (5) | 56 (15) | 71 (28) |
| Full balance | 61 (36) | 2 (14) | 35 (16) | 30 (13) | 37 (13) | 20 (6) | 43 (9) | 33 (6) | 178 (96) | 22 (4) | 64 (12) | 80 (29) |
| Vegetables | | | | | | | | | | | | |
| Partial balance | 125 (-) | 88 (41) | 305 (34) | 141 (41) | 125 (-) | 29 (12) | 109 (39) | 57 (18) | 1498 (-) | 101 (66) | 170 (85) | 272 (160) |
| Full balance | 91 (-) | -23 (19) | 1 (1) | -4 (17) | 128 (-) | 31 (12) | 112 (39) | 60 (18) | 1507 (-) | 110 (66) | 176 (84) | 280 (160) |

[*] Values are means of 6 annual models for the system R-HF, 8 for the system R-MF, and 8 for the system O-LF

[**] R-HF: rice-based and high-input fish system; R-MF: rice-based and medium-input fish system and O-LF: orchard-based and low-input fish system

(-): only one farm

(35 kg ha$^{-1}$) because of small output of P via harvested fruits. The K full balance was relatively high in the orchards because of high inputs of crop residue (e.g., rice straw) used to mulch the orchard beds (e.g., the R-HF). The relatively high K partial and full balance in the vegetable fields was impacted by a large storage of rice straw (e.g., 11 tons) on vegetable beds in the R-HF system.

The N full balance of fish ponds (52 kg ha$^{-1}$) in the R-HF system was caused by high feed input, and the N full balance in the O-LF system was small because of low input of feed (10 kg ha$^{-1}$) in this extensive fish farming system. In the O-LF system the P full balance was small in fish production compared to the other two systems. A positive K full balance of 14 kg ha$^{-1}$ in fish production was found in the R-HF system. Fish ponds are considered as redistribution units. Through feeding the fish with inputs from outside nutrients are brought into the system and also leave the system via fish and sediment. For all farms in the three systems, the annual contribution was 16 kg N and 5.5 kg P ha$^{-1}$ of farm area. Accumulation of K in fish pond sediment was not considered as there were no data available.

## 4.4 Discussion

### *4.4.1 Adapting Nutmon in the MD*

Adaptation of Nutmon resulted in major changes in the calculation procedures for various flows. Nutmon-Asia takes into account many different activities influencing nutrient stocks (Tables 4.2 and 4.3) and flows on the farms, and produces information for a more efficient use of nutrients on the different crops and animals in the IAA farms in the MD.

Rice and orchards are the most important components of the IAA farms because of their large share of the farm area (Table 4.1). The extreme variation in rice yield between systems is due to the use of different cultivars and farming techniques. Besides, in O-LF only one crop is cultivated per year, in R-HF and R-MF two or three. Vegetables are commonly grown on small areas, mainly for household consumption. In many farms soils under vegetables are comparable to those under orchards as farmers combine their orchard and vegetables areas. Therefore, the estimation of N losses in Nutmon-Asia (Figure 4.1) places the emphasis on paddy and orchard soils. Hung *et al.* (1995) stated that leaching was not an important loss mechanism in rice soils in the MD. N losses in paddy soil were presumed important but due to gaseous losses, not leaching.

Soil material used to build the orchard beds may be turned over during fertilization and soil aeration. The raised beds are surrounded by water in ditches that are used for irrigation and fish culture. These ditches can saturate part of the soil beds, especially in the wet season when water levels are high. In the dry season, the ditches can be drained to control tree flowering. The alternate drying and wetting of soils enhancing the release of $N_2O$ and NO to the atmosphere (FAO, 2001) in combination with the fine soil textures and low soil pH in the MD (Nguyen *et al.,* 2006) results in very different leaching and gaseous losses in orchard soils in the MD from that of upland soils for annual crops as referred from the literature.

In crop production of IAA-farms 68% of the fertilizers are compound and 29% is urea. Compound fertilizers can lead to different gaseous losses when compared to single urea. Gaseous losses result from volatilization and from denitrification. However, the literature reviews that were found only included total gaseous N losses.

Nutmon-Asia may underestimate farm scale nutrient flows in some ways: (1) internal nutrients transferred to the household and part of the nutrients used for growth of animals are eventually exported from the farm; (2) part of the nutrients is used for the standing biomass of the trees (Dalsgaard and Oficial, 1998) but is not captured in the model; (3) losses of N in orchard soils in the MD can differ from upland soils in other Asian countries because of specific soil management, e.g., groundwater level control; (4) flows of nutrients out of the farms through the death of animals are not taken into account, and modifications in the quantity of fish (birth, death, sales, and transfer) is difficult to monitor; (5) off-field gaseous losses are not considered, as well as losses of nutrients from a fish pond through diffusion processes.

### *4.4.2 The effect of farm management on the soil nutrient balance*

Crop selection can also affect the nutrient balances. In the O-LF system, fruits were the main crop (Table 4.1). Fruits have commonly low nutrient and dry matter contents (FAO, 1972; FNRI, 1990) which led to low nutrient outputs (Table 4.6). This is also found in Northern Vietnam where a high surplus of nutrients (85-882 kg N ha$^{-1}$ y$^{-1}$, 109-196 kg P ha$^{-1}$ y$^{-1}$, and 20-306 kg K ha$^{-1}$ y$^{-1}$) was recorded in vegetable farming systems (Khai *et al.,* 2007). In our study only relatively high P and K surpluses were found in vegetable production (Table 4.7). The negative full balance of N in vegetable fields was caused mainly by high leaching of N and gaseous losses which were not considered in the study in Northern Vietnam. Rice biomass in the two rice-based systems contributed importantly to farm production (Tables 4.1 and 4.6). A farm producing three rice crops per year is expected to have a lower positive balance than a farm with two crops. For example, total annual mineral fertilizer application by MD farmers with three crops is about 200 kg N ha$^{-1}$, 55 kg P ha$^{-1}$, and 67 kg K ha$^{-1}$ with a total yield of 11 tons ha$^{-1}$ (Huan *et al*., 2005). In our IAA farms the annual fertilizer applied per ha for rice was 209 kg N, 62 kg P, and 29 kg K but the total yield was only 5.8 tons ha$^{-1}$. High N and P applied but low yield resulted in a larger surplus in the rice fields of the IAA farms. In case of a negative balance of K (Table 4.7), the low K application for rice is the main reason (Hoa *et al.,* 2006).

Rice (209 kg N ha$^{-1}$) and vegetables (144 kg N ha$^{-1}$) receive a much higher annual input of N-fertilizer than fruit trees (55 kg ha$^{-1}$). The farmers apply nutrients on a regular basis but disregard nutrient balances of the farm because of lack of appropriate information. A high surplus of nutrients in the three systems (Table 4.6) implies an accumulation of nutrients within the soil pools. It looks like the farmers are over-fertilizing. Normally the farmers decide how much fertilizer to be used for crops on intuition. They do not consider the contents of N, P and K in the fertilizers nor in soil pools. This may lead to excess fertilizations and imbalances in the soil.

For all farms, the feed used for animals accounted for 42, 53 and 60% of the N, P and K farm inputs (e.g., fertilizers and feeds), respectively (Table 4.6). Purchased feeds as concentrates and organic feeds (e.g., rice and bran) contributed to a nutrient surplus in animal production in all three systems. In terms of nutrient surplus pig production is more intensive than poultry or fish in all three systems. Pigs were considered as a source of saving money, poultry was mainly used for household consumption. This pattern of livestock production causes fluctuations in numbers of animals kept on farms. Consequently there are changes in feed use over the year which affects nutrient use efficiencies.

Animal manure produced in farms can contribute importantly to nutrient recycling (De Ridder and Van Keulen, 1990). In the IAA farms pig manure was frequently used as input to the fish ponds to reduce the external feeds for fish. The use of pig manure can cause polluted water (Nhan *et al.,* 2007) whereas poultry drop their manure mainly on orchard beds and this manure decomposes there. It was estimated that 32 kg N, 14 kg P and 10 kg K ha$^{-1}$ from poultry were left to decompose in the orchards.

In the fish pond of IAA farms wastes of the family, crop and livestock are accumulated. Use of sediment for covering orchard beds and vegetable fields is a practice to bring back nutrients to the soil (Muendo, 2006). However this practice was not done annually in the IAA farms because of labour shortage. How much pond sediment accumulates depends on the intensity of exchange with surface water. A low water exchange rate results in low nutrient losses (Nhan *et al.,* 2007), for example, in the R-MF system. Amounts of N and P from the pond sediments were not large compared to N and P from the applied inorganic fertilizer, but can help to maintain soil fertility of the PPUs, reduce nutrient inputs in crop production of the IAA farms and risk for the environment from nutrient losses.

### *4.4.3 How to achieve a neutral balance in the IAA systems?*

Nutrient surpluses accumulate within the soil pools and improve soil fertility but may also result in a threat for environmental contamination (Nielsen and Kristensen, 2005). Given the relatively high inherent soil fertility in the MD, one should aim for a (near) neutral nutrient balance which can be achieved through better use of on-farm resources and reduction of external inputs.

The results of this study suggest that farmers are over-fertilizing. Therefore, an improvement of the nutrient balance of the IAA farms can start by lowering the quantity of fertilizers applied. IAA farms use mainly inorganic fertilizers, organic fertilizers are rare. This is due to shortage of labour for composting, fluctuation of the number of animals on the farms, and the slow effect of organic fertilizers in farmer’s thinking. In the R-MF system, for instance, instead of burning, rice straw could be used to compost or mulch the orchard beds or vegetable fields. In the three systems pig manure, instead of direct use in the fish ponds can also be used to raise earthworms to feed fish (Mason *et al.,* 1992), and the residues then can be used as fertilizer. Keeping the soil covered with crop residues in the farms reduces runoff, and enhances the soil organic matter (Powel and Unger, 1997).

Farmers sometimes act impulsively when applying fertilizers. In the O-LF system a water melon disease occurred in the second crop when a farmer applied 42 kg N but harvested only 6 tons of fruit $ha^{-1}$ compared to 25 kg N for 14 tons of fruit $ha^{-1}$ in the first crop. Market price fluctuations in the MD (Phong *et al.,* 2008) also impact farmer decision to fertilize crops, especially in the case of fruit trees. For example, three farmers, one in each system, did not fertilize their orchards because of financial constraints.

For future development of the model a link should be made between the farm nutrient budgets and total soil nutrient stocks in order to improve the interpretation of the nutrient balances, and the existing knowledge of subsoil exploitation should be involved (Van den Bosch *et al.,* 1998). Data collection for reliable parameterization of the model is time-consuming. Improvement can be achieved when more research is done on losses of N in orchard soils.

In this study data were monitored and measured in the farms. However, nutrient contents of farm materials were based mainly on literature in Asian and MD conditions because of many different farm materials to be used, and also due to manpower and financial constraints in laboratory analysis. Nutrient contents in farm outputs can vary with different levels of intensification of the farms (e.g., amount of N applied), therefore direct analysis should be taken into account.

## 4.5 Conclusions

This study adapted Nutmon to the IAA systems found in Asia. Generally nutrient surpluses are found with a large variation between IAA farms in the three systems which can be explained by the variation of production goals, priorities and farming practices. Large surpluses of nutrients in the three systems indicate that inputs far exceed outputs. This is an evidence of over-fertilization by farmers and a reflection of low nutrient use efficiency. The crop choice, inorganic fertilizer application, internal farm resources use, livestock holding, and cultural practices contribute to the farm nutrient balances. At crop level, high surpluses of P and K were accounted for in vegetable fields, and a negative K balance was found in rice fields in all three systems. It is evident that farmers tend to focus on the field level rather than the nutrient balances of the whole farm. Fish ponds can be considered as a trap to capture nutrients in the IAA farms to limit nutrient losses. The IAA farms in the three fish input systems certainly maintain their soil fertility but there is a risk for pollution. It is important that the nutrient balances per cropping system should be improved including the individual nutrient flows. Nutmon-Asia can be applied in the MD to quantify the nutrient balances of IAA farms. However, N leaching and gaseous losses in upland soils for fruit trees and vegetables should be further investigated for model improvement.

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# Chapter 5

# Life Cycle Assessment of food production in Integrated Agriculture-Aquaculture Systems of the Mekong Delta

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## Abstract

This study evaluated the environmental impact of integrated agriculture-aquaculture (IAA) farming systems in the Mekong Delta that differ in types of aquaculture intensification. Daily inputs and outputs for rice, fruits, vegetables, pigs, poultry, and fish were collected on 11 farms over a period of two years: three farms in a rice-based and high input fish system (R-HF); four in a rice-based and medium input fish system (R-MF); and four in an orchard-based and low input fish system (O-LF). For each farm, a detailed cradle-to-farm-gate life cycle assessment was performed. Kcal as functional unit (FU) enabled a comparison of the integral environmental impact among farming systems, and identification of major processes influencing the outcome of an impact category. Kg product as FU enabled evaluation of impacts for the different products of IAA farms. The environmental impact was quantified also for each farm to identify which farm components explained the majority of the environmental impact in absolute terms. Land use and energy use per kcal farm product did not differ among the three farming systems. Global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP) per kcal farm product were higher in O-LF than in R-HF and R-MF, mainly due to the low calorie content of the two main products, fruits and vegetables, and the small fish yield in O-LF. One kg of fish produced in O-LF farms showed 28% higher land use, 36% higher energy use, 45% higher GWP, 60% higher EP, and 52% higher AP than the average kg of fish produced in the other two systems, due to the pond management system and small fish yield in O-LF. The average impacts per kg pig and poultry protein were 1.6-1.8 times higher than the impacts per kg fish protein. Overall, rice and pigs were the main contributors to the environmental impact of food production in the MD. Excessive and inefficient use of fertilizers, and $CH_4$ emission from the paddy fields contributed most to the environmental impact in rice production, whereas the use of external feeds contributed most to the impact in pigs.

**Key words:** Integrated agriculture-aquaculture; environmental impact; LCA; Mekong Delta

## 5.1 Introduction

In contrast to the global trend of specialization in farming, in the Mekong Delta of Vietnam (MD), integrated agriculture-aquaculture (IAA) systems with rice, fruit trees, vegetables, pigs, poultry, and fish have become the common farming system (Bosma *et al.*, 2006; Phong *et al.*, 2008). An IAA system contributes to income diversification of households and is expected to be more sustainable than specialised farming systems, as livestock manure and other farm wastes are used to fertilize fish ponds, pond sediment is used to fertilize crops, and crop by-products are used to feed livestock and fish (Devendra, 1992; Prein, 2002). The IAA systems intensify in response to increasing market demands and the need to improving livelihoods (Bosma *et al.*, 2006; Phong *et al.*, 2008). The Vietnamese government promotes intensification of fish production, in particular, to reduce dependence on rice and to contribute to economic development (Luu, 2002). Intensification of fish production is done through the use of compound feeds, higher stocking rates, and different species of fish. The level of intensification differs among regions, depending on distance to markets and agro-ecological conditions (Nhan, 2007; Phong *et al.*, 2008). Little and Edwards (2003) concluded that intensive fish production, based on external inputs, causes considerably more environmental pollution than extensive forms of fish production.

Other components in integrated farming systems, such as livestock and crop production, are also changing. In the MD livestock production is expected to grow rapidly. Consequently, the application of livestock excreta per unit area of agricultural land will increase two to three fold, which might become a major source of environmental pollution (Watanabe and Nagumo, 2001; Emonet-Denand *et al.*, 2006). Intensification of crop production in IAA systems is done through increased use of high yield cultivars, which commonly require high application of pesticides and inorganic fertilizers (Huan *et al.*, 2005), resulting in eco-toxicity and nitrate leaching.

Nutrient balances of IAA systems in the MD indicated surpluses of N, P, and K, caused mainly by high inorganic fertilizer applications (Phong *et al.*, 2009). Intensification of agricultural production in MD, however, not only affects N, P and K surplus but might also affect emission of greenhouse gases and use of farm inputs. Life cycle assessment (LCA) has been shown to be a suitable technique to quantify the integral environmental impact in the life cycle of an agricultural product, and to provide insight into ways to mitigate this impact (Guinée *et al,* 2002; Thomassen *et al.*, 2008; 2009). So far, LCA has not been used to assess the environmental impact of systems with components that are integrated and that produce different outputs, such as IAA farms in the MD. The aim of this study was to quantify and evaluate the integral environmental impact of IAA farming systems in the MD that differ in forms of aquaculture intensification, and to identify processes that contribute most to the environmental impact of IAA systems.

## 5.2 Materials and methods

### *5.2.1 Study sites and characteristics of IAA systems*

The MD is a flat and low-lying area of about 4 million ha. It has agro-ecological conditions that favour IAA systems. We chose the fresh water alluvial zone as an important IAA farming systems area (WES Programme, 1997).

