Transition of waste management in rural Hanoi: A material flow analysis of nitrogen and phosphorus during 1980-2010

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Abstract

Human and livestock excreta were intensively used as a source of nutrients in crop cultivation in Asia over the years. However, rapid economic growth induced changes in waste management and subsequently in nutrient flow. Recently, chemical fertilizers became a more popular source of nutrients than human and livestock excreta. In northern Vietnam, a large amount of human and livestock excreta have been traditionally applied to paddy fields, but much of them are not used currently and especially a significant amount of the latter is discharged directly into ponds for fish farming. Fish ponds, in this context, may play an important role for waste management and material cycle in the area. This study investigated the historical changes in waste management and clarified the impact of fish ponds on those changes as a case study in an agricultural community in suburban Hanoi, Vietnam. A material flow model of nitrogen and phosphorus was applied to the study area. The results showed that the crop-livestock system that intensively used human and livestock excreta in the area changed between 1980 and 2010, which led to an increase of pollution loads to open water body. In 2010, nitrogen and phosphorus loads to open water body were 1.9- and 3.2-fold higher, respectively, than those in 1980. Nutrients inputs to fish ponds were 41.7 kg-N·ha^{-1} and 9.8 kg-P·ha^{-1} in 2010; these values were 7.2- and 6.2-fold higher than those in 1980, respectively.

Beside, 41% of nitrogen and 82% of phosphorus released to fish ponds still remained in the sediment or discharged unintentionally after a heavy rainfall. As a conclusion, the system was transformed from crop-livestock system into crop-livestock-fish system, and fish ponds has play a role of nutrient sink in the system. The use of pond sediment as a source of nutrients in paddy fields would improve the material cycle.

Keywords: material flow analysis, fish pond, historical changes, nitrogen, phosphorus.

1. Introduction

Human and livestock excreta was widely used as a source of nutrients in crop cultivation in Asia over the years, and the system that involved the intensive use of human and livestock excreta as a source of nutrients in crop cultivation was called crop-livestock system (Berg, 2002; Devendra and Thomas, 2002; Edwards *et al.*, 1990). However, rapid economic growth induced changes in waste management and subsequently in nutrient flow. In northern Vietnam, chemical fertilizers recently became more popular than human and livestock excreta as a source of nutrients. While human excreta are currently preferred to be treated in septic tanks, a large amount of livestock excreta is released into fish ponds for fish farming although a significant amount of them are still used for agriculture. Crop-livestock system is likely to be replaced by crop-livestock-fish system.

Since farming activities changed and likely affected material balance, it is required to understand the transitions of waste management manners and clarify the impact of fish ponds on those transitions from the aspect of pollution control and nutrient management. Recently, several studies have been conducted using material flow analysis (MFA) that is a systematic tool for quantifying flows and stocks of materials within a well-defined system in space and time (Brunner and Rechbenger, 2004). Yan *et al.* (1999) and Chen *et* *al.* (2008) applied MFA to estimate nutrient budget in agricultural systems and their environmental impact in China. Briggs and Fvnge-Smith (2008) applied MFA to estimate nutrient balance in shrimp ponds in Thailand. Similarly, Montangero *et al.* (2007), Harada *et al.* (2010), and Nga *et al.* (2011) applied MFA to develop nutrient flows and estimate nutrient loads delivered to the environment in northern Vietnam.

Although material balances of farming activities likely changed in many Asian countries, due to the rapid socio-economic development, previous studies focused on current waste and nutrient management and evaluated their impact on environmental pollution at a specific time. Little is known about the role of fish ponds in a system along with the historical changes in waste management, and subsequently in nutrients flow. The objective of this study was to understand the historical changes in waste management from 1980 to 2010 and the impact of fishponds on the nutrient management and water pollution by a material flow model of nitrogen (N) and phosphorus (P).

2. Materials and methods

2.1 Study area

The study area was Trai hamlet, Phu Xuyen district, which is 40km south of central Hanoi, the capital of Vietnam and extends approximately 1 km along the bank of the Nhue River (**Figure 1**). This hamlet is located at a typical suburban agricultural district, where farming is the main occupation of locals and rice is the dominant crop. Paddy fields, which did not change in area from 1980 to 2010, cover more than 90% of the total area. Nhue river is a main irrigation source for paddy fields in the area. Some general information on Trai hamlet is summarized in **Table 1**.