In early 2002, we identified three districts (O Mon, Tam Binh, and Cai Be) representing three main IAA systems based on the dominant type of crop (rice or orchard) and the intensity of fish culture (high, medium and low) (Nhan, 2007; Phong *et al*., 2008). District O Mon represented a rice-based and high input fish system (R-HF); Tam Binh a rice-based and medium input fish system (R-MF); and Cai Be an orchard-based and low input fish system (O-LF). Rivers and canals were the main water sources for irrigation. Both the R-HF and R-MF systems were located in lowlands with poorly fertile soils and soil texture of clay to silty clay. The flood depth was from 0.5 to more than 1 m. The two rice-based systems differed mainly in distance to input and output markets and, consequently, in intensity of fish production (Phong *et al*., 2008). The O-LF system was located in an area with fertile alluvial soils and soil texture of silty clay; flood depth was from 0.3 to 0.5 m. The fish component could be distinguished based on feed inputs, species and fish management. In R-HF, fish were fed mainly pelleted feed, some by-products from a fish-processing factory, and manure and human excreta; in R-MF, fish were fed pig manure, human excreta, crop residues, and some pelleted feed at fingerling stage; and in O-LF, fish were fed crop residues from the farm, farm manure, and human excreta. In R-HF, fish farming was mainly monoculture of catfish for export, whereas in the other two systems it was polyculture for domestic markets and home consumption. In R-HF and R-MF, fish were raised in ponds, whereas in O-LF, fish were mainly raised in ditches between orchard beds.

We selected 11 farms for monitoring farm inputs, outputs, and on-farm resource flows: three in the R-HF system, four in the R-MF system, and four in the O-LF system. Farms were monitored by the farmers daily, from September 2002 to September 2004. Table 5.1 presents the results of monitoring land use, inputs, outputs, and animal numbers of these farms. The R-HF farms had a larger farm area (2.90 ha) than R-MF (1.16 ha) and O-LF (0.64 ha) farms. In particular, the fish pond and rice field area were larger in R-HF farms than in the other two farming systems. Consequently, fish and rice production, but also poultry numbers were higher in R-HF farms than in O-LF farms. The R-MF farms had higher rice, but smaller fruit production than O-LF farms. The O-LF farms had the smallest fish production but the highest fruit production.

### *5.2.2 LCA methodology*

An LCA can be divided into four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 1997). Each step is described in detail below.

**Table 5.1** Mean land use, animal numbers, inputs and outputs of the study farms in the three systems (standard error between parentheses) (Phong *et al.*, 2009)

| Parameter | Unit | R-HF[1] | R-MF | O-LF | All farms |
|---|---|---|---|---|---|
| Monitored farms | n | 3 | 4 | 4 | 11 |
| Land use | | | | | |
| - Orchard | ha | 0.33 (0.03) | 0.40 (0.05) | 0.44 (0.10) | 0.39 (0.04) |
| - Rice field | ha | $2.05^{a}$ (0.78) | $0.48^{b}$ (0.06) | $0.08^{b}$ (0.05) | 0.76 (0.27) |
| - Vegetable field | ha | 0.02 (0.01) | 0.04 (0.01) | - | 0.02 (0.01) |
| - Fish pond | ha | $0.48^{a}$ (0.08) | $0.15^{b}$ (0.01) | $0.11^{b}$ (0.02) | 0.23 (0.04) |
| - Whole farm | ha | $2.90^{a}$ (0.86) | $1.16^{b}$ (0.12) | $0.64^{b}$ (0.09) | 1.45 (0.30) |
| Purchased materials | | | | | |
| - Inorganic fertilizers | kg ha$^{-1}$* y$^{-1}$ | 364 (49) | 336 (58) | 741 (229) | 491 (93) |
| - Diesel | kg ha$^{-1}$ y$^{-1}$ | 29 (11) | 7 (2) | 21 (8) | 18 (5) |
| - Pesticides | kg ha$^{-1}$ y$^{-1}$ | 5 (1) | 3 (1) | 8 (3) | 5 (1) |
| - Concentrates | kg y$^{-1}$ | 1695 (1188) | 1093 (217) | 251 (64) | 951 (337) |
| - Rice by-products[2] | kg y$^{-1}$ | 7053 (5617) | 3718 (560) | 2423 (589) | 4156 (1514) |
| - Other feeds[3] | kg y$^{-1}$ | 3636 (1690) | 1179 (529) | 832 (290) | 1723 (544) |
| Crop production | | | | | |
| - Rice | kg ha$^{-1}$ y$^{-1}$ | $4113^{a}$ (1349) | $4014^{a}$ (721) | $674^{b}$ (506) | 2827 (582) |
| - Fruits[4] | kg ha$^{-1}$ y$^{-1}$ | $1295^{b}$ (494) | $1147^{b}$ (182) | $5263^{a}$ (1142) | 2684 (599) |
| - Vegetables[5] | kg ha$^{-1}$ y$^{-1}$ | 23 (23) | 1431 (231) | 3002 (2084) | 1618 (775) |
| Animal production | | | | | |
| - Pigs | n | 10 (8) | 16 (3) | 7 (2) | 11 (3) |
| - Poultry | n | $196^{a}$ (43) | $145^{ab}$ (23) | $56^{b}$ (13) | 126 (19) |
| - Pigs | kg y$^{-1}$ | 2210 (2020) | 1118 (168) | 602 (196) | 1228 (541) |
| - Poultry | kg y$^{-1}$ | 286 (75) | 297 (83) | 109 (37) | 226 (42) |
| - Fish[6] | kg ha$^{-1}$ y$^{-1}$ | $830^{a}$ (302) | $480^{ab}$ (98) | $200^{b}$ (45) | 474 (101) |

-: Not applicable. Different superscripts ($^{a,b}$) denote significant differences between means within rows ($P<0.05$); *: ha farm area

[1] R-HF: rice-based and high input fish system; R-MF: rice-based and medium input fish system; O-LF: orchard-based and low input fish system

[2] Rice grain, milled rice, broken rice, and bran

[3] Crab, snail, weeds/grasses, banana stem, kitchen leftover, alcoholic draft

[4] In the O-LF system: longan, rose apple, citrus, banana; in the R-MF system: longan, citrus, coconut, cherry, rose apple, mango, banana, and in the R-HF system: mango, sapodilla, cherry, banana

[5] In the O-LF system: water melon; in the R-MF system: hot pepper, onion, water spinach, cucumber, bitter melon, cabbage, mushroom, and in the R-HF system: hot pepper, mungbean, cabbage

[6] Tilapia, kissing gourami, giant gourami, silver barb, common carp, silver carp, *Pangasius* catfish

### *Goal and scope definition*

This first step includes definition of the system boundary, the functional unit(s) (FU), the method of allocation, and the impact categories to be analyzed. The system boundary for a "cradle to farm-gate" LCA of an IAA farm is in Figure 5.1. Tree and crop by-products were fed to livestock and fish. Family waste (e.g., kitchen leftover, human excreta), dead livestock (e.g., ducks, chickens), and pig manure were used also to feed fish. Fish pond water was used to irrigate trees and crops. Poultry manure was supplied to tree and crop cultivation by free-ranging in the orchards and farm yards. Meat and eggs from livestock, fish meat, rice, fruits, and vegetables were the main farm outputs sold. Part of the products from trees and crops, livestock, and fish ponds were

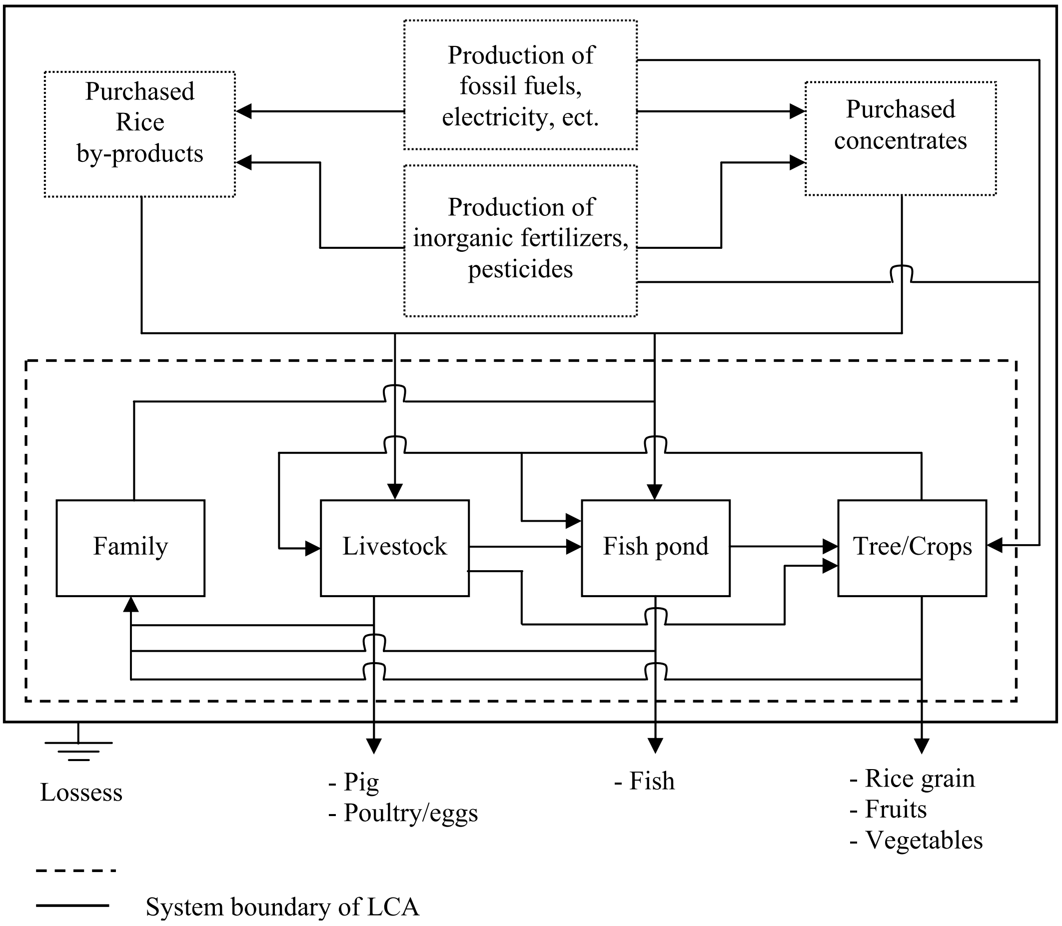

**Figure 5.1** System boundaries for "cradle to farm-gate" LCA of IAA farms

used for household consumption. The environmental impact of individuals in the family, however, was not taken into account because of unavailable information.

Purchased concentrates and rice by-products were fed to livestock and fish. Inorganic fertilizers, pesticides, fossil fuels, and electricity required for farming and transport of feed ingredients and rice by-products were included in the LCA.

The appropriate FU in an LCA analysis, to which all environmental impacts are related, should represent the main functions of the analyzed system. An IAA farm produces multiple outputs. Because of this multi-functionality, two FUs were selected: kilocalorie (kcal) of total farm output and kg of the various farm products. To identify which farm components explained the majority of the environmental impact in absolute terms the environmental impact was quantified also for each farm. Total kcal of farm output was computed by summing kcal of total amount of each farm product sold. The calorie content of the farm products was based on FAO (2003). Economic allocation was used to express environmental impact per kg of farm product (Guinée *et al.*, 2004). In R-HF, the farm-gate economic allocation of sold products was 34% rice, 10% fruits, 0.3% vegetables, 19% pigs, 10% poultry, and 27% fish; R-MF, 16% rice, 7% fruits, 9% vegetables, 45% pigs, 11% poultry, and 12% fish; and in O-LF, 3% rice, 42% fruits, 9% vegetables, 32% pigs, 8% poultry, and 6% fish. Economic allocation was used also for other multifunctional processes along the food chain, such as production of feed ingredients. An important function of pigs, poultry and fish is the production of animal protein. To compare the animal protein produced by these farm components it was assumed that pork (the edible fraction of a kg of pig produced) contained 14.1% protein, poultry 18.2% and fish 18.3% (FAO, 1972; Manh *et al.*, 2009).

The life cycle for the production of meat (pigs, poultry, and fish), rice, fruits, and vegetables was analyzed from the production of inputs to products leaving the farm. The transport associated with the production of purchased inputs was included. Purchased medicines, seed, and machinery were excluded because of their small impact (Cederberg, 1998). Purchased animal stocks were excluded because of their small numbers. Impact categories included in this LCA for the MD were land use, fossil energy use, climate change, eutrophication, and acidification (EEA, 2001; Brentrup *et al.*, 2004; De Vries and de Boer, 2010).

*Inventory analysis*

In the inventory analysis, the computation of emissions to air, water, or soil along the production chain is described. We separated on-farm and off-farm emissions.

*On-farm emissions*

Agricultural processes contribute to global warming potential (GWP) through emission of three main greenhouse gases: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). Emission of $CO_2$ results from combustion of fossil energy used on the farm (Michaelis, 1998). Emission of $CH_4$ results from enteric fermentation of livestock, from animal manure, from paddy fields, and from diffusion processes in a fish pond. Emission of $CH_4$ from enteric fermentation in pigs (1 kg $CH_4$ $pig^{-1}$ $y^{-1}$) and poultry (0.006 kg $CH_4$ $individual^{-1}$ $y^{-1}$) were based on IPCC (2006) and Battye *et al.* (1994). Pig manure was deposited in the fish pond. Emission of $CH_4$ from poultry manure (0.023 kg $CH_4$ $individual^{-1}$ $y^{-1}$) was based on IPCC (2006). Emission of $CH_4$ from goats and rabbits was ignored, because of their small numbers. A $CH_4$ emission of 12.1 mg $m^{-2}$ $h^{-1}$ was assumed for fish ponds (Frei and Becker, 2005). Emission of $CH_4$ from paddy soil was based on a daily emission of 1.3 kg $ha^{-1}$ (IPCC, 2006). In upland soils (orchards and vegetables), annual emission of $CH_4$ (Yang *et al.*, 2003) was ignored, because of its small value (0.4 to 2.4 kg $ha^{-1}y^{-1}$).

Emission of $N_2O$ occurs directly from poultry manure during free-ranging in the farm yard, which was estimated as 2% of total amount of nitrogen excreted (Oenema *et al.*, 2005). Direct emission of $N_2O$ from paddy and upland soils depends on amount of inorganic fertilizers used, and was quantified based on an empirical relation as described by Phong *et al.* (2009):

$$N_{\text{gaseous, paddy}} = 0.88\ N_{\text{fertilizers}} - 76.5 \qquad (1)$$

From the total gaseous N-losses, as quantified by equation (1) 73% was assumed to be lost in the form of ammonia ($NH_3$) (Fillery *et al.*, 1986), whereas 27% was assumed to be lost in the form of $N_2O$.

In upland soils, total gaseous N-losses were predicted as:

$$N_{\text{gaseous, upland}} = 0.52\ N_{\text{fertilizers}} + 1.4 \qquad (2)$$

From the total gaseous N-losses, as quantified by equation (2), 31% was assumed to be lost in the form of $NH_3$ (Fillery *et al.*, 1986), whereas 69% was assumed to be lost in the form of $N_2O$ (Liang *et al.*, 2005). Indirect $N_2O$ emission from atmospheric deposition of N volatilized from managed soils resulted from the sum of N inorganic fertilizers multiplied by 0.1 and N animal manure multiplied by 0.2, which then multiplied by 0.01. Indirect $N_2O$ emission from N leaching from managed soils was calculated as the sum of N inorganic fertilizers, N animal manure, and N crop residue, which multiplied by 0.0075 (IPCC, 2006).

To determine on-farm eutrophication potential (EP), we quantified emission of nitrate ($NO_3^-$), phosphate ($P_2O_5$), ammonia ($NH_3$), and nitrogen oxide ($NO_x$) on the farm. Leaching of $NO_3^-$ from paddy soils was estimated at 6 kg N $ha^{-1}$ $y^{-1}$, based on Phong *et al.* (2009). Leaching of nitrate in upland soils was computed as a linear function of the amount of inorganic N fertilizers applied:

$$N_{\text{leaching, upland}} = 0.37\ N_{\text{fertilizers}} + 20.7 \qquad (3)$$

Leaching of $P_2O_5$ was assumed negligible, because soils in the MD are clayey and have low pH (e.g., 4.7), and the P in the soil was assumed to be bound by iron and aluminium (Saffigna and Phillips, 2006). Calculation of $NH_3$ was described in the above paragraph. Emission of $NO_x$ from fossil fuel combustion was based on Michaelis (1998).

On-farm acidification potential (AP) was based on emission of $NH_3$ from inorganic fertilizers from paddy soils (e.g., 73% of total gaseous N-losses) and upland soils (e.g., 31%), and from livestock manure during free-ranging in the farm yard, which was estimated as 8% of total N manure excreted (Oenema *et al.*, 2005). The $SO_2$ and $NO_x$ emissions resulted from fossil fuel combustion (Michaelis, 1998).

*Off-farm emissions*

The GWP, EP, and AP due to off-farm processes were computed by multiplying the amount of purchased inorganic fertilizers, concentrates, rice by-products, pesticides, and fossil fuels, by emissions related to the production and transport of these inputs. Emissions related to supply and use of fossil fuels were based on Michaelis (1998), whereas emissions related to production and transport of inorganic fertilizers were based on Davis and Haglund (1999) and of pesticides on Brand and Melman (1993) (as cited by Thomassen *et al.*, 2008). Emissions related to the production and transport of purchased feed were based on at least 75% of its main ingredients. Concentrates for livestock included, on average, 20% soybean meal, 15% wheat flour, 2% coconut meal, 40% maize, 5% broken rice, and 15% rice bran. Concentrates for fish included 35% soybean meal, 15% wheat flour, 6% coconut meal, 8.5% rape seed meal, 12.5% tapioca, 7.5% broken rice, and 7.5% rice bran. In concentrates, fish meal content varied from 2-7%. Emissions from fish meal production, however, were not taken into account because of unavailable information.

For each imported ingredient, information needed to compute emissions during cultivation, transport, and economic allocation was based on FAO (1967); Mosluh *et al.* (1978); Bentley *et al.* (1982); Cederberg (1998); Michaelis (1998); FAO (2004); Mandal and Sinha (2004); Hungria *et al.*, (2005); and Roy (2007). Transportation distance of feed ingredients for concentrate production was based on VOSCO (2007).

The information for local feed ingredients such as rice and its by-products, and tapioca, was based on their cultivation conditions in the MD (Huan *et al.*, 2005; Berg, 2002; Bien *et al.*, 2002). The processing information for rice was based on FAO (1967).

For each ingredient (Table 5.2), a life cycle inventory was computed. The computation procedure was based on Thomassen and de Boer (2005). For local feed ingredients, the atmospheric deposition, gaseous losses, and nutrient leaching were calculated as in the on-farm inventory analysis above. For imported feed ingredients, the direct $N_2O$ emission from soils was calculated as the sum of total inorganic fertilizers, animal manure, and crop residues, multiplied by 0.01. The indirect $N_2O$ emission was calculated as in on-farm emission (IPCC, 2006). The $NH_3$ volatilizes during application of manure, and was computed as 13.8% of total amount of nitrogen applied (Mosier *et al*, 1998), and 10% of total inorganic N fertilizers applied (FAO, 2001). Leaching of N was calculated as total inorganic N fertilizers and manure applied, nitrogen fixation, and N deposition subtracted from $NH_3$ emitted from inorganic N fertilizers and manure applied, N extraction from total harvested crops, and direct $N_2O$ emission. Leaching of P was calculated as the sum of inorganic P fertilizer and manure subtracted from P extraction from total harvested crops (IPCC, 2006; Thomassen *et al.*, 2008).

### *Impact assessment*

Land use was expressed as $m^2$ and energy use as kJ (Guinée *et al.*, 2002) per kcal or kg of farm product. To assess GWP at an IAA-farm, emission of $CO_2$, $CH_4$, and $N_2O$ were summed up based on their equivalence factors in terms of g $CO_2$-eq. (100-year time horizon): 1 for $CO_2$, 25 for $CH_4$, and 298 for $N_2O$ (IPCC, 2007). EP was computed based on the four main eutrophying components: $NO_3^-$, $NO_x$, $NH_3$, and $PO_4^{3-}$, and expressed as g $NO_3^-$-eq per kcal or kg of farm product: 1 for $NO_3^-$, 1.35 for $NO_x$, 3.64 for $NH_3$, and 10.45 for $PO_4^{3-}$ (Weidema *et al.*, 1996). AP was computed based on three main components: $SO_2$, $NO_x$, and $NH_3$, and was expressed as g $SO_2$-eq. per kcal or kg of farm product: 1 for $SO_2$, 0.7 for $NO_x$, and 1.88 for $NH_3$ (Audsley *et al.*, 1997).

**Table 5.2** Country of origin, yield, nutrient contents, econmic allocation, and vessel and truck transportation distance for feed ingredients

| Items | Rice grain | Milled rice | Broken rice | Rice bran | Tapioca | Rape seed meal | Palm kernel expeller | Maize gluten meal | Soybean meal | Wheat flour |
|---|---|---|---|---|---|---|---|---|---|---|
| Country of origin | MD | MD | MD | MD | MD | India | Philipines | Brazil | Argentina | Argentina |
| Main yield (kg dm ha$^{-1}$ y$^{-1}$) | 4 730 | 2 885 | 426 | 473 | 3 255 | 775 | 629 | 134 | 1763 | 2400 |
| Crop residue (kg N ha$^{-1}$ y$^{-1}$) | 58 | 58 | 58 | 61 | 5 | 87 | 102 | 181 | 120 | 71 |
| Co-yield (kg dm ha$^{-1}$ y$^{-1}$) | 5124 | 5124 | 5124 | 5362 | 3255 | 1353 | 4028 | 4763 | 1544 | 4000 |
| N content (g kg$^{-1}$ dm) | 11.3 | 11.3 | 11.3 | 12.5 | 1.6 | 64.0 | 25.4 | 38.0 | 77.8 | 17.8 |
| P content (g kg$^{-1}$ dm) | 2.4 | 1.4 | 1.4 | 13.9 | 0.3 | 4.4 | 6.2 | 10.1 | 7.4 | 3.2 |
| Economic allocation | 1 | 0.78 | 0.12 | 0.08 | 1 | 0.33 | 0.03 | 0.1 | 0.72 | 0.83 |
| Vessel transportation (km) | 0 | 0 | 0 | 0 | 0 | 5097 | 1644 | 15338 | 16006 | 16006 |
| Truck transportation (km) | 200 | 200 | 200 | 200 | 60 | 0 | 0 | 0 | 0 | 0 |

dm: dry matter

*Interpretation*

In this step the environmental impact categories from food production in the IAA-systems were analysed and evaluated. ‘Hotspots’ were identified as the major processes influencing the outcome of an impact category for a component or the whole farm (Thomassen *et al*., 2009).

### *5.2.3 Statistical analysis*

Analysis of variance by one-way ANOVA (SPSS Inc., 2004) was performed to analyze the variation in the different environmental impact categories per kcal and per kg product with farming system as factor. One-way ANOVA was also used to analyze the variation in the different environmental impact categories per kg product with farm component as factor. Differences between means were based on Duncan's multiple range test in SPSS 13 (SPSS Inc., 2004).

## 5.3 Results

### *5.3.1 Impact per kcal farm product*

For each farming system, Table 5.3 shows the total amount of farm calories produced and the environmental impact per kcal farm product. The total amount of farm calories was highest ($P<0.05$) in R-HF (7044 Mcal compared with 2180 Mcal in R-MF and 573 Mcal in O-LF) due to its relatively large farm size (Table 5.1) and its relatively large calorie yield per ha. Total land use required per kcal farm product (about 0.018 $m^2$), however, did not differ among systems. On-farm land use contributed 53% to total land use. Off-farm land use was mainly land required for production of feed ingredients (raw materials for concentrates and rice by-products).

Total energy use required per kcal (about 19.3 kJ) did not differ among the three systems. Energy was used mainly for off-farm processing and transport of inorganic fertilizers (27%), production of rice by-products (27%), and feed ingredients (25%).

Production and transport of animal feed (concentrates and rice by-products) per kcal was a hotspot for land use (44% of total land use) and energy use (52% of total energy use).

Total GWP, EP, and AP per kcal were higher ($P<0.05$) in O-LF than in the other two systems (Table 5.3). In O-LF, on-farm GWP accounted for 82% of total GWP; in R-HF, this was 73%, and in R-MF, 71%. Emission of $N_2O$ from application of inorganic fertilizers was a hotspot contributing 50% to total GWP in O-LF, 37% in R-HF, and 31% in R-MF. The leaching of nutrients from application of inorganic fertilizers resulted in a high total EP in O-LF (0.560 g $NO_3^-$ $kcal^{-1}$) compared with R-HF (0.238 g $NO_3^-$ $kcal^{-1}$), and R-MF (0.214 g $NO_3^-$ $kcal^{-1}$). Leaching of $NO_3^-$ accounted for 67% of the total EP in O-LF; 54% in R-HF, and 35% in R-MF. The high $NH_3$ emission from inorganic fertilizers applied in paddy and upland soils of farms in O-LF, together with its low total kcal production, caused a high total AP per kcal of farm product (0.152 g $SO_2$ $kcal^{-1}$) compared with R-HF (0.064 g $SO_2$ $kcal^{-1}$), and R-MF (0.056 g $SO_2$ $kcal^{-1}$). On-farm $NH_3$ emission contributed 66% to total AP in O-LF, 65% in R-HF, and 57% in R-MF.

**Table 5.3** Total farm calories produced, and impact categories per kcal of farm product in the three systems (standard error between parentheses)

| Impact | R-HF* | R-MF | O-LF | All farms |
|---|---|---|---|---|
| Number farms | 3 | 4 | 4 | 11 |
| Total calories per farm (Mcal) | 7044$^a$ (2819) | 2180$^b$ (386.5) | 573$^b$ (79.95) | 2922 (927.7) |
| Land use (m$^2$ kcal$^{-1}$) | | | | |
| On-farm | 0.009 (0.003) | 0.007 (0.002) | 0.013 (0.002) | 0.010 (0.002) |
| Off-farm | 0.007 (0.002) | 0.010 (0.001) | 0.008 (0.001) | 0.007 (0.002) |
| Total | 0.016 (0.006) | 0.015 (0.004) | 0.023 (0.002) | 0.018 (0.002) |
| Energy use (kJ kcal$^{-1}$) | | | | |
| On-farm | 1.248 (0.581) | 0.349 (0.148) | 1.404 (0.661) | 0.978 (0.298) |
| Off-farm | 15.38 (5.769) | 13.49 (2.388) | 25.36 (3.652) | 18.32 (2.418) |
| Total | 16.62 (6.010) | 13.84 (2.531) | 26.77 (3.707) | 19.30 (2.522) |
| GWP (g $CO_2$-eq. kcal$^{-1}$) | | | | |
| On-farm | 7.05$^b$ (1.34) | 6.60$^b$ (1.23) | 17.99$^a$ (5.30) | 10.86 (2.26) |
| Off-farm | 2.56 (1.01) | 2.65 (0.42) | 3.92 (0.50) | 3.09 (0.37) |
| Total | 9.61$^b$ (2.30) | 9.25$^b$ (1.58) | 21.91$^a$ (5.60) | 13.95 (2.48) |
| EP (g $NO_3^-$-eq. kcal$^{-1}$) | | | | |
| On-farm | 0.128$^b$ (0.070) | 0.081$^b$ (0.027) | 0.413$^a$ (0.128) | 0.214 (0.059) |
| Off-farm | 0.111 (0.050) | 0.133 (0.024) | 0.147 (0.022) | 0.132 (0.017) |
| Total | 0.238$^b$ (0.117) | 0.214$^b$ (0.049) | 0.560$^a$ (0.127) | 0.346 (0.066) |
| AP (g $SO_2$-eq. kcal$^{-1}$) | | | | |
| On-farm | 0.044 (0.011) | 0.035 (0.008) | 0.121 (0.041) | 0.069 (0.017) |
| Off-farm | 0.020 (0.009) | 0.021 (0.004) | 0.031 (0.004) | 0.025 (0.003) |
| Total | 0.064$^b$ (0.019) | 0.056$^b$ (0.008) | 0.152$^a$ (0.042) | 0.093 (0.019) |

[*] R-HF: rice-based and high input fish system; R-MF: rice-based and medium input fish system; O-LF: orchard-based and low input fish system

Different superscripts ($^{a,b,c}$) denote significant differences between means within rows ($P<0.05$)

### *5.3.2 Impact per kg farm product*

The environmental impacts per kg product did not differ among the three systems, except for the fish component. Impacts per kg of farm product, therefore, were pooled for all farms in Table 5.4.

All impact categories per kg product were higher ($P<0.05$) for the animal (pigs, poultry, fish) components of the farms than for the crop components (rice, fruits, and vegetables), with pigs and poultry showing the highest impacts in terms of on-farm, off-farm and total impacts. The averages of the impacts per kg pig and poultry were 6.8-8.3 times higher than per kg crop (average of all crops) product. The average of the impact per kg pig and poultry was 1.6 times higher for total land use, and 1.5 times higher for all other impact categories than the average impact per kg fish. The differences between pigs and poultry, and fish were significant for all impact categories, except for on-farm GWP, and on-farm and total AP (Table 5.4). Per kg of protein, pigs and poultry had 1.6 (GWP) to 1.8 (land use) higher impacts than fish.

The impacts per kg fish were higher ($P<0.05$) in O-LF than in the other two systems, in terms of land use (7.31 m$^2$ kg$^{-1}$ vs 5.24 for R-HF and 5.33 for R-MF), energy use (8.35 MJ kg$^{-1}$ vs 5.09 for R-HF and 5.48 for R-MF), GWP (7.30 kg $CO_2$-eq kg$^{-1}$, vs 4.27 kg

**Table 5.4** Impact categories per kg of farm product for each of the farm components (standard error between parentheses)

| Impact | Rice | Fruit | Vegetables | Pigs | Poultry | Fish |
|---|---|---|---|---|---|---|
| Number of farms | 7 | 11 | 6 | 11 | 11 | 11 |
| Land use (m$^2$ kg$^{-1}$) | | | | | | |
| On-farm | 0.57$^c$ (0.09) | 0.82$^c$ (0.16) | 0.70$^c$ (0.12) | 4.63$^a$ (0.39) | 5.20$^a$ (0.43 | 3.35$^b$ (0.35) |
| Off-farm | 0.43$^c$ (0.07) | 0.59$^c$ (0.07) | 0.65$^c$ (0.13) | 4.48$^a$ (0.51) | 4.37$^a$ (0.54) | 2.68$^b$ (0.30) |
| Total | 1.00$^c$ (0.06) | 1.41$^c$ (0.16) | 1.35$^c$ (0.20) | 9.11$^a$ (0.69) | 9.57$^a$ (0.68) | 6.02$^b$ (0.39) |
| Energy use (kJ kg$^{-1}$) | | | | | | |
| On-farm | 81$^b$ (46) | 85$^b$ (27) | 83$^b$ (57) | 314$^{ab}$ (79) | 583$^a$ (176) | 353$^{ab}$ (92) |
| Off-farm | 1122$^c$ (88) | 1453$^c$ (146) | 1519$^c$ (239) | 9717$^a$ (895) | 9898$^a$ (771) | 6415$^b$ (618) |
| Total | 1203$^c$ (118) | 1539$^c$ (159) | 1602$^c$ (254) | 10031$^a$ (873) | 10481$^a$ (789) | 6768$^b$ (626) |
| GWP (g $CO_2$ -eq. kg$^{-1}$) | | | | | | |
| On-farm | 714$^b$ (101) | 962$^b$ (210) | 861$^b$ (153) | 5505$^a$ (716) | 5801$^a$ (792) | 4084$^a$ (788) |
| Off-farm | 197$^c$ (18) | 249$^c$ (24) | 284$^c$ (53) | 1747$^a$ (177) | 1720$^a$ (156) | 1087$^b$ (95) |
| Total | 911$^c$ (98) | 1211$^c$ (223) | 1145$^c$ (191) | 7252$^a$ (792) | 7521$^a$ (822) | 5171$^b$ (835) |
| EP (g $NO^-_3$ -eq. kg$^{-1}$) | | | | | | |
| On-farm | 6$^b$ (1) | 13$^b$ (3) | 9$^b$ (1) | 90$^a$ (19) | 95$^a$ (22) | 69$^a$ (20) |
| Off-farm | 8$^c$ (1) | 10$^c$ (1) | 13$^c$ (3) | 79$^a$ (10) | 74$^a$ (9) | 45$^b$ (5) |
| Total | 15$^c$ (2) | 24$^c$ (3) | 22$^c$ (4) | 168$^a$ (20) | 169$^a$ (23) | 114$^b$ (21) |
| AP (g $SO_2$ -eq. kg$^{-1}$) | | | | | | |
| On-farm | 5$^b$ (1) | 6$^b$ (1) | 6$^b$ (1) | 36$^a$ (7) | 37$^a$ (7) | 26$^a$ (6) |
| Off-farm | 1$^c$ (0) | 2$^c$ (0) | 2$^c$ (0) | 14$^a$ (1) | 13$^a$ (1) | 8$^b$ (1) |
| Total | 6$^b$ (1) | 8$^b$ (1) | 8$^b$ (2) | 50$^a$ (7) | 50$^a$ (7) | 34$^a$ (6) |

Different superscripts ($^{a,b,c}$) denote significant differences between means within rows ($P<0.05$)

for R-HF and 3.72 kg for R-MF), and EP (184 g $NO_3^-$ kg$^{-1}$ vs 62 for R-HF and 84 for R-MF). These high impacts per kg for fish in O-LF were mainly due to the small fish yield in this system.

### *5.3.3 Impact per farm*

Figure 5.2 shows the relative contribution of each farm component (rice, fruits, vegetables, pigs, poultry, and fish) to total GWP of a farm for the three farming systems. Rice and pigs contributed most to GWP, in particular in R-HF (42% from rice; 41% from pigs) and R-MF (20% from rice; 44% from pigs), due to the large rice field area and pig production on these farms. In O-LF, fruits (36%), vegetables (28%) and pigs (20%) contributed most to GWP per farm. In rice production, $CH_4$ emission from paddy fields (47% of the total emission from rice production) and $N_2O$ emission from applied inorganic fertilizers (47% of total GWP from rice) were hotspots. In pig production GWP from purchased feed use was a main contributor (86% of total GWP emission from pigs). In fish production, $CH_4$ emission from ponds was a hotspot (95% of total GWP emission from fish).

The other impact categories showed the same trends in the relative contribution of the different components per farm as GWP. Therefore, they are not presented here.