(**Figure 1** Map of Hanoi and Trai hamlet)

(**Table 1** General information in the study area)

Recently, rapid socio-economic development and modernization in this area led to changes in farming systems. Along with crop cultivation and small-scale livestock breeding, fish farming has been practiced in many households. The hamlet has 21 ponds, which were originally excavated prior to 1980 to obtain soil materials to construct dikes (Local socio-economic report, 2010). The area of the ponds has not changed from 1980 to 2010 and out of 21, 18 ponds are currently utilized for fish cultivation. At the beginning of fish farming season, water from irrigation channel is used to fill up the ponds before adding new fish stock. Livestock excreta are these days commonly discharged to these ponds along with commercial fish feed. When fish are harvested, pond water flows back into the irrigation channels and ends up to the Nhue River. After fish harvesting, a new fish-farming season starts.

2.2 Material flow model

A material flow model for N and P was developed based on Harada *et al.* (2010) and applied to the study area for nutrients balance flows from 1980 to 2010. Conceptual framework of the model was illustrated in **Figure 2**. The model is composed by eight components (X_j), of which household (X_1) including two sub-components: septic tanks and biogas systems, livestock (pigs, poultry, and cattle) (X_2), fish pond (X_3), and paddy field (X_4) are within the boundary, while market (X_5), open water bodies including Nhue river and drainage systems (X_6), soil/ground water (X_7), and atmosphere (X_8) are out of the boundary. The arrows represent for the flows/reaction processes of relevant goods such as human excreta, livestock excreta, chemical fertilizers, etc. transferred from one component to other components. Within the system, the net reaction rate of a single component may be affected by a number of different input or output processes. Based on the principle of Mass Conservation Law, the net reaction rate for a component inside the boundary is considered to be the mass balance:

$$\sum_1^n I_i = \sum_1^m O_j \qquad \text{(Eq.1)}$$

Most of flows can be calculated by unit value method:

$$I_i = \sum(U_k \times C_k \times R_k) \qquad \text{(Eq.2)}$$

$$O_j = \sum(U_l \times C_l \times R_l) \qquad \text{(Eq.3)}$$

where I_i : an input flow of a component (g/ha/year)

O_j: an output flow of a component (g/ha/year)

U_k, U_l: composition of good *k*, *l* (g/unit amount/year)

C_k, C_l : amount of good *k*, *l* (amount)

R_k, R_l : ratio of good *k*, *l* transferred from a component to another component.

n, *m* : total number of input and output flows of a component

The flow which could not be calculated by unit value method was calculated based on mass conservation law:

$$I_i = \sum_1^m O_j - \left(\sum_1^{i-1} I_i + \sum_{i+1}^n I_i\right) \qquad \text{(Eq.4)}$$

Thus, the details description of each reaction process of the material flow model is shown in **Table 2**.

(**Figure 2** A flow model in the study)

(**Table 2** Description of reaction processes of the material flow more via matrix expression)

2.3 Data collection

2.3.1 Characterization of fish ponds

All the 18 fish ponds owners were interviewed on daily activities and management practices, including the intensity of excreta use and the frequency of water exchange. Each interviewee was asked to describe the current (in 2010) and past activities around 1980, 1990 and 2000, and the answers were used as data in 2010, 1980, 1990 and 2000, respectively. Also, all the fish ponds were surveyed from October to November 2012 to identify the pond shape, depth, area, and water quality. Pond shape was marked using on-site Global Positioning System (GPS) plotting and then pond area was calculated using a Geographical Information System (GIS). Pond depth was measured by a flow rate meter (AEM213-D, JFE Advantech Co., Ltd) at the central point of the pond, in cases that it was accessible by boat. The depth of 11 ponds was measured, while for the other seven ponds information on the depth was collected from the interviewees due to the difficulties in accessibility. Water samples were collected from all ponds (n=18) and irrigation canals (n=1) to measure the total nitrogen and total phosphorus concentrations using Hach DR 2800 and DRB 200 (Hach Ltd).

2.3.2 Secondary data

Secondary data that used in this study are presented in **Table 3**. Some of data were only available at a single year. Among these, greywater and kitchen waste composition had a larger possibility of the significant change but the impact of these composition change on the whole material balance was limited according to the sensitivity analysis of the model. Therefore, we assumed that data of waste composition did not change from 1980 to 2010. For the N and P concentration in the Nhue River water quality, although N and P concentration data in 2010 were available, the available oldest data were those in 2007 by VEA (2012). Since the socio-economic growth in the area has been accelerated from the middle of 2000s, we assumed that the concentrations had not changed significantly from 1980 to 2007; and the concentration data in 2007 were used as those in 1980, 1990 and 2000, as the impact of N and P concentrations in 2007 was limited on the flows.