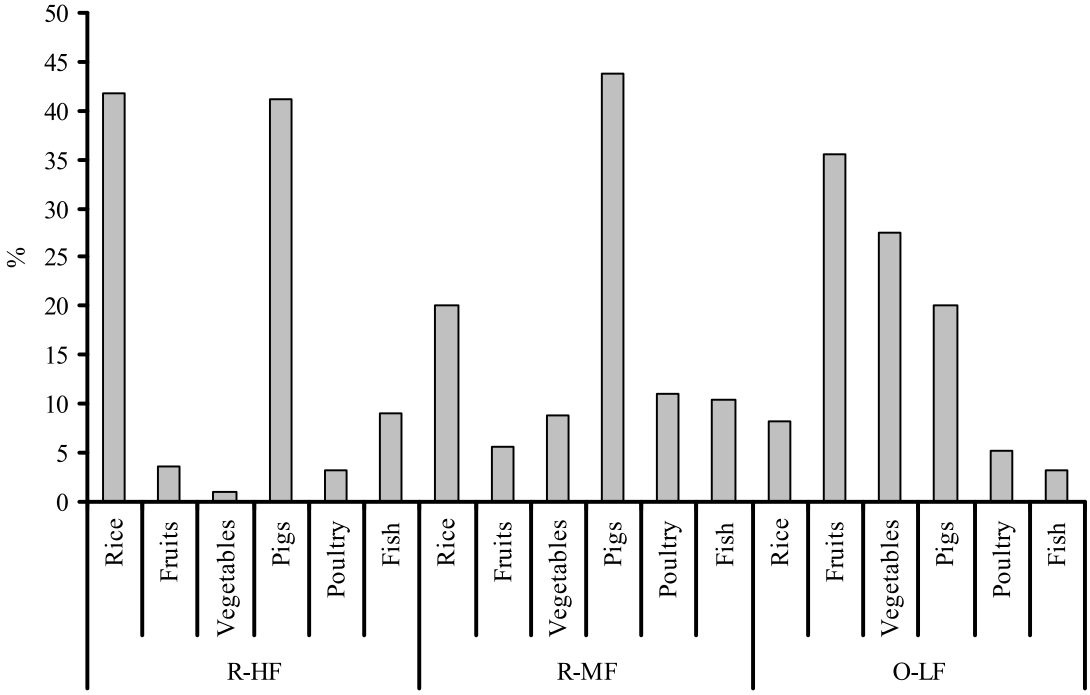

**Figure 5.2** Contribution of each farm component to total GWP of a farm for the three farming systems

## 5.4 Discussion

### *5.4.1 The methodology*

This study shows that some advantages of applying LCA for environmental impact assessments, which include learning about the use of resources (land and energy), the emission of pollutants throughout the production chain of a product, and the processes that contribute most to impacts, also hold for multi-functional farming systems. Kcal was chosen as functional unit (FU) because it represents a vital human food requirement for resource-poor households. This was a suitable method to compare environmental impacts of different farming systems, and to identify hotspots. A disadvantage of kcal as FU, however, is that there is no information from literature to compare results from the MD with results from other regions.

Kg product was chosen as FU to estimate the contribution of impact categories per kg farm product, based on economic allocation. Use of economic allocation, based on farm-gate prices of sold products, has some disadvantages, however, in smallholder farming systems. Not only do market prices fluctuate in the MD (Phong *et al.*, 2008), but also home consumption was not included. Home consumption was estimated to be about 4% of total production in the three systems (Phong *et al.*, 2009). In particular, rice (41% of home consumed farm products), fish (20%), and poultry (17%) are used for home consumption.

A major disadvantage of LCA for multifunctional systems is the density of input data we had to collect. We collected daily inputs and outputs for rice, fruits, vegetables, pigs, poultry, and fish of 11 farms over a period of two years. Added to this, information for off-farm processes and for on-farm and off-farm emissions was needed.

### *5.4.2 Environmental impact of different farming systems*

The selected 11 farms were representative for fresh water and irrigated farming systems in the MD. The main differences in farming between the three systems were the relative importance of rice and fruit production, and the intensification of fish production. The O-LF system had fruits and vegetables as main products, which contributed to its high farm yield per ha (10348 kg $ha^{-1}$ $y^{-1}$) compared with R-MF (8394 kg $ha^{-1}$ $y^{-1}$), and R-HF (7036 kg $ha^{-1}$ $y^{-1}$). The low content of calories in these two products, however, resulted in relatively high total GWP, EP, and AP per kcal farm product in O-LF compared with the two rice-based systems.

The other reason why O-LF had higher resource uses and emissions than the other two systems was its fish production system. The fish component of O-LF showed a 28% higher land use, 37% higher energy use, 46% higher GWP, and 60% higher EP per kg than the average kg of fish produced in the other two systems. Feed inputs, water exchange rate, and pond depth and width contributed most to levels of fish production in the three farming systems (Nhan, 2007). Pig manure was the main feed for fish. Use of concentrates per ha of fish pond was low in O-LF (161 kg $y^{-1}$) and R-MF (263 kg $y^{-1}$) compared with R-HF (735 kg $y^{-1}$). Fish yields per ha of fish pond were 1531 kg $y^{-1}$ in O-LF, 3035 kg $y^{-1}$ in R-MF, and 3581 kg $y^{-1}$ in R-HF. In O-LF, shading by fruit tree canopies in the orchards reduced phytoplankton biomass as fish feed in ditches, high water exchange due to irrigation needed for fruit trees also caused a loss of feed sources for fish, which together with low inputs of feeds caused low fish yields in O-LF. The wide ponds in R-HF and R-MF received more sunlight, which stimulated phytoplankton biomass to supply feeds to fish. In R-MF, feed input and low water exchange rate resulted in higher availability of feed sources for fish than in O-LF. In R-HF, the water exchange rate was also high in the fish ponds, but the relatively high feed input for fish in these farms led to high fish production. The differences in concentrate feed inputs for fish and in fish yields between the two rice-based systems did not result in differences in environmental impacts per kg fish produced between R-HF and R-MF.

### *5.4.3 Environmental impact of different components of farming systems*

The productivity of components had an important effect on the results for the five impact categories. In the MD, rice production is already well-advanced; the GWP per kg of rice (0.91 kg $CO_2$ -eq.), EP (15 g $NO_3^-$ -eq.), and AP (6 g $SO_2$-eq.) in this study are quite similar to GWP (0.78 kg $CO_2$ -eq.), EP (23 g $NO_3^-$ -eq.), and AP (5 g $SO_2$-eq.) per kg of rice in Thailand (Yossapol, 2008). For vegetable production, the GWP per kg in this study (1.1 kg $CO_2$ -eq.) is comparable with the average (1.3 kg $CO_2$ -eq.) per kg of carrot, onion, and tomato in industrialized farming systems (Mogensen *et al.*, 2009). No impact of GWP in tropical fruit production was available for comparison.

In fish production, the GWP of 5.2 kg $CO_2$-eq. per kg (Table 5.4) was smaller than the GWP of 8.9 kg $CO_2$-eq. per kg in the intensive pangasius sector in the MD (Bosma *et al.*, 2009). However, the GWP was larger than the 1.8-2.8 kg $CO_2$ -eq. per kg for rainbow trout in France (Papatryphon *et al.*, 2003). The contribution of fish to EP (114 g $NO_3^-$-eq. per kg) was smaller than the 463-748 g $NO_3^-$-eq. per kg, and to AP (34 g $SO_2$ -eq. per kg) was larger than the 12.1-19.1 g $SO_2$ -eq. per kg in Papatryphon *et al.* (2003). The differences in impacts between IAA farms and rainbow trout farming in France were probably due to the lower yields and lower use of external feeds in the IAA farms in the MD.

Small-scale pig and poultry production in the MD is very different from industrialized pig and poultry production. No data from other small-scale systems were available for comparison, but we could compare our results with a comparative review of livestock LCA results in OECD (Organization for Economic Cooperation and Development) countries (de Vries and de Boer, 2010). To compare our results with this review we converted our estimates per kg product to per kg edible product (71% of pigs and 74% of poultry are considered edible in Vietnam; Van *et al.*, 2004; Bot and Trong, 2004; Xuan *et al.*, 2004). Our estimate of land required for pig production (12.9 $m^2$ per kg pork) was slightly larger than the range of 8.9-12.1 $m^2$ per kg pork in the review. Our estimate of land required for poultry production (13 $m^2$ per kg poultry) was larger than the range 8.1-9.9 $m^2$ per kg poultry meat in the review. Our estimate of energy use for pigs (14.2 MJ per kg pork) was within the range of 9.5-23.9 MJ per kg pork in the review. Our estimate of energy use for poultry (14.3 MJ per kg poultry meat) was also within the range of 15-29 MJ per kg poultry meat in the review. The contribution of pigs to GWP (10.2 kg $CO_2$-eq. per kg) was in the top of the range of 3.9-10 kg $CO_2$-eq. per kg pork in the review. The contribution of poultry to GWP (10.2 kg $CO_2$-eq per kg) was larger than the range of 3.7-6.9 kg $CO_2$-eq per kg poultry meat in the review. The relatively high land use and GWP per kg pork and poultry in the MD were due mainly to high impacts of feed ingredients and the low yields of these farm components. The relatively low amounts of energy used in pigs and poultry was from low on-farm energy use. In the MD, pigs do not only produce pork, they also are a financial security in times of urgent cash needs. Such security function of pigs was not considered in our methodology.

In general, our impacts per kg of product for the different components of the farming systems were slightly larger or comparable to the values found in literature, although most of the LCA literature on agricultural products deals with intensive agricultural production systems with high production levels.

Farming systems in the MD are based mainly on rice and other crops. So, despite the much higher impacts per kg for animal products, crop production (rice, fruits, and vegetables) contributed most to total GWP (63%), EP (52%) and AP (64%) which resulted mainly from use of inorganic fertilizers. Pigs were the main contributor to total land use (33%) and energy use (40%).

### *5.4.4 Improvement of the hotspots*

Fertilizer use was a main environmental hotspot on the IAA farms. The hotspot identification per kcal of farm product indicated that on-farm $N_2O$ from inorganic fertilizers was the biggest contributor to GWP. On-farm leaching of $NO_3^-$ from inorganic fertilizers was a main contributor to EP, and $NH_3$ from inorganic fertilizers was a main contributor to AP. Improving the efficiency of nitrogen use (amount, kind, and time of fertilizer application) can be an important tool to reduce the impacts of fertilizers. This will not only reduce $N_2O$ emission, leaching, and $NH_3$ emission, but will also increase crop yields through better nutrient uptake (Dawson *et al*., 2008), and this will also reduce impacts of GWP, EP, and AP per kcal or kg crop product. In rice production, site-specific nutrient management (Buresh *et al*., 2005) can be applied to reduce fertilizer rates and improve rice yields. Moreover, diversifying crop rotations such as applying double rice and legumes can help to reduce $CH_4$ emission from dry soils (Yang *et al*., 2003). Other methods as mulching soils by cover crops and reducing tillage (Dinnes *et al*., 2002) can also help to reduce leaching. Added to this, more disease control measures should be applied to protect crop yields (Strange, 2003), see the yield losses for watermelon in the O-LF farms.

Impact of GWP from fish farming in the three systems was due mainly to $CH_4$ emission of fish ponds (Frei and Becker, 2005), which increases with a longer growth cycle of fish (328 days in O-LF, 259 days in R-MF, and 205 days in R-HF). Shortening the growth cycle requires improvements in pond management and feeding. This will increase fish yields, and consequently will reduce environmental impacts per kg of fish, seeing the much higher impacts per kg of fish in the low fish input system compared to the other two fish farming systems.

To reduce impacts per kg of pig and poultry, pig and poultry production should become more efficient and should use more local feed ingredients. At present, farmers sell their rice immediately after the harvest because of cash need, later they buy rice and rice by-products again for home consumption and for feeding pigs and poultry. Rice products could be stored on the farm to reduce the use of external feeds.

Further integration of the farm components in these IAA farms could be an option to improve nutrient use efficiency (Luu, 1999; Prein, 2002; Burgos and Burgos, 2006), e.g., using pig manure, not only for feeding fish, but also for composting and fertilisation of crops; and building poultry pens over or next to fish ponds, so poultry manure can be used to feed fish.

## 5.5 Conclusions

LCA proved to be a useful tool to assess the environmental impacts of complex IAA systems, as it provided insights into the environmental performances of the farming systems as whole and per component, and in potential ways to mitigate these impacts. Total land use and total energy use required per kcal of farm product did not differ between the rice-based and high input fish (R-HF), the rice-based and medium input fish (R-MF) and the orchard-based and low input fish (O-LF) farming systems. Total GWP, EP, and AP per kcal farm product were higher in O-LF than in R-HF and R-MF, mainly because of the low calorie content of the two main products, fruits and vegetables, and the small fish yield in O-LF. The impacts per kg fish were significantly higher in O-LF than in the other two systems. The differences in fish intensification level (concentrate feed inputs and fish species kept) between the two rice-based systems, however, did not result in differences in environmental impacts per kg fish produced. On average, the different impacts were 1.6 (GWP) to 1.8 (land use) times higher per kg of pig and poultry protein than per kg of fish protein. Overall, rice and pigs were the main contributors to the environmental impact of food production in the MD. To reduce the environmental impact of IAA farms, the efficient use of nutrients and increasing farm yields are two main considerations.

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# Chapter 6

# General Discussion

## 6.1 Introduction

In the Mekong Delta (MD), the Doi Moi economic reform policy (1986) has been a major force driving diversification in farming systems (Chapter 2). The cooperative movement was abandoned, which led farmers to decide on land use themselves. Extension services provided farmers with new farm technology, and imported animal breeds and crop cultivars were supplied. The increased rice production from modern rice varieties introduced in 1972 contributed to food security in the MD and also impacted on animal production, because extra feed sources became available. Together with introduction of modern rice varieties, market demands and impact of natural disasters (which led to changes in farm components after flooding) changed the integrated agriculture-aquaculture (IAA) systems gradually from monoculture of rice and keeping fish, pigs and poultry for home consumption to diversified and integrated, market-oriented IAA systems. Major strengths of the IAA systems are said to be their favourable soil and water conditions (Duong *et al.*, 1998), recycling of farm bio-resources, improvement of farm income and food security, and spread of economic risks (Berg, 2002). Major weaknesses identified are nutrient losses from farms via discharging pond water (Pekar *et al.*, 2002), low farm nutrient use efficiency (Prein, 2002), potential human health risks from use of manure and human excreta, and labour requirements (Petersen and Dalsgaard, 2003).

The Vietnamese Ministry of Agriculture and Rural Development (MARD) has estimated that by 2020 the population in the MD will increase by three million people. So, food demands will increase in the coming decade, and urbanization will compete with agricultural land use. In the period 2000 to 2008 rice occupied 60% of total agricultural land in the MD (Chapter 1). MARD believes that the rice yield in the MD has reached its peak (5.2 tons per hectare on average), and that the rice yield will not increase much anymore in the coming years (VietNamNet Bridge, 2009). The Vietnamese government aims to diversify agricultural production and intensify fish production to reduce dependence on rice. The expected further intensification of IAA farming practices and the expected climate change cause concern about sustainable use of natural resources in the MD (Watanabe and Nagumo, 2001; Little and Edwards, 2003; Reiner *et al.*, 2004). A hypothesis underlying the present research was that when farming systems intensify, the benefits of integration may be lost.

In this study three IAA systems, which differed in the intensity of fish culture, were selected (Chapter 2): orchard-based and low-input fish (O-LF); rice-based and medium-input fish (R-MF); and rice-based and high-input fish (R-HF). The aim was to understand drivers for changes in IAA farming practices, to evaluate agro-ecological attributes, nutrient balances, and environmental impacts of IAA farming, and to explore sustainable development options. In this final discussion, methodologies for assessing agro-ecological performances are compared. We also discuss farmer awareness of the need for sustainability in IAA systems, and their prospects for exploiting sustainable development.

## 6.2 Comparison of ECOPATH, Nutmon, and LCA approaches in analysis of agro-ecological performances

There is a wide range of tools available that can provide insight in agro-ecological performances of farms and different farming strategies. This section compares the use of three of them in the integrated farming context of the MD.

### *6.2.1 Use of ECOPATH, Nutmon, and LCA*

The IAA farms in the MD are characterised by cultivation and utilization of a wide range of species of crops and animals (Chapter 2). When we only focus on yields of the different farm components we may not adequately capture the productive and ecological performances of such complex farming systems (Dalsgaard and Oficial, 1997).

ECOPATH was applied to visualize individual IAA farm components (rice, fruits, vegetables, bamboos, phytoplankton, pigs, poultry, and fish) and to estimate their biomass, production and consumption parameters and linkages to other components, including detritus as indicator for denoting the soil resource base. ECOPATH quantified a wide range of system ‘attributes’ on basis of inventarisation of resource flows and farm activities. Factor analysis combined attributes into four factors representing indicators of sustainability for the farms and the respective farming systems (Chapter 3). Soil nutrient balances are important indicators to determine nutrient use efficiency of farming systems (Van der Pol, 1992; Vlaming *et al*., 2001; Stoorvogel, 2003). ECOPATH does not have routines for automatic calculation of nutrient balances itself. It uses the Ecotrophic Efficiency (EE), the ratio of N flows out of and into soils for respective farm components, to estimate N accumulation or depletion in soils. We applied Nutmon (Vlaming *et al*., 2001) for detailed analysis of nutrient budgets (Chapter 4). Nutmon was originally developed for African low external input farming systems (Stoorvogel and Smaling 1990) having quite different conditions compared to the MD. Therefore Nutmon needed to be adapted for application in South-East Asia conditions (Nutmon-Asia). Nutmon-Asia takes into account the effects of the different IAA activities on the nutrient stocks and flows to quantify nutrient balances at levels of field and farm.

LCA was used to quantify the use of resources and environmental emissions per kcal and kg farm product, and per farm (Chapter 5). This enabled identification of hotspots, the major processes influencing the outcome of an impact category.

All three approaches aimed to point out farming practices that contributed most to the environmental impact. This information is expected to contribute to improvements in farm management that can reduce environmental impacts.

### *6.2.2 Data collection*

Table 6.1 shows the minimum dataset needed to perform the three approaches. Eleven farms were monitored daily for two years to collect farm and farm component input and output data. These data were complemented with information from the literature to

**Table 6.1** Minimum dataset for the three methodologies

| Group of processes | ECOPATH | Nutmon-Asia | LCA |
|---|---|---|---|
| Bio-resource flow of farm components | ✓ | ✓ | |
| Inorganic fertilizer input (quantity, pattern) | ✓ | ✓ | ✓ |
| Feed input (quantity, pattern) | ✓ | ✓ | ✓ |
| Input and output organic matters (quantity, pattern) | ✓ | ✓ | ✓ |
| Dry matter content; N, P, and K contents of input and output materials | ✓ | ✓ | ✓ |
| Production of farm components | ✓ | ✓ | ✓ |
| Animal holding (initial and ending size) | ✓ | ✓ | ✓ |
| Dynamic vegetation (biomass) | ✓ | | |
| Economic value of input and output materials | | ✓ | ✓ |
| On-farm soil characteristics | ✓ | ✓ | ✓ |
| Rainfall | | ✓ | |
| Inventory data of input materials (e.g., emission, transportation, economic allocation) | | | ✓ |

✓ : data requirement

complete the necessary input data for the three approaches. The 11 farms were three in R-HF, four in R-MF, and four in O-LF. They were selected from the 90 farms surveyed in the two baseline surveys (Chapter 2). The sizes and activities of the selected farms were comparable to these respective farm types in the baseline survey (Chapter 2).

Data collection was time consuming. All three approaches required daily inputs and outputs for rice, fruits, vegetables, pigs, poultry, and fish. ECOPATH required also information on dynamics in vegetation biomass, whereas Nutmon-Asia required information on soil analysis and precipitation for application of transfer functions, and LCA required information on off-farm processes and on-farm and off-farm emissions. This resulted in 22,966 entries in the ECOPATH, 14,166 in the Nutmon-Asia, and 26, 354 in the LCA data-set.

### *6.2.3 Strengths and weaknesses*

Table 6.2 compares model properties, model outcome, application and interpretation, and sustainability indicators of the three approaches. Agro-ecosystems are characterised by fluctuations and complexity. Therefore, identification of factors which affects their performance is difficult. All three approaches contributed in their own way to insight into relevant sustainability issues in smallholder IAA farming.

The strength of ECOPATH lies in its ability to analyse complex agro-ecosystems with agro-ecological attributes using simple mass-balance equations and limited data and computing power. ECOPATH is a static model; it is good for analyzing short-term, but not for long-term impact of changes in farming activities. This is also the case for the Nutmon and LCA approaches. An ECOPATH model is based on food webs, and does not incorporate other features of ecosystems which may also be important, for example, the role of physical factors in driving ecological processes (e.g., weather) and ecological interactions as competition of species for space. In ECOPATH individual stocks are

**Table 6.2a** Comparison of the Ecopath, Nutmon and LCA approaches for evaluation of sustainability of IAA systems in the M

| Approaches | Ecopath | Nutmon | LCA |
|---|---|---|---|
| **Model properties** | | | |
| Type of model | Mass balance, nutrient balance | Nutrient balance | Environmental impact |
| Static or dynamic | Static | Static | Static |
| Role of nutrient flows in the model | Quantification of nutrients flows, balancing flows into, out of, and between crops, animals and soil | Uses detailed nutrient flows and budgets on-farm | Nutrient balance is used to calculate GWP, AP and EP in combination with off-farm emissions |
| Scale | Farm (based on multispecies) | Field and farm (based on land use) | Farm and regional (based on system boundary) |
| Data origin | Mainly on-farm data | Mainly on-farm data | On- and off-farm data |
| Data requirements | Heavy | Heavy | Very heavy |
| Costs of data collection | Not so costly | Not so costly | Costly (e.g., off-farm data) |
| Ease of data collection | Difficult for hard-to-obtain data such as diet composition, biomass of perennials, phytoplankton | Less difficult | Difficult |
| Default data from literature used | Yes, e.g., atmospheric deposition, nitrogen fixation, gaseous losses | Yes, for some hard to quantify flows | Yes, for some hard to quantify flows |
| Documentation of the methodology | Well documented | Well documented | Well documented, but complex |
| Time needed for data & analysis | Time consuming | Moderately time consuming | Time consuming |
| **Model outcome, application and interpretation** | | | |
| Final outcome | Quantified sustainability attributes of productivity, diversification, integration, maturity, nutrient use efficiency | Quantified nutrient balances | Resource use and emissions indicators |
| Use of model | Explores ecological performances IAA farms | Explores nutrient management IAA farms | Explores environmental impact IAA farms and possible trade-offs along the food chain; identifies hotspots |

**Table 6.2b** Comparison of the Ecopath, Nutmon and LCA approaches for evaluation of sustainability of IAA systems in the M

| Approaches | Ecopath | Nutmon | LCA |
|---|---|---|---|
| Missing | Nutrient losses by leaching, percolation and erosion/run-off were not included, but they can be accounted for by assuming exports from the system | Exact local data for atmospheric deposition, fixation, leaching and gaseous losses; Nutmon can perform an economic assessment but this was not used in this study | Only potential losses are computed not actual environmental impacts |
| Model useful for policy assessment | Yes, for assessment of agro-ecologial performances | Yes, for land use and nutrient management | Yes, for environmental impact of farming and reducing impact of hotspots |
| Transfer to farmers | Yes, possible | Yes, easy | Yes, but not easy |
| **Sustainability indicators** | - Productivity-Efficiency: ao Actual and Apparent efficiencies, System harvest index, Net system yield, Net system production, Production/Biomass ration, Animal Gross efficiency, Ecotrophic Efficiency of crop soils<br>- Diversity: ao Functional agricultural diversity, Sum all production, Biomass/total system throughput<br>- Maturity: ao Total system biomass, Biomass/total system throughput, EE plants<br>- Aquaculture Integration: Nutrient cycling index, EE of pond soil | - N, P, and K nutrient flows in land use<br>- Nutrient balances of N, P, and K in kg ha$^{-1}$ | - Land use per kcal and kg farm product<br>- Energy use per kcal and kg farm product<br>- GWP: $CO_2$-eq. per kcal,kg farm product, farm<br>- AP: $SO_2$-eq. per kcal, kg farm product, farm<br>- EP: $NO_3^-$-eq. per kcal, kg farm product, farm |

aggregated into groups, so age effects (e.g., body development in animals) are not explicitly considered. In ECOPATH, the EE of detritus (ratio between nutrient inflows and nutrient outflows in soil) of rice, orchards, vegetables, and fish ponds can be used to evaluate nutrient balances in the soil of farm components. This attribute gives a ratio.

The strength of Nutmon is the quantification of nutrient balances, based on land use, taking into account the effects, on the nutrient stocks and flows, of the many different activities on the farm (crop and livestock activities, manure management, waste management, and off-farm activities). Nutmon-Asia used regression models for leaching and gaseous losses of nitrogen in upland crops and paddy rice. For nitrogen fixation in paddy soils, wet atmospheric deposition, and irrigation water reference values were used. The resulting nutrient balance of Nutmon-Asia is, however, an incomplete indicator for sustainability with respect to soil fertility, because it does not differentiate between nutrients in soil solution and in different types of organic matter (Shepherd and Soule, 1998). Nutmon treats the soil nutrient dynamics as a “black-box”. Interpretation of nutrient balances is difficult, because they are not directly related to soil nutrient stocks and their replenishment by weathering of minerals and desorption. The quantification of the consumption of feeds and the amounts of excreted manure of pigs and poultry is based on simple assumptions. In Nutmon-Asia almost all internal nutrients transferred to the household and part of the nutrients used for growth of pigs, poultry, and fish are eventually exported out of the farm. The part of the nutrients used for building the standing biomass of the trees (Table 6.1) is also not taken into account; and gaseous losses are not adequately estimated (e.g., $N_2$, $N_2O$, $NH_3$, and $CH_4$). It is an important feature of Nutmon-Asia that it uses information available from previous scientific work to estimate hard-to-quantify flows (e.g., estimation of atmospheric deposition, biological nitrogen fixation, sedimentation, emission and leaching). These flows are usually not measured in the field, because of the high costs and long duration of such experiments.

LCA results depend strongly on the definition of the system under study and the choice of the functional unit(s). In this study, a cradle to farm-gate LCA was used, so the off-farm product processing and transport were not included. We used different functional units to get an overall picture of the environmental impact of food production in the MD. A weaknesses of LCA is that farm component interactions are not explicitly represented. Economic allocation was used to allocate impacts to farm products. Use of economic allocation can affect the outcomes of environmental contribution impacts on farm products because of fluctuations in market prices in different periods. The data on off-farm processes were based on literature. Some of these data might have been out-of-date. LCA is very much an expert tool; it is difficult to communicate the results to non-experts.

Nutmon and LCA are complementary. The nutrient balance components of Nutmon-Asia were an important data source for the LCA. Data to perform LCA (Table 6.1) are more difficult to collect than for ECOPATH and Nutmon-Asia, because both on- and off-farm data are required. Flows that are hard to quantify are a weakness of all three models. The only way to improve this is to get field data for processes that are always taken from literature, such as denitrification, leaching, volatilization and N-fixing. Development of better field methods for these flows would really bring progress in parameterization of these models.

### *6.2.4 MD sustainability issues identified by ECOPATH, Nutmon-Asia, and LCA*

*Productivity-Efficiency*

The factor analysis applied in the ECOPATH chapter showed that the Productivity-Efficiency factor (Table 6.2) was responsible for about one-third of the variation between farms (Chapter 3). Farms scoring high on Productivity-Efficiency had a high productivity that was achieved with relatively low discharges of nutrients to the environment, and had a relatively low biomass. It was concluded that this factor was a good indicator of sustainability of farming. In general, the rice-based farms had a higher Productivity-Efficiency than the orchard-based farms, because of their large rice, fruits, and pigs harvest in relation to total farm inputs. A high farm output in relation to external input use could be achieved both by farms with low external input use and by farms with a relatively high external input use. This indicates that farm integration is important for farms with low input use to increase nutrient use efficiency by using internal nutrient flows (e.g., R-MF farms).

*Agricultural diversity and Maturity*

The ECOPATH analysis identified two factors that represented the role of farms in mimicking natural ecosystems: Diversity and Maturity. Diversity was responsible for close to 20 percent of the variation between farms (Chapter 3). Both the baseline survey (Chapter 2) and the ECOPATH analysis indicated that the R-MF farms were the most diverse farms. More diverse agro-ecosystems are assumed to be more resilient to fluctuations in market prices and environmental disturbances. R-MF farms, however, showed large changes in scores on Productivity-Efficiency between the two monitored years. More long-term monitoring is needed to measure and compare stability in production.

Maturity accounted for almost 13% of the total variation between farms (Chapter 3). It represents farms with a high total biomass but low turnover of biomass. Chapter 3 indicated that a high farm production was negatively related with maturity. The O-LF farms scored higher on Maturity than the rice-based farms, because their fruit trees had a high biomass compared with rice and vegetables. Maturity could be related to other ecological sustainability characteristics, such as provision of habitat for natural biodiversity; this we did not monitor.

*Aquaculture integration*

The ECOPATH factor Aquaculture Integration was responsible for 10 percent of the variation between farms. It is associated with the pond sediment in the cycling of nutrients through the system. Amounts of N and P from the pond sediments were small compared with N and P from the applied inorganic fertilizers, they, however, can help to maintain soil fertility in crop production (Chapter 4). The EEs of the fish pond detritus in the three systems indicated that the ponds and ditches contributed to the same extent to the nutrient supply of other components in the respective systems, despite the differences in intensity of fish keeping between the three systems. The R-MF system tended, however, to score best for the Aquaculture Integration factor. The accumulation of pond sediment depends not only on the level of fish feeding but also on the intensity of exchange with surface water. The low water exchange rates in the R-MF system resulted in low nutrient losses, this resulted in more natural feed (phytoplankton) for fish. R-HF farmers applied high water exchange rates to avoid water quality deterioration within their ponds, because of their high feed inputs for fish. This practice polluted surrounding surface waters: about 1.5 times more N and 3.1 times more P were discharged than the amounts received through inflowing fish pond water (Nhan *et al.*, 2006). This indicates that intensification of fish farming in R-HF can lead to reduced benefits of farm integration in terms of availability of nutrients in pond sediment for fertilizing crop soils. The LCA indicated, however, that per kg fish the low input fish farms (O-LF) had significantly higher resource use and emissions than the average kg of fish produced in the other two systems, due to the pond management system and small fish yield in O-LF.

*Use of resources*

In the two monitored years, land use intensities of rice, orchard, and cash crops were quite stable in the three systems (Chapter 2). The land use intensity of fish ponds increased significantly, which indicated development of fish culture in the MD. The LCA indicated that land (off-farm and on-farm) required for pig production (9.1 $m^2$ per kg pig), poultry (9.6 $m^2$ per kg poultry), and fish (6.0 $m^2$ per kg fish) was relatively large (Chapter 5), which reflected the low input-low output animal production in the IAA farms. The low input fish component in O-LF farms had a significantly higher land use per kg fish than the fish components in the other two systems.

The LCA showed that the sustainability indicator energy use per kg of the respective products was relatively low. Commonly, crop, livestock and fish production in IAA farms do not consume much on-farm energy. Energy use in IAA farms was mainly from off-farm inorganic fertilizer and feed use, in which off-farm energy use for animals was a hotspot (Chapter 5). Energy use per kg fish was higher in the low input fish component in O-LF than in the fish components in the other two systems. In contrast, intensive mono-culture fish farms are high consumers of energy (MARD-DAQ, 2009).

*Nutrient balances*

The results of Nutmon-Asia showed a positive balance of N, P, and K at farm and field level in the three systems, resulting from high nutrient inputs but low nutrient outputs. There was, however, a negative K balance in the rice fields. This can be attributed to farms with triple annual rice crops in the two rice-based systems (Chapter 4). These farms use N and P fertilizers but not K (Hoa, 2003). The Actual efficiency in the three systems was low (Chapter 3) reflecting an accumulation of N in the soil. This corresponds to the N surpluses of Nutmon-Asia. At field level, EEs of soil of rice, orchard, vegetables, and fish ponds were also below 1, indicating an accumulation of N (Chapter 3). The EE of rice soils in O-LF farms was much smaller than in R-MF farms, suggesting more N accumulation in the paddy soil of the orchard-based system. Nutmon-Asia estimated the N surplus in paddy soil in O-LF at 32 kg N $ha^{-1}$ (Chapter 4). Generally the positive farm nutrient balances in the three systems indicate that soil fertility is maintained in the IAA farms. This is an advantage point for sustainable farming. However, on the other hand, the Nutmon-Asia analysis indicated that, in general, farmers are over-fertilizing. The LCA results showed that this high fertilizer use was a hotspot in the environmental impacts per kcal farm product in the three farming systems.

*Eutrophication and acidification*

Surpluses of N and P can have an eutrophication impact. On-farm leaching of $P_2O_5$ was assumed negligible, because $P_2O_5$ is bound by iron and aluminium in acid soil conditions (pH 4 - 4.5) (Saffigna and Phillips, 2006). This can be an advantage point because of less contribution of P surplus to eutrophication. The eutrophication impact in IAA farms is mainly by on-farm leaching of $NO_3^-$ from surplus of N-fertilizer used, and $NH_3$ from N-fertilizer was the main contributor to acidification (Chapter 4). The LCA showed that EP and AP per kcal farm product were higher in O-LF than in R-HF and R-MF, due to the small calorie content of fruits and vegetables compared to rice and the small fish yield in O-LF. This small fish yield was also responsible for the 60% higher EP and 52% higher AP per kg fish in O-LF compared to R-HF and R-MF. Overall, fish production proved to be more environmentally friendly in terms of EP and AP per kg and per kg animal protein than pig and poultry production.

*Greenhouse gases*

Worldwide, livestock production is a major contributor to greenhouse gas emissions (Steinfeld *et al*., 2006). $CH_4$ emission from paddy fields also contributes substantially to the increase in the $CH_4$ content of the atmosphere. (Banik *et al*., 1995; Inubushi *et al*., 2001). The IPCC (2006) estimated that $CH_4$ emission from paddy fields is about 5-20 per cent of the total emission from all anthropogenic sources. The LCA showed that in the IAA farms $CH_4$ emission from paddy fields contributed importantly to GWP together with $N_2O$ emitted from applied inorganic fertilizers and the off-farm $CO_2$ emission from feed ingredients production for pigs. In future, rice will remain the main crop in the MD. Therefore for mitigation of the impact of GWP in IAA farms, attention should be paid primarily to rice production. The average GWP per kg protein from pork and poultry was 1.6 times higher than the impact per kg fish protein. So, fish farming is an alternative for pig and poultry keeping to reduce the climate change impact from animal production.