(**Table 3** Secondary data used in the material flow model)

3 Results and Discussion

3.1 Characteristics of fish ponds and harvesting manner

The study area included 18 fish ponds and their characteristics are presented in **Table 4**. Fish ponds regularly received greywater, kitchen waste, human excreta, livestock excreta, and commercial fish feed. When fish were harvested, pond water was pumped out to the irrigation channels. The frequency of fish harvesting ranged from zero to three times per year. However, in 1980, fish were harvested without water removal, probably due to the small scale of fish farming, and as a result, no water exchange occurred.

(**Table 4** Characteristics of fish ponds in the study area)

3.2 Historical changes in nutrients flow

N and P flows in the study area are illustrated in **Figure 3** and **4**. The dominant input to the system was chemical fertilizer from market both with N and P flow in 1980 and 2010; dominant output from the system was paddy field runoff to open water bodies with N and soil accumulation and discharge with P both in 1980 and 2010. It was indicated that paddy fields, which cover more than 90% of the total area, played a major role in nutrient flow in the study area. Additionally, fish ponds covering only 6% of the total area had the highest contribution of P load to open water bodies.

(**Figure 3** Flow of nitrogen in 1980 (left) and 2010 (right) (kg·ha^{-1}·year^{-1}). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff; Em: Emission.)

(**Figure 4** Flow of phosphorus in 1980 (left) and 2010 (right) (kg·ha^{-1}·year^{-1}). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff.)

The biggest differences between N and P flows in 1980 and those in 2010 were the appearance of septic tanks and biogas systems in 2010, leading to the changes of compost and manure recycling manners. As a custom in Vietnam, the application of compost to paddy fields has a long history. In 1980, 97% of total N and P from human excreta (25.8 kg-N·ha^{-1}·year^{-1} and 3.8 kg-N·ha^{-1}·year^{-1}) were applied to paddy fields. Those ratios were decreased to 50% in case of N and 49% in case of P in 2010. Instead of being used to intensively apply to paddy fields, human excreta were flowed to septic tanks or fish ponds. From the effects of modernization, 44% of households changed their traditional dry chamber toilets to flush toilets connected to septic tanks in 2010. Similar to compost, the recycling practices of manure have also changed remarkably. Although the amount of manure increase since the government has a policy of livestock production increase (ACI, 2002), the ratio of N and P derived-manure apply to paddy fields decreased from 54 and 80% in 1980 to 30 and 42% in 2010. Instead, those to biogas systems or fish ponds were increased because biogas promotion program were implemented in 2006 in the study area (Dung *et al.*, 2009) and fishing activities became more popular in many households in 2010. Indeed, under the modernization process, the farming system has changed from crop-livestock system to crop-livestock-fish one and fish ponds seemed to become more important in waste and nutrient management in the study area.

As shown in **Figure 5**, the differences in N and P loads to open water bodies were significant between 1980 and 2010. Total N and P load to open water bodies increased by 2.1- and 4.0-fold, respectively between 1980 and 2010. In addition, N load derived from the paddy fields accounted for a large proportion of the total N load; 131.3 kg-N·ha^{-1}·year^{-1} in 2010, which was 1.8-fold higher than that in 1980. In contrast, fish ponds were the main contributor of P, which accounted for 59% of total P load to open water bodies. In 2010, P load from fish ponds to open water bodies was 6.2-fold higher than that in 1980.

(**Figure 5** Nutrient inputs to open water bodies)

Thus, significant differences were observed between N and P balances. The differences can be partly explained by the higher runoff ratio of N to surface water and the larger proportion of P that is accumulated in the sediment. (Carpenter *et al.*, 1998). The increase in N load from the paddy fields was probably a result of the excessive application of N. As shown in **Figure 3** and **4**, chemical fertilizers was already a major source of nutrients than human and livestock excreta even in 1980. N input from chemical fertilizers in paddy fields was 174.3 kg·ha^{-1} in 2010, which was 1.3-fold higher than that in 1980, and also exceeded the optimum levels (100-140 kg N·ha^{-1}·year^{-1}; Huan *et al.*, 2000).