*Farm economy*

The three approaches did not consider the farm economy. The two baseline surveys (Chapter 2) showed that in the three systems the most important contributors to the gross margins were rice, orchard, and fish pond. The relatively large gap between the poor and the rich in the R-HF and O-LF systems could have been the result of small land area, poor farming skills due to low education, unavailable capital investment, and many children in the poor households. The rich have sufficient financial resources to invest and intensify their farming whereas the poor may have to stop farming when facing risks (e.g., natural disaster or crop failure) and become hired labourers for the rich or have to work in the service sectors in town. The household income was relatively low in R-MF farms. However, this farming system had a high percentage of moderately wealthy households (78% of all households). A correlation analysis between farm gross margins and ecological sustainability indicators showed that most correlations were of a low value. The Recycling index showed the highest positive correlation with farm gross margins (r=0.45). This indicates that increased farm integration could contribute to increased farm gross margins.

### *6.2.5 Future applications*

ECOPATH models might be applied routinely if default values for parameters (such as PB and QB ratios) and for the N content of boxes could be used without measuring them in the field. This would make the models less accurate but would facilitate routine estimation of farm models and allow easier comparison of farming systems. In future, ECOPATH could also be applied to evaluate agro-ecological attributes at regional level to assess the environmental behaviour of farming in an eco-system context. When assessing long term impacts, the potential biomass changes of the different groups/stocks should be considered.

For future application of Nutmon-Asia in IAA farms a link should be made between the nutrient budgets, available nutrients in soil organic matter, and total nutrient stocks to improve the interpretation of the nutrient balances. Existing knowledge of soil mineralisation should be incorporated. Improvement of loss estimates can be achieved by the development of more sophisticated transfer functions and better estimates of feed consumption and manure excretion by livestock (Van den Bosch *et al*., 1998). The results in this study showed that total losses of nitrogen from leaching and gaseous losses were as high as 63% of applied inorganic nitrogen fertilizers (Chapter 4). This surplus is an important contribution to the environmental impacts. There were no on-farm experimental data available to validate this estimate. Fish pond nutrient balances need to be estimated in much more detail than is possible at this moment in Nutmon-Asia. This requires estimates of the size of fish populations (birth, death, sales, and transfer). The hard-to-quantify flows are important in contributing to the full nutrient balances of each unit or at the farm level. Those flows should be area specific (FAO, 2003).

In LCA more impact categories, downstream processes (including product processing and transport), uncertainty analyses, and validation of potential LCA impacts with measured data could be included. The LCA results can be used as a first step towards documentation of environmental labelling of farm products in the MD. This requires further harmonization of the LCA methodology (De Vries and de Boer, 2010).

The application of the three approaches in future will depend on specific objectives in evaluation of sustainability of farming systems. Suggestion for use of integrated models to evaluate impacts of IAA farming activities on ecological sustainability can be as follows:

- evaluation of changes in land use, and livestock and fish production in terms of natural resource flows, diversity, integration, maturity, nutrient use efficiencies, and soil fertility (e.g., management of crop residues and manure): ECOPATH and Nutmon-Asia
- evaluation of changes in land use, and livestock and fish production on soil fertility, and resource use and emissions: Nutmon-Asia and LCA
- impact assessment of low-cost local technologies in terms of nutrient use efficiencies, system attributes, resource use, and emissions: ECOPATH, Nutmon-Asia and LCA.

## 6.3 Farmer awareness of sustainable development in IAA systems

In order to get feedback from the IAA farmers on their opinion about sustainability of their farming practices, a participatory community appraisal (Pretty and Hine, 1999) was used to collect general information on ecological (land use, nutrient use, environmental pollution, and intensified farming), economic (household income, farm capital, off-farm income, credit, and market demand), and social (household members, education of children, family labor, urbanization, extension services, and health care) issues related to IAA farming. Thirty-six R-HF, 32 R-MF, and 33 O-LF farmers were asked to score (using beans) their considerations on ecological, economic, and social issues. Table 6.3 presents the awareness of the farmers in the three farming systems separately for Ecology, Economy and Society. In reality, farmers scored societal issues more often (42%) than economic (31%) and ecological issues (27%).

Land use (27%), nutrient balances (27%), and environmental pollution (28%) were the main ecological issues. Farmers expected to get involved in more farm components to deal with market fluctuations, and they wanted to have a larger farm area. This underlines the trend for diversification (Ruben, 2007). Farmers understood the concept of a farm nutrient balance. They thought that appropriate nutrient use can help them to get higher farm yields, but nutrient use efficiency was ignored. The environmental impact from the relatively high use of inorganic fertilizers (Chapter 4) did not worry the farmers. The basis of farming systems in the MD is stable crop production for consumption and food security (Berg, 2002). Farmers did worry about use of agro-chemicals and wastes from animal production (manure), which can cause polluted water. Intensification of farming was considered a less important topic (18%).

**Table 6.3** Awareness of farmers (%) in R-HF, R-MF, and O-LF on sustainability issues

| Issue | R-HF | R-MF | O-LF |
|---|---|---|---|
| **Ecology** | | | |
| Land use | 24 | 31 | 27 |
| Nutrient balance | 31 | 27 | 22 |
| Environment pollution | 29 | 33 | 22 |
| Farm intensification | 16 | 20 | 19 |
| **Economy** | | | |
| Household income | 30 | 29 | 35 |
| Farm capital | 19 | 22 | 17 |
| Off-farm income | 10 | 10 | 4 |
| Credit | 14 | 8 | 10 |
| Market demand | 28 | 31 | 34 |
| **Society** | | | |
| Household member | 9 | 13 | 11 |
| Education of children | 30 | 24 | 29 |
| Family labor | 14 | 17 | 16 |
| Urbanization | 7 | 11 | 6 |
| Extension services | 19 | 18 | 20 |
| Health care | 21 | 18 | 19 |

R-HF: rice-based and high input fish system; R-MF: rice-based and medium input fish system; O-LF: orchard-based and low input fish system

Household income (32%), market demand (31%), and farm capital (19%) were the main economic issues. Because of large household sizes the farmers need money for food, investments in education for their children, and participation in community and family festivities and ceremonies (e.g., religious festivals, ancestor memory ceremony). The capital needed for investments in farming relates to land use. The farmers did not regard off-farm income (8%) and credit (11%) important, because off-farm income depends on time available and off-farm opportunities, and farmers do not want to impose debts on their family.

Education of their children (28%), extension services (19%), health care (19%), and labour use (15%) were the main social issues. Farmers did not want their children to become farmers, as farming is thought to be related to a poor living. From investment in education they expected a good job opportunity for their children in the city. Extension services were regarded important to improve their farming skills, in particular in fertilizer application techniques, pest control, and improvement of fish culture. Health care was mentioned with regard to use of agro-chemicals, and facilities for health care in case of accidents. Family labour use in farming was less often mentioned due to their large family sizes. Farmers paid less attention to household size (11%), because they expected that a large family can supply more labour for farming. Also urbanization (8%) was not mentioned much, in particular not in remote areas.

Figure 6.1 gives relative values of gross returns (average values for the two years) (Chapter 2), Actual efficiency, N full balance, GWP per kcal (Chapters 3, 4, and 5), and opinions of the farmers on important ecological sustainability issues. The results show that O-LF farmers were less concerned about nutrient balances and environmental

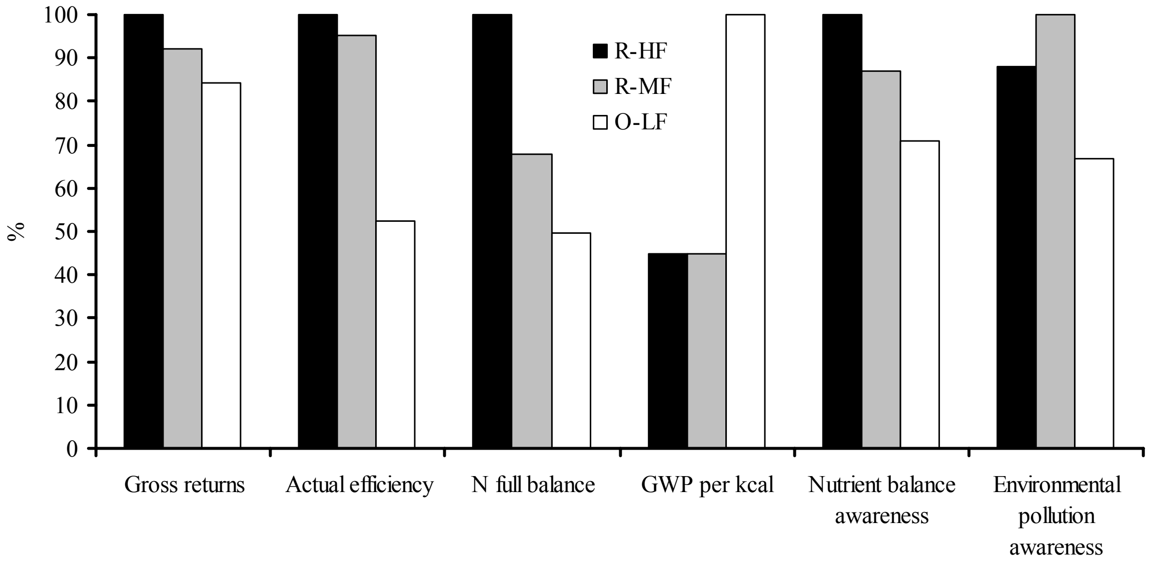

**Figure 6.1** Relation between gross returns and ecological parameters and farmer awareness in the three input fish systems. The highest value for one system is 100% and the other two systems are expressed as percentage of the highest value

pollution than farmers in the two rice-based systems, which corresponded with the lower values for actual efficiency and N full balance in O-LF. The relatively low positive N full balance in O-LF resulted from its high gaseous and leaching N losses, resulting in the highest GWP per kcal farm product in this system. The gross returns were also relatively lower in O-LF compared with the other systems. So, there is some indication that O-LF farmers are less aware of environmental issues and that their farming practices score less on some of the ecological sustainability indicators, compared to R-HF and R-MF farms.

## 6.4 Prospects for sustainable development of IAA systems

In the IAA farms, rice fields and orchards are likely to always be present on the farms with a high land use intensity. Farming these crops requires high inputs of inorganic fertilizers (Chapter 4). This causes high environmental impacts (Chapter 5). Pigs are considered as a savings account for a household. In recent years there has been a change-over from local pigs to hybrids. Hybrids need relatively large amounts of concentrates. Intensification of fish production also requires external feed input. The intensification of farming activities based on increased use of external inputs led to nutrient surpluses (Chapter 4), eutrophication, acidification and greenhouse gas emissions (Chapter 5). A question is to what extent can farmers increase farm yield by using low-cost and locally available technologies and inputs? And what impacts do such methods have on the environment? To answer these questions, a variety of farming practices can be considered, such as enhancing farm diversity and integration, integrated nutrient management, and better integration of aquaculture in farms.

### *6.4.1 Farm diversity and integration*

Holling (1995) stated that mixed farming systems have a high potential to absorb shocks from the natural and economic environment. This is a sustainability issue of major importance. The recurrent outbreaks of AI, which started in 2003 can be considered as a test-case for the resilience of IAA farming through farm diversity and integration. In Vietnam, 65% of all poultry are kept at smallholder farms (Rushton *et al.*, 2004). Backyard poultry production seems inherently more risky with regard to AI outbreaks than other forms of poultry production. In the IAA farms healthy ducks could be a reservoir for the AI virus especially in regions with paddy land and with a dense network of rivers and canals (Bong, 2005). In the MD, during the first outbreak one-third of the poultry were killed. This first outbreak took place in 2003, in between our surveys of 2002 and 2004 (Chapter 2). The surveys were complemented with an inventory of practices and perceptions of farmers with regard to AI (Phong *et al.*, 2007; 2008). In December 2005, a semi-structured questionnaire was used in a sub-sample of 55 of the 90 surveyed farms keeping or having kept poultry, to identify changes in IAA farms due to the AI outbreak.

These outbreaks caused a considerable decrease in demand and prices for poultry products, whereas the demand and prices for pork and fish increased. Close to half (49%) of the farmers said that they had concentrated more on pigs. Also specialization in fish (33%), fruit trees (16%) and rice production (12%) were mentioned frequently. Two farms had started commercial poultry production with 4000 and 1300 chickens in 2004. They hoped to benefit from the collapse of industrial chicken production in the MD. However, a second outbreak of AI at the end of 2004 caused huge losses on these farms.

The AI outbreaks did have also an impact on social issues. People had become afraid to consume poultry products. Almost all farmers in the sub-sample survey from 2005 said that it was very difficult to sell poultry products. In 2004, most difficult to sell were poultry meat and live poultry, while the market of eggs was slightly better. In 2005, all poultry products were difficult to sell. Most (73%) farmers had become afraid of keeping poultry. They did not eat poultry anymore. Poultry was no longer an appropriate gift or dish for guests. At parties poultry products were replaced by pork and fish. Some farmers said that they were scared to visit farmers in their neighbourhoods with a lot of poultry. Close to 80% expressed a higher awareness of animal health, although they had not really changed their farming activities.

Fourteen of the 18 farmers, who stopped keeping poultry between 2002 and 2004, started again in 2005. In 2005, a vaccination program was carried out. Other motives for resuming poultry production were the hope for a better market in future, the annual festivals, Tet (Vietnamese New Year), and the thought that own poultry are safer to consume than poultry from the market.

Between 2002 and 2004, household characteristics and land areas in the three study areas remained fairly similar but internal changes affected the farm economy (Chapter 2). The farm gross margins were not significantly different between 2002 and 2004, although they had increased 38% in 2004. Poultry contributed little to the gross margins (Chapter 2). In 2004, the returns for poultry were even negative resulting from the AI outbreaks in 2003 and 2004. The decreased income from poultry was compensated by an increased income from other farm sub-systems. So, the AI outbreaks have not really affected the gross margins, however the gross margins composition and farm management changed. Thus, the farmers were able to respond very quickly to the changes in market demand for animal protein. This shows the resilience of IAA farms. The AI outbreaks, however, very much affected farmers that had solely specialized in poultry production. In 2009, AI is still present, scattered in small farms. The local government controls AI by destroying diseased poultry, banning transportation and marketing of diseased poultry, and vaccinations. In cities, free-AI disease poultry is available with permits of veterinary authorities (stamping poultry meat). In rural areas, people eat poultry and serve poultry again at social occasions. This AI example shows that IAA farms profit from their diversity (Chapter 3) and flexibility during unstable market situations.

Future integration of animals in farming systems will depend on availability of sufficient feed. This is easier in rice-based farming systems. In the orchard-based system, less by-products are available for integrating animal components. Therefore, animal production in this system will rely mainly on external inputs. It is expected that the resilience characteristics of integrated farming will be better maintained in the two rice-based systems than in the orchard-based system.

### *6.4.2 Integrated nutrient management (INM)*

The R-MF farms were the most integrated (Chapter 2) and diverse (Chapter 3). The N from internal flows was also higher in R-MF (301 kg N $ha^{-1}$) compared to R-HF (239 kg N $ha^{-1}$) and O-LF (182 kg N $ha^{-1}$) farms, but their total external N input was lower (209 kg N $ha^{-1}$) than in R-HF (239 kg N $ha^{-1}$) and O-LF (240 kg N $ha^{-1}$) farms. R-HF was characterised by intensive rice and fish production and O-LF by intensive fruit production. It seems that intensification, based on external inputs, tends to decrease farm diversity and integration.

Examples of integrated nutrient management are the use of crop by-products for feeding animals, feeding pig manure to fish and using mud from fish ponds to capture nutrients, that can be used in orchards and vegetable fields. IAA farmers mainly use inorganic fertilizers for their crops because of quick effects and cheap supply. In the IAA farms applied N-fertilizer for crops accounted for 63% of the total N used for crops. The high amount of inorganic fertilizers caused high nutrient losses into the environment (Chapters 4 and 5). Added to this, in the IAA farms rice straw was commonly burnt instead of used as a cover on orchard beds. As long as agriculture remains a land-based activity, major increases in productivity are unlikely to be attained without ensuring an adequate and balanced supply of nutrients. Reduced nutrient losses and better mutual contribution of nutrients between farm components can be achieved by an INM approach (Peter *et al.*, 2000). INM seeks to balance the need to fix nutrients within farm systems with the need to apply a mix of inorganic and organic sources of nutrients. Also, reduction of nutrient losses into the environment can be attained by periodical demand assessment and timing of the nutrient supply. For avoiding contamination of soil and water from nutrient losses on-farm nutrient cycling through livestock integration should be exploited. Manure offers scope for multiple use: to fertilize fruit trees and vegetables, to feed fish, and to improve soil quality and fertility.

### *6.4.3 Aquaculture integration*

The MD is an agro-ecological region amply using irrigation. Excavated ponds are the source of water supply for many farm activities. Incorporating fish or shrimp into farms, such as in irrigated rice fields and fish ponds, leads to increased protein consumption for the household and can improve farm income (Pretty *et al*., 2006). Integrating fish ponds in IAA farms also helps to increase awareness of farmers in limiting pesticide use.