The dramatic increase in P load to open water bodies could be explained by the increase in livestock excreta discharged into the fish ponds. **Figure 6** shows the historical changes of P load derived from livestock excreta from 1980 to 2010. Based on the national policy on the increase of livestock production (ACI, 2002), livestock number in the study area greatly increased in 2000 as presented in **Table 1**. Corresponding to this increase, P load from livestock excreta in 2000 was 2.9-fold higher than that in 1980. A slight decrease from 2000 to 2010 can be explained by poultry influenza H5N1 and pig diseases by porcine reproductive and respiratory syndrome virus. Practices of livestock excreta use for paddy field also changed significantly. The ratio of P flowed from livestock to paddy fields decreased from 80% in 1980 to 42% in 2010; in contrast, the load to fish ponds and biogas system greatly increased. P input of livestock excreta to fish ponds in 2010 was 30-fold higher than that in 1980. In 2010, livestock excreta were contributed 3.9 kg $P \cdot ha^{-1}$ to fish ponds, which accounted for 40% of the total P load into fish ponds.

Figure 6 Phosphorus (P) load derived from livestock excreta

Biogas promotion program in the Vietnam Livestock Sector, especially for pigs, was implemented in 2003 for suburban and rural areas, aiming to increase farm income and reduce environmental pollution (Dung *et al.*, 2009). This program was introduced to the study area in 2006, resulted in significant increase of the load from livestock to biogas system. However, in 2010, only 16% of households breeding pigs had a biogas system to treat livestock excreta, and 53% of households discharged pig excreta into fish ponds. According to Vu *et al.*, (2010), some fish farmers in northern Vietnam breed pigs mainly to obtain excreta for their fish ponds because they believe that livestock excreta help fish to grow faster than other feed. Thus, fish ponds likely received more P from livestock excreta.

3.3 Historical changes in nutrient balance of fish ponds

Differences in the nutrient balance of the fish ponds between 1980 and 2010 are presented in **Table 5**. In 2010, the total nutrient input to fish ponds was 41.7 kg $N \cdot ha^{-1} \cdot year^{-1}$ and 9.8 kg $P \cdot ha^{-1} \cdot year^{-1}$, which was 7.2- and 6.2-fold higher, respectively, than those in 1980. In 1980, when nutrient from household and livestock were intensively applied to paddy fields (**Figure 3**, **4** and **6**), nutrient inputs to fish ponds were mainly from commercial fish feeds. In 2010, livestock excreta became a source of feed for fish ponds together with commercial feed and accounted for 41% of the N and 40% of the P inputs. Although livestock excreta became the main source of nutrients for fish ponds, the nutrients derived from commercial fish feed increased rapidly too and was 4.0- and 4.3-fold higher for N and P, respectively, in 2010 than in 1980. Nutrients in fish production were 8.5 kg $N \cdot ha^{-1}$ and 1.3 kg $P \cdot ha^{-1}$ in 2010, which accounted only for 20% and 13% of the N and P inputs, respectively. The results of this study were in accordance with those reported by Briggs and Fvnge-Smith (2008), who reported that only 24% of nitrogen and 13% of phosphorus inputs were incorporated into shrimp harvest. Jackson *et al*. (2002)

also showed that shrimps could use only 22% of N input. The remaining N and P are either accumulated in the sediment or discharged intentionally during the removal of water from the pond and unintentionally after a heavy rainfall.

(**Table 5** Nutrient balances of fish ponds in the study area)

Excessive application of nutrients to fish ponds led to the high accumulation in the sediment. If the sediment is used as a nutrient source in paddy fields, it may have a positive impact on not only nutrient management but also the control of water pollution; however, this practice was not popular in the study area. According to our interview, 61% of fish ponds never practiced sediment removal, 39% did at least once before, and only 11% did regular removal, every two or three years. Removed sediment were mostly used for the construction of dikes in the area. Only one out of 18 pond owners used the sediment as a vegetable fertilizer. Some recent studies investigated the possibility of utilizing the sediment as a crop fertilizer. According to Rahman *et al*. (2004), plants absorbed 62%, 67%, and 64% of available nitrogen, phosphorus and potassium in sediment, respectively. Phu *et al*. (2012) confirmed the possibility to use the sediment from catfish (*Pangasianodon hypothalamus*) ponds for paddy field fertilization. Thus, the use of the sediment to paddy fields could be promoted for establishing better nutrient cycle and reducing water pollution in the area, especially of P, because of its higher accumulation in sediment compared to N.