Another benefit of integrating aquaculture in farming could be an improvement in nutrient use efficiency (Chapter 3). In the IAA farms nitrogen is added to the fish ponds through pig manure, incoming water, dry and wet atmospheric deposition, and biological N fixation (Chapter 3). Only 25% of N applied as a pond input is assimilated in fish (Edwards, 1993). Improved mechanisms of re-using nutrients trapped from fish ponds are therefore important (Muendo, 2006). At present, the high levels of water exchange in fish ponds lead to local pollution (Little *et al*., 2005; Nhan *et al*., 2006). Annual agricultural activities in the MD drain about 457 million $m^3$ of waste mud to rivers, in which more than 2 million tons are from aquaculture activities (Don, 2008). Nutrient-rich pond water can go directly to adjacent rice fields to supply nutrients in a rice-fish sub-system before draining away to rivers. Appropriate changes in management such as reducing water exchange rates to prevent nutrient losses, and adapting pruning of fruit trees to limit shading of fish ponds, can be suggested as promising improvements (Nhan, 2007).

Intensive aquaculture with high-value fish species is expected to become more popular in the two rice-based systems to meet the demand of high-income consumers. In the two rice-based systems large fish ponds can be created for intensified aquaculture. The rice fields can be turned into fish ponds as the frequency and severity of flooding increases. The use of external feeds will increase. This de-coupling of aquaculture from the rest of the farm will give an increased risk for environmental contamination. Enlarging ditches in the orchard-based system to increase fish density will not be easy because fruit trees will remain the main farm component. In the orchard-based farming system, extensive aquaculture will continue, and use of crop residues, livestock manure, and household food wastes to feed the fish will stay common practice.

### *6.4.4 Predicted changes in farming systems*

The use of triple rice, with its dependency on inorganic fertilizers, agro-chemicals and energy, will remain the major farm activity in the two rice-based systems. Reducing inorganic fertilizer inputs with nutrient-scavenging cover crops can increase productivity and reduce adverse environmental impacts of crop production. In addition, upland crops in rotation with rice can be considered as option to reduce $CH_4$ emission especially in triple rice fields in the MD.

Total food demand and market demand for high-value meat and crops in the MD will increase at a fast rate due to population growth, rising incomes, and changing diet preferences with urbanization. High yields and quality will be demanded. This will require modernization of agriculture in rural areas (VietNamNet Bridge, 2009). This might benefit large-scale farms and result in land accumulation by rich farmers. Chapter 2 showed that well-off farmers with good farming skills and enough capital tended to intensify their farming systems, while the poorer farmers tended to move towards diversification, in order to safeguard their living and avoid risks.

New challenges are predicted, including climate change and sea level rise which might increase water shortages in the dry season, and cause increased flooding in the wet season and saline intrusion in the dry season (ADPC, 2003).

The changing environment is likely to intensify the challenges that people in the MD are facing, in particular, the most vulnerable farmers whose livelihoods depend heavily on natural resources. Research, development and extension services should pay attention to strategies for increasing resilience of IAA systems in the MD, by focusing on reducing external farm inputs and improving farm nutrient management, selecting crop varieties and animals for high yield and quality, and tolerance to the environmental changes (e.g., sea level rise, flooding).

In the MD the demands for animal proteins will increase as in the rest of Asia. The LCA results suggest that stimulation of aquaculture seems more appropriate than stimulation of pig and poultry production, seeing that the environmental impacts per kg protein for fish were lower than for pigs and poultry (Chapter 5).

## 6.5 Conclusions

- Over the past 30 years, integrated agriculture-aquaculture (IAA) systems have been dynamic, following a trend from specialization (monoculture of rice ) to diversification and intensification. The main forces driving changes in these systems were Vietnam's economic liberalization, introduction of modern rice varieties, increasing market demands, availability of production technologies and natural disasters. Well-off farmers with good farming practices and enough capital tended to intensify their farming practices, while the poorer farmers tended towards diversification to safeguard their livelihoods.
- Rice, fruit, and vegetable production were intensive in terms of land use and use of external inputs, whereas pig and poultry production were far less intensive. Three different types of fish-input systems could be distinguished based on feed inputs, species and fish management. The biggest contributors to farm gross margins were rice, fruits and fish. Household income was relatively low in the rice-based and medium input fish system, however, this system had a high

percentage of moderately wealthy households, which might be related to their more diverse and integrated farming practices.

- Despite the differences in intensity of fish keeping between the three study areas, the fish ponds in the rice-based systems and fish in ditches in the orchard-based system contributed to the same extent to the nutrient supply of other components.
- Variability in ecological sustainability indicators among farms was high, caused by differences in land use, financial and crop disease constraints, market opportunities and family conditions.
- The positive balance of nitrogen, phosphorus and potassium at farm and field level in the three systems originated from high farm nutrient inputs but low nutrient outputs. Inefficient nutrient use was an important problem. Variation in nutrient efficiency among the farming systems resulted primarily from inefficient orchard and rice components on the orchard-based and low fish input farms. Improvements could be achieved by reducing the use of inorganic fertilizer inputs. In general, fertilizer use was the main environmental hotspot in IAA farms.
- The eutrophication impact in IAA farms resulted mainly from leaching of N from excess fertilizer use and from imported feed ingredients for animals. $NH_3$ from N-fertilizer was the main contributor to acidification. Eutrophication potential (EP) and acidification potential (AP) per kcal farm product were higher in the orchard-based and low input fish system than in the two rice-based systems.
- Methane emission from paddy soils contributed importantly to global warming potential (GWP) together with nitrous oxide emitted from applied inorganic fertilizers and the $CO_2$ emitted by the off-farm production of feed ingredients for pigs.
- One kg of fish produced in the low input fish system showed considerably higher environmental impacts than one kg of fish produced in the other two systems, due to the pond management system and small fish yield in the orchard-based and low input fish system. The differences in feed inputs for fish between the two rice-based systems did not result in differences in environmental impacts per kg fish produced between the high and medium input fish components in these systems.
- The average GWP per kg protein from pork and poultry was higher than the impact per kg fish protein. So, fish farming rather than pig and poultry keeping should be promoted to reduce the climate change impact from animal production.
- The Avian Influenza outbreak showed the resilience of IAA farms: farmers responded very quickly to the changes in market demands. The resilience of integrated farming will be better maintained in the two rice-based systems than

in the orchard-based system. Farm intensification can lead to reduced benefits of farm diversity and integration.

- The ECOPATH, Nutmon-Asia and LCA modeling approaches proved complementary in analysing agro-ecological performances, identifying ecological sustainability issues and quantifying sustainability indicators at farm and farming system level. Field experiments are needed to validate some of the ‘hard-to-quantify’ input data. Analyses at regional level and impact assessments of low-cost local technologies could be future research topics.
- Public institutions should work with farmers to improve our understanding of sustainability and its importance in the development of integrated agriculture-aquaculture.

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## Summary

Population growth, urbanization, and income growth in developing countries are forcing a massive increase in demand for food. Modern farming systems need to enhance productivity and profitability for the farmer, yet still preserve the quality of the environmental resources. Therefore, we will need to depend on the best knowledge, technology and farming practices that are, or become, available. Smallholder integrated agriculture-aquaculture (IAA) in the Mekong Delta (MD) is a form of diversified agriculture, in which aquaculture is developed as a component on a farm with existing crops, trees or livestock components or a combination. An output from one component of the IAA system which otherwise might have been wasted becomes an input into another component resulting in the greater efficiency of the production of desired outputs. After Doi Moi (reform) policy (1980s), in the MD of Vietnam, industrialization with foreign investments has taken place as well as modernization of the agriculture, forestry and fisheries sectors. Due to this rapid change, the IAA farming structure supported by traditional culture or customs has been strained and many problems have arisen related to natural resources management and sustainable development of farming. The goal of this study was to evaluate sustainability of IAA farming systems that differ in cropping patterns and degrees of aquaculture intensification by explaining the trends in development and farm attributes of IAA systems; quantifying and evaluating agro-ecological attributes by use of a mass balance approach; analyzing the farm nutrient balances to evaluate farm nutrient use efficiency; and assessing the integral environmental impact of IAA systems in producing different farm products. The research was done on-farm in three freshwater regions of the MD. Three major IAA systems were selected: rice-based and high input fish system (R-HF), rice-based and medium input fish system (R-MF); and orchard-based and low input fish system (O-LF). A participatory community appraisal and two surveys were carried out in 2002 and 2004, involving 90 farms in the three areas, in order to explain the trends in the development and farm attributes of IAA systems. A survey at the end of the study was conducted to evaluate the awareness of farmers on sustainability issues. In 2005, an extra survey was done to analyse the impact of the Avian Influenza (AI) outbreaks on IAA farming. Eleven IAA farms were selected in the three systems for detailed monitoring of inputs, outputs and internal bio-resource flows. The selection was based on a combination of farm characteristics representing IAA farming (e.g., rice, orchards, vegetables, poultry, pigs, and fish) and practical considerations. System analysis was used to analyse changes in farming activities. Three modeling approaches, ECOPATH, Nutmon, and Life Cycle Assessment (LCA), were applied to assess the sustainability of farm development.

Chapter 2 addresses the dynamics of farming activities. Over 30 years the rice-based systems in the MD have developed into IAA systems, following a trend from specialization (or monoculture) with extensive farming towards diversification and intensification. The main forces driving changes in the farming systems were the introduction of modern rice varieties, economic liberalization policy, market demand,

availability of production technologies and natural disasters. The increased rice production contributed importantly to food security in the MD. It also impacted on animal production because extra feed became available. Agro-ecological conditions, level of technology support by public extension services and access to credit accounted for the differences between the three systems. The main attributes of the IAA farms were the diversified farm resources and household economy. Hard-to-change farm characteristics were the land-use intensity of orchard, rice and other cash crops. Easy-to-change farm characteristics were the number of farm components, the land-use intensity of fish pond, on-farm family labour, off-farm and non-farm income and farm inputs. The most important contributors to the farm gross margins were rice, fruits and fish. Off-farm (32%) and non-farm (36%) incomes made an important contribution to total household income. Farm developments that helped to sustain improvements in the household's livelihood were diversification and intensification and changing the land-use intensity of a particular activity. Well-off farmers with good farming skills and enough capital tended to specialize and intensify their farming practices, while the poorer farmers tended towards diversification in order to safeguard their livelihood and avoid risks.

In Chapter 3, a mass balance approach, ECOPATH, was applied to quantify properties related to ecological sustainability of IAA farming. Nineteen agro-ecological attributes in IAA farms were quantified for evaluating farm sustainability, and from these attributes four factors: Productivity-Efficiency; Diversity; Maturity; Aquaculture Integration, were identified. Productivity-Efficiency, which explained 36% of the total variation amongst farms, was most directly related to the sustainability of farms: it was associated with efficiency of nutrient use, high productivity and yields and high utilization of nutrients from orchard and rice soil in farms that had high production relative to their biomass. The rice-based farms (R-HF and R-MF) were more efficient and productive than the orchard-based farms (O-LF) and they recycled nitrogen more intensively. Functional agricultural diversity was highest in the R-MF system. The O-LF system was the least productive and diverse, but its Maturity factor was highest. Improved nutrient use efficiency should be achieved through more rational use of fertilizers and applying traditional farm practices such as recycling of pond soil and re-use of farm wastes. As agro-ecosystems in the MD develop and intensify, sustainability should be safe-guarded by maintaining these beneficial practices rather than by focusing on promoting a specific farming system.

With a trend towards intensified farming, for satisfying and sustaining production of IAA farms from the environmental standpoint, estimating the farm nutrient balance can help assess practices that seek to integrate the use of organic and inorganic fertilizers, livestock and soil water conservation. Chapter 4 presents an adapted Nutmon (Nutmon-Asia) approach for the MD farming conditions, which was used to quantify farm nutrient balances. Estimates of nutrient balances showed surpluses with large variation amongst IAA farms in the three systems, which were explained by the variation in production goals and priorities, and farming practices. The large surpluses of nutrients in the three systems (e.g., 121 kg N $ha^{-1}$ $y^{-1}$ in R-HF, 82 kg N in R-MF, and 60 kg N in O-LF) were a reflection of low nutrient use efficiency. Crop choice, inorganic fertilizer application, internal farm-resources use, livestock holding and cultural practices contributed to the variation in farm nutrient balances. High surpluses of P and K were accounted for in the vegetable fields, while a negative K balance was found in rice fields in all three systems. Surpluses of N in pig production (e.g., 118 kg $y^{-1}$) in R-HF and in poultry (e.g., 29 kg $y^{-1}$) in R-MF and in fish production (e.g., 52 kg $ha^{-1}$ $y^{-1}$) in R-HF, resulted from high feed inputs and the low output of products. In the IAA farms the fish ponds captured nutrients, thereby limiting nutrient losses. However, it is important that the nutrient balances of each cropping sub-system should be improved by avoiding using excess fertilizer. Nutmon-Asia can serve to quantify the nutrient balances of IAA farms. N leaching and gaseous losses in upland soils for fruit trees and vegetables should be further investigated in order to improve the model.

Intensification of IAA farms in the MD not only affects N, P and K imbalances but may impact negatively on the environment through use of external inputs. Chapter 5 addresses the environmental impact of IAA farming systems in the MD. Life cycle assessment (LCA) was used to quantify the integral environmental impact in the whole life cycle of an agricultural product, and to provide insights into ways to mitigate the impact. The results showed that using the kcal as the functional unit (FU) enabled the evaluation of farming systems and identification of hotspots, while the use of the kg of product as the FU enabled the evaluation of impacts for different products and identification of components that contributed most to the overall environmental impact of IAA farms. Total global warming potential (GWP), eutrophication (EP), and acidification (AP) per kcal of farm product were higher in O-LF than in R-HF and R-MF, mainly because the low calorie content of the two main products, fruits and vegetables, and the small fish yield in O-LF. One kg of fish in O-LF showed 28% higher land-use, 36% higher energy use, 46% higher GWP, 60% higher EP, and 52% higher AP than the average kg of fish produced in the other two systems. One kg of fish in O-LF showed 28% higher land-use, 36% higher energy use, 45% higher GWP, 60% higher EP, and 52% higher AP than the average kg of fish produced in the other two systems. Inorganic fertilizer use was a main environmental hotspot on the IAA farms. The hotspot identification per kcal of farm product indicated that on-farm $N_2O$ from inorganic fertilizers was the biggest contributor to GWP. On-farm leaching of $NO_3^-$ was a main contributor to EP, and $NH_3$ was a main contributor to AP. Crop production (rice, fruits, and vegetables) contributed most to total GWP (63%), EP (52%) and AP (64%) which resulted mainly from use of inorganic fertilizers. Pigs were the main contributor to total land use (33%) and energy use (40%). The high impact of pigs was mainly from off-farm processes. The average GWP per kg protein from pork and poultry was higher than the impact per kg fish protein. So, fish farming rather than pig and poultry keeping should be promoted to reduce the climate change impact from animal production.

In Chapter 6, the strengths and weaknesses of the ECOPATH, Nutmon-Asia and LCA modeling approaches were evaluated and a minimum dataset required for their application in IAA systems was proposed. The three approaches proved complementary in analyzing agro-ecological performances, identifying ecological sustainability issues and quantifying sustainability indicators at farm and farming system level. Field experiments are needed to validate some of the 'hard-to-quantify' input data. Analyses at regional level and impact assessments of low-cost local technologies could be future research topics.

Farmers' perceptions about the sustainable development of IAA systems were compared with ecological sustainability issues resulting from the ECOPATH, Nutmon-Asia and LCA analyses. Farmers scored societal issues more often than economic and ecological issues. For social issues the farmers focused mainly on education of children, extension services, health care, and labour use. For economic issues the farmers focused mainly on household income, market demand, and farm capital. Ecological issues such as land-use, nutrient balances, and environmental pollution were emphasized by the farmers. In order to sustainably develop IAA-systems resource-conserving technologies and practices for farm integration and diversity, integrated nutrient management, and aquaculture integration were proposed.

The resilience of IAA farms resulting from farm integration and diversity was tested by outbreaks of Highly Pathogenic Avian Influenza (AI), which started in 2003. The decreased income from poultry was compensated by increased income from the other farm sub-systems. Nearly half of the farmers concentrated more on pigs, while others focused on fish (33%), fruit trees (16%) and rice production (12%). By intensifying their fish and pig sub-systems the farmers were able to respond very quickly to the changes in market demands. Therefore IAA farms profited from their integration and diversity, which contributed to the sustainability of these family farms. It was concluded that the resilience of integrated farming will be better maintained in the two rice-based systems than in the orchard-based system.

Because of the inefficient nutrient use in the IAA farms, an integrated nutrient management approach should balance the nutrient cycle within farms: required are periodic assessments of nutrient demand matched by timely supply. Improved mechanisms of re-using nutrients trapped in fish ponds will be important. Crop rotations (e.g., rice and vegetables) should be considered to reduce emission from paddy soils, and the use of manure from livestock and crop residues to reduce the application of inorganic fertilizers. Keeping fruit trees can help maintaining the biomass for farm diversity and maturity.

Public institutions should work with farmers to improve our understanding of sustainability and its importance in the development of integrated agriculture-aquaculture.

## Tóm lược

Phong, L.T., 2010. Những biến động về tính bền vững của các hệ thống nông nghiệp tích hợp có thủy sản ở đồng bằng sông Cửu Long. Luận văn tiến sĩ, Đại học Wageningen, Hà Lan.

Ở đồng bằng sông Cửu Long, thâm canh và hiện đại hóa sản xuất cây trồng, cá và gia súc gây ra những quan ngại về sử dụng bền vững nguồn tài nguyên thiên nhiên. Mục tiêu tổng quát của nghiên cứu nầy là để hiểu rõ những lực tác động làm thay đổi kỹ thuật canh tác, lượng hóa và đánh giá các thuộc tính sinh thái nông nghiệp, cân bằng dinh dưỡng và đánh giá các tác động môi trường trong các hệ thống nông nghiệp tích hợp có thủy sản (IAA). Ba huyện khác nhau về mô hình cây trồng và mức độ thâm canh cá: hệ thống nuôi cá thâm canh ở vùng canh tác lúa (R-HF) huyện Ô Môn; hệ thống nuôi cá bán thâm canh ở vùng canh tác lúa (R-MF) huyện Tam Bình; hệ thống nuôi cá quảng canh ở vùng thâm canh cây ăn trái (O-LF) huyện Cái Bè được chọn để nghiên cứu. Hai điều tra (năm 2002 và 2004) bao gồm 90 nông hộ được thực hiện để phân tích những lực tác động làm thay đổi các hệ thống IAA. Một điều tra vào cuối giai đoạn nghiên cứu được thực hiện để đánh giá nhận thức của nông dân về các vấn đề bền vững. Một điều tra thêm vào năm 2005 được thực hiện để phân tích tác động của dịch cúm gia cầm (AI) trên nông hộ. Mười một nông hộ trong ba hệ thống được chọn lọc để giám sát chi tiết đầu vào, đầu ra và các dòng tài nguyên sinh học bên trong nông hộ của lúa, cây ăn trái, rau màu, heo, gia cầm và cá trong thời gian 2 năm (2002-2004). Các thuộc tính sinh thái nông nghiệp của các nông hộ được lượng hóa qua việc sử dụng mô hình ECOPATH, các cân bằng dinh dưỡng trong đất được lượng hóa bằng mô hình Nutmon có điều chỉnh (Nutmon-Asia), và đánh giá tác động môi trường của canh tác IAA được thực hiện bằng phương pháp đánh giá vòng đời (LCA) từ lúc bắt đầu canh tác đến khi nông sản vừa ra khỏi nông hộ. Chính sách mở rộng kinh tế, du nhập các giống lúa cao sản, gia tăng nhu cầu thị trường và thiên tai là những lực tác động chính làm thay đổi các hệ thống canh tác IAA. Những nông dân khá giả có kỹ thuật canh tác tốt và đủ vốn có chiều hướng thâm canh trong khi các nông dân nghèo hơn có khuynh hướng về đa dạng canh tác để bảo đảm an toàn cho sinh kế và tránh rủi ro. Mười chín thuộc tính sinh thái nông nghiệp được kết hợp thành bốn nhân tố bền vững: Sản lượng-Hiệu quả, Đa dạng, Trưởng thành và Tích hợp thủy sản. Các hộ canh tác dựa vào lúa (R-HF và R-MF) thì sản xuất hiệu quả hơn những hộ canh tác dựa vào cây ăn trái (O-LF) và có sự tái sử dụng đạm mạnh mẽ trong nông hộ. Nhân tố Sản lượng-Hiệu quả có quan hệ trực tiếp đến sự bền vững nông hộ. Đầu ra cao của nông hộ liên hệ với dinh dưỡng đầu vào có thể nhận được ở nông hộ có đầu vào thấp và cả nông hộ có đầu vào tương đối cao. Tất cả nông hộ trong ba hệ thống đều có sự dư thừa đạm, lân và kali. Sự thiếu hụt kali được tìm thấy trong canh tác lúa ở cả ba hệ thống. Các kết quả của Nutmon-Asia cho thấy nông dân đã bón phân dư thừa. Các cải thiện về cân bằng dinh dưỡng có thể bắt đầu từ sự giảm bớt lượng phân bón sử dụng. Hiệu ứng nhà kính (GWP), phú dưỡng hóa (EP) và chua hóa (AP) trên mỗi kcal của nông sản trong hệ thống O-LF cao hơn các hệ thống R-HF và R-MF chủ yếu là do lượng kcal thấp trong hai loại nông sản chính là trái

cây và rau cải và năng suất cá thấp ở hệ thống O-LF. Mỗi kg cá sản xuất từ các nông hộ thuộc hệ thống O-LF có sử dụng đất, sử dụng năng lượng, GWP, EP và AP cao hơn so với trung bình mỗi kg cá được sản xuất từ hai hệ thống còn lại. Nhìn chung, lúa và heo là hai nguồn đóng góp tác động môi trường chính trong sản xuất thực phẩm ở đồng bằng sông Cửu Long. Dư thừa và không hiệu quả của phân bón và phát thải $CH_4$ từ ruộng lúa đóng góp nhiều nhất vào tác động môi trường trong sản xuất lúa trong khi sử dụng thức ăn từ bên ngoài nông hộ đóng góp tác động nhiều nhất trong việc nuôi heo. Các nông dân IAA được hưởng lợi từ tính linh động và đa dạng canh tác trong giai đoạn dịch cúm gia cầm. Nông dân quan tâm nhiều về những vấn đề bền vững kinh tế và xã hội hơn là sinh thái. Hệ thống O-LF được ghi điểm kém về một số vấn đề bền vững sinh thái và nông dân trong hệ thống O-LF nhận thức kém về những vấn đề nầy. Thâm canh trong kỹ thuật canh tác sẽ tiếp tục. Để tăng sự tái sử dụng dinh dưỡng trong nông hộ cần nhấn mạnh sự duy trì những kỹ thuật canh tác truyền thống bền vững như tái sử dụng chất thải từ gia súc và dư thừa cây trồng trong nông hộ và tích hợp ao cá và sử dụng bùn ao làm phân bón cho cây trồng. Nghiên cứu, phát triển và phục vụ khuyến nông cần chú ý đến chiến lược gia tăng tính linh hoạt của các hệ thống IAA ở đồng bằng sông Cửu Long qua việc chú ý giảm dinh dưỡng đầu vào từ bên ngoài nông hộ và cải thiện việc quản lý dinh dưỡng trong nông hộ. Nhu cầu về đạm động vật sẽ gia tăng ở đồng bằng sông Cửu Long. Khuyến khích nuôi thủy sản có lẽ thích hợp hơn khuyến khích nuôi heo và gia cầm do tác động môi trường trên mỗi kg protein sản xuất của cá thì thấp hơn heo và gia cầm.

## Samenvatting

De intensivering en modernisering van plantaardige en dierlijke productie stelt het duurzaam gebruik van natuurlijke hulpbronnen in de Mekong Delta ter discussie. De doelstellingen van dit onderzoek waren het begrijpen van de sturende krachten achter veranderingen in bedrijfsvoering, en het kwantificeren en evalueren van agro-ecologische eigenschappen, nutriënten balansen en de milieubelasting van geïntegreerde gemengde landbouw systemen met gewassen, vee en vis ("Integrated Agriculture-Aquaculture", IAA bedrijven). Drie districten, welke verschilden in geteelde gewassen en visteelt intensiteit, werden geselecteerd voor dit onderzoek: een op rijst gebaseerd systeem met intensieve visteelt (R-HF) in O Mon district, een op rijst gebaseerd systeem met semi-intensieve visteelt (R-MF) in Tam Binh district, en een op fruit gebaseerd systeem met extensieve visteelt (O-LF) in Cai Be district. Twee veldonderzoeken werden uitgevoerd in 2002 en 2004 bij 90 huishoudens om de sturende krachten achter de veranderingen in de bedrijfsvoering te onderzoeken. Aan het einde van het onderzoek werd nogmaals een veldonderzoek uitgevoerd in de drie districten om te evalueren hoe boeren het belang van verschillende duurzaamheidsaspecten waardeerden. In 2005 werd een veldonderzoek uitgevoerd met als doel het effect van vogelgriep op de levensomstandigheden van boerenhuishoudens te onderzoeken. Op elf van de 90 bedrijven werd een gedetailleerd onderzoek uitgevoerd naar alle binnenkomende en uitgaande stromen en de interne stromen tussen de verschillende componenten, rijst, fruit, groentes, varkens, kippen en vis, gedurende een periode van twee jaar (2002-2004). De agro-ecologische eigenschappen van deze bedrijven werden gekwantificeerd met behulp van ECOPATH modellen. Het Nutmon model werd aangepast voor gebruik in Azië (Nutmon-Asia) en gebruikt voor kwantificeren van nutriënten balansen. Een gedetailleerde levenscyclusanalyse (LCA) werd uitgevoerd om de integrale milieubelasting van de voedselproductie op deze IAA bedrijven te schatten.

De economische liberalisering, introductie van moderne rijstvariëteiten, toenemende vraag naar landbouwproducten en natuurrampen waren de voornaamste sturende krachten achter de veranderingen op IAA bedrijven. Relatief welgestelde boeren gingen eerder over naar intensivering van hun bedrijfsvoering, terwijl de armere boeren eerder overgingen naar diversificering, dit om hun levensomstandigheden te waarborgen en bedrijfsrisico's te vermijden.

De drie modelbenaderingen waren complementair in het formuleren van duurzaamheidsonderwerpen en -indicatoren voor deze onderwerpen voor IAA bedrijven. ECOPATH kwantificeerde 19 agro-ecologische kenmerken, welke met behulp van factor analyse gecombineerd werden in vier duurzaamheids indicatoren: Productiviteit-Efficiëntie, Diversiviteit, Maturiteit en Visteelt Integratie. De op rijst gebaseerde bedrijven (R-HF en R-MF) waren productiever en efficiënter dan de op fruit-gebaseerde bedrijven (O-LF) en het hergebruik van N was groter op de op rijst gebaseerde bedrijven. Productiviteit-Efficientie stond in direct verband met duurzaamheid van de bedrijfsvoering. Een hoge productiviteit kwam zowel voor bij

bedrijven met een hoog gebruik van externe inputs als bij bedrijven met een laag gebruik van externe inputs. Nutriënten balansen zijn ook belangrijke duurzaamheids indicatoren. Alle bedrijven hadden positieve N, P en K balansen. De rijstvelden vertoonden een negatieve K balans. De Nutmon-Asia resultaten gaven aan dat veel bedrijven teveel kunstmest gebruiken. Het verminderen van de kunstmest gift kan een start zijn in de verbetering van de nutriënten balansen. De LCA gaf een beeld van het grondstoffengebruik en de emissies van processen op het bedrijf zowel als noodzakelijke processen buiten het bedrijf. Het broeikas-, vermestings- en verzuringspotentieel per kcal product waren hoger in O-LF dan in R-HF en R-MF, voornamelijk vanwege het lage caloriegehalte van twee hoofdproducten, fruit en groente, en de lage opbrengsten aan vis in O-LF. Eén kg vis geproduceerd op O-LF bedrijven had een aanzienlijk hoger land- en energiegebruik, broeikaspotentieel, vermestingpotentieel, en verzuringpotentieel dan een kg vis geproduceerd in de andere twee systemen. Op een gemiddeld IAA bedrijf leverden de rijstcomponent en de varkens de grootste bijdrage aan de milieubelasting. Overmatig en inefficiënt kunstmestgebruik, en de methaanemissie van de rijstvelden leverden de grootste bijdrage aan de milieudruk van rijst, terwijl de productie van gewassen voor krachtvoer de grootste bijdrage leverde aan de milieudruk van varkens.

De IAA bedrijven profiteerden van hun diversiteit en flexibiliteit tijdens de vogelgriep uitbraken. Boeren in de drie districten waren meer bezorgd over maatschappelijke dan economische en ecologische duurzaamheid. Het O-LF systeem scoorde slechter op een aantal duurzaamheidindicatoren dan R-HF en R-MF, O-LF boeren waren ook minder bewust van het belang van deze indicatoren voor hun bedrijfsvoering en hun levensomstandigheden. Intensivering van de bedrijfsvoering op IAA bedrijven zal zich doorzetten. Voor het sluiten van de nutriëntenkringloop op IAA bedrijven, moet er meer nadruk gelegd worden op traditionele bedrijfsvoeringen, zoals hergebruik van gewasresten en mest, het beter integreren van visvijvers in het bedrijfssysteem en het gebruik van sediment uit de visvijvers als organische mest bron voor gewassen.

Onderzoek, ontwikkeling en voorlichting moeten meer aandacht besteden aan strategieën die de veerkracht van IAA bedrijven verhogen. In de Mekong Delta zal de vraag naar dierlijke eiwitten veder toenemen. Stimuleren van visteelt is hiervoor meer op zijn plaats dan stimuleren van varkens- en kippenhouderij, aangezien de milieubelasting per kg eiwit voor vis lager was dan voor varkens en kippen.

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## Curriculum vitae

Le Thanh Phong was born on May 08, 1956 in Hau Giang Province, Vietnam. He obtained his BSc in Agronomy at Can Tho University in 1979. After graduation till 1996 he worked as a lecturer at the Agronomy Faculty, and now at the College of Agriculture and Applied Biology of Can Tho University. In January 1998, he received his MSc in Crop Production at Wageningen University. At present, he is senior lecturer at the Crop Sciences Department, College of Agriculture and Applied Biology, Can Tho University. In 2002 he started his Sandwich PhD program at Wageningen University.

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## Publications

### Peer-reviewed articles

Bosma, R.H., Phong, L.T., Kaymak, U., Van Den Berg, J., Udo, H.M.J., van Mensvoort, M.E.F., Tri, L.Q., 2006. Assessing and modeling farmers' decision-making on integrating aquaculture into agriculture in the Mekong Delta. NJAS 53, 281-300.

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**Training and Supervision Plan**

Le Thanh Phong

| Description | Year | ECTS[1] |
|---|---|---|
| **The Basic Package** | | |
| - WIAS Introduction Course | 2003 | 1.5 |
| - Course on ethics for social scientists | 2006 | 1.0 |
| **International conferences** | | |
| - AAAP 11th, 30/08-3/09, Malaysia | 2004 | 1.1 |
| - AHAT-BSAS International conference, Thailand | 2005 | 1.1 |
| - INREF-POND International Workshop, Vietnam | 2006 | 1.1 |
| - AAAP 13th, 22/09 - 16/09, Vietnam | 2009 | 1.1 |
| **Seminars and workshops** | | |
| - INREF-POND, 14 April , the Netherlands | 2004 | 0.6 |
| - POND-LIVE workshop, Thailand | 2003 | 0.6 |
| - Farmer workshop, October, Vietnam | 2005 | 0.3 |
| - WIAS Science Day, March, the Netherlands | 2007 | 0.3 |
| **Presentations** | | |
| - Oral presentation, INREF-POND, the Netherlands | 2003 | 1.0 |
| - Oral presentation, POND-LIVE, Thailand | 2003 | 1.0 |
| - Oral presentation, ASP, the Netherlands | 2004 | 1.0 |
| - Oral presentation, INREF-POND Symposium, Vietnam | 2006 | 1.0 |
| **In-Depth Studies** | | |
| - Managing Diversity in Living Systems | 2002 | 1.5 |
| - GIS Applications in Land Resource and Land Use studies, June, Vietnam | 2004 | 1.5 |
| - Analysis of Multivariate Data from Ecology and Environmental Science, Using PRIMER for Windows (v5), March 2006, Vietnam | 2006 | 1.5 |
| - Longitudinal Data and Repeated Measurements | 2006 | 0.6 |
| - Statistics for Life Sciences | 2007 | 1.5 |
| **Professional Skills Support Courses** | | |
| - Written English | 2004 | 1.5 |
| - Project and Time Management | 2006 | 1.5 |
| **Research Skills Training** | | |
| - Preparing PhD research proposal | 2002 | 4.0 |
| - Participatory Community Appraisal training, Thailand | 2002 | 1.5 |
| **Didactic Skills Training** | | |
| - Lecturer General cultivation, Vietnam | 2003-‘06 | 4.0 |
| - Lecturer Fruit tree production, Vietnam | 2003-‘06 | 4.0 |
| - Lecturer Crop ecology, Vietnam | 2003-‘06 | 4.0 |
| - Lecturer Use of SPSS in statistical analysis, Vietnam | 2003-‘06 | 3.0 |
| - Supervising 4 MSc students | 2002-‘03 | 5.0 |
| **Management Skills Training** | | |
| - Organize INREF-POND Symposium, Vietnam | 2006 | 1.0 |
| **Total** | | **48.8** |

[1] One ECTS (European Credit Transfer System) credit equals a study load of 28 hours

## Colophon

The study was funded by Wageningen University, through the INREF-POND (Interdisciplinary Research and Education Fund) project.

Cover design by Phong Le Thanh and Fokje Steenstra. Pictures taken by Phong Le Thanh during field visits:

Front cover:
The large picture shows an IAA farm in the rice-based and medium input fish system. Pig pen connects with fish pond by plastic tubes to supply fish with pig manure. Poultry pen is built on the surface of fish pond also to supply fish with manure, and trees surround the farm house.
Small pictures from left to right show: farmer feeds fish with concentrates, vegetables are grown in beds along rice field, and fruit trees are grown in beds next to ditches where fish are cultured extensively in orchard-based and low input fish system.

Back cover:
The large picture shows intensified Pangasius catfish in rice-based and high input fish system. Pictures on top: fish pond behind house together with coconut and banana, and female farmer uses bean seeds to score sustainability issues in a participatory community appraisal. Pictures at bottom: sow and her piglets in a simple layout pig pen in IAA farm, and ducks in farmyard next to their pen.