4 Conclusions

By developing a material flow model of nitrogen and phosphorus, this study showed the historical changes in nutrient flow of the study area and estimated the impact of fish ponds on these temporal changes. Due to modernization, farming systems changed from a crop-livestock system to a crop-livestock-fish system. As a result, traditional waste recycling manners changed and led to changes in material balance in the study area. Nitrogen and phosphorus loads in open water body gradually increased by 1.9- and 3.2-fold, respectively, from 1980 to 2010. In 2010, fish ponds were considered the largest contributor of phosphorus, which accounted for 71% of phosphorus load in open water body. The results show that fishponds play an important role in nutrient cycle within the study area, especially for phosphorus, because of its higher accumulation in the sediment than nitrogen.

Nutrient input into and accumulation in the fish ponds were highly increased from 1980 to 2010. A large amount of nutrients was estimated to remain in the sediment and to be released unintentionally after a heavy rain, accounted for 41% and 82% of total nitrogen and phosphorus inputs in 2010, respectively. If sediments were applied in paddy fields, the application of equivalent amount of chemical fertilizers could be potentially reduced, accounting for 10% for nitrogen and 14% for phosphorus. It would not only improve a material cycle, but also would lead to an improved water quality in the study area, especially for phosphorus, because of its higher accumulation compared to nitrogen. Thus, fish ponds play a key role in material cycle and water pollution control in the area.

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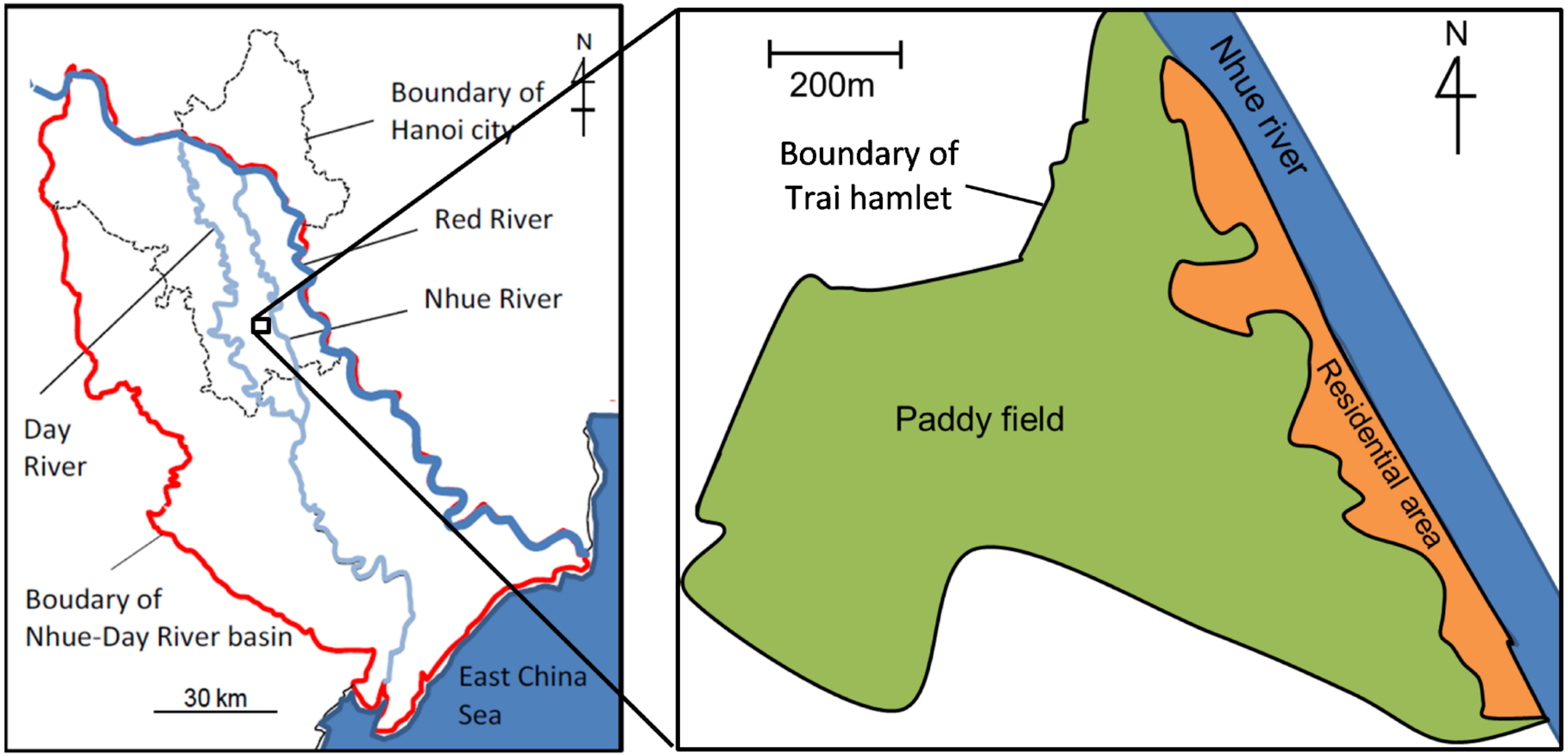

Figure 1 Map of Hanoi and Trai hamlet

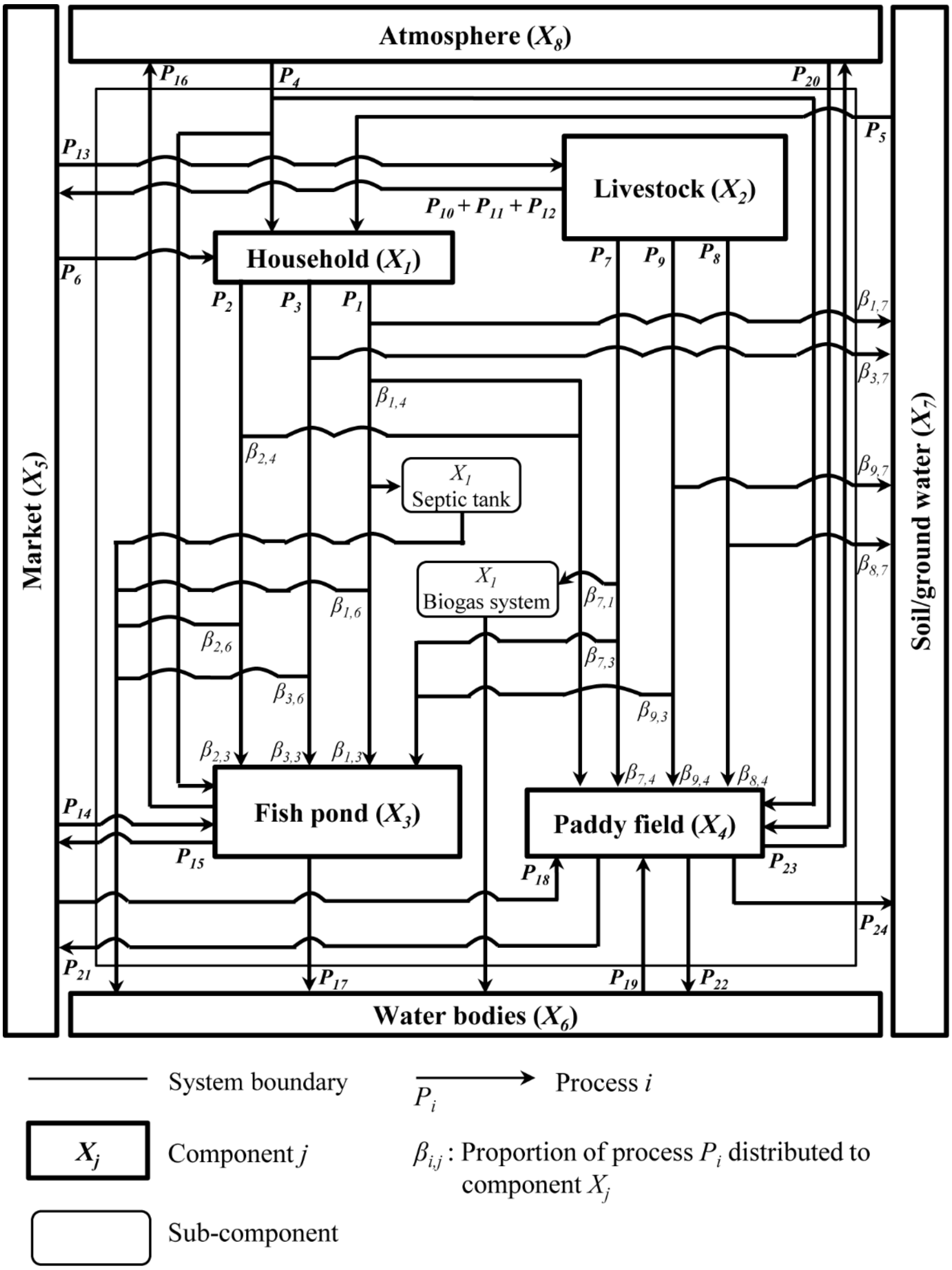

Figure 2 A material flow model in this study

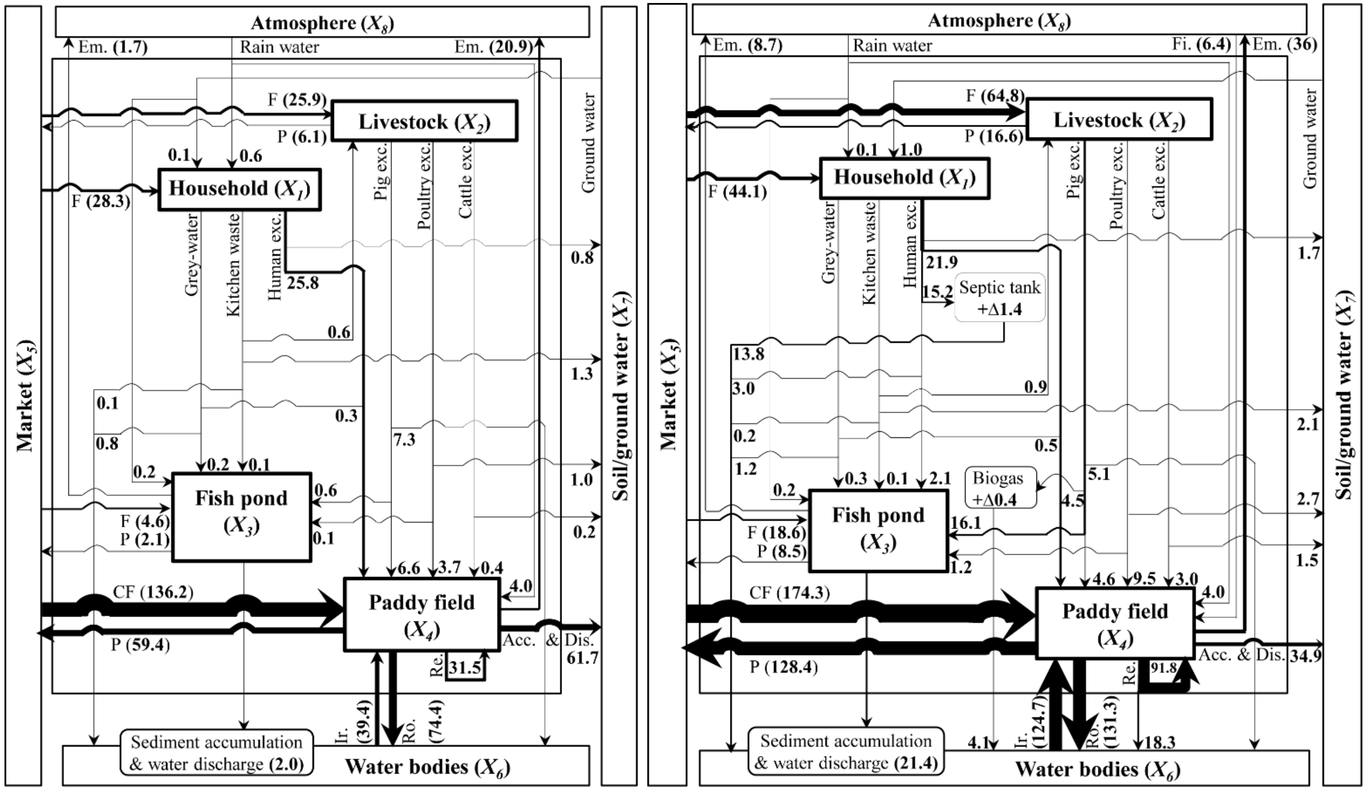

Figure 3 Flow of nitrogen in 1980 (left) and 2010 (right) (kg·ha^{-1}·year^{-1}). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff; Em: Emission.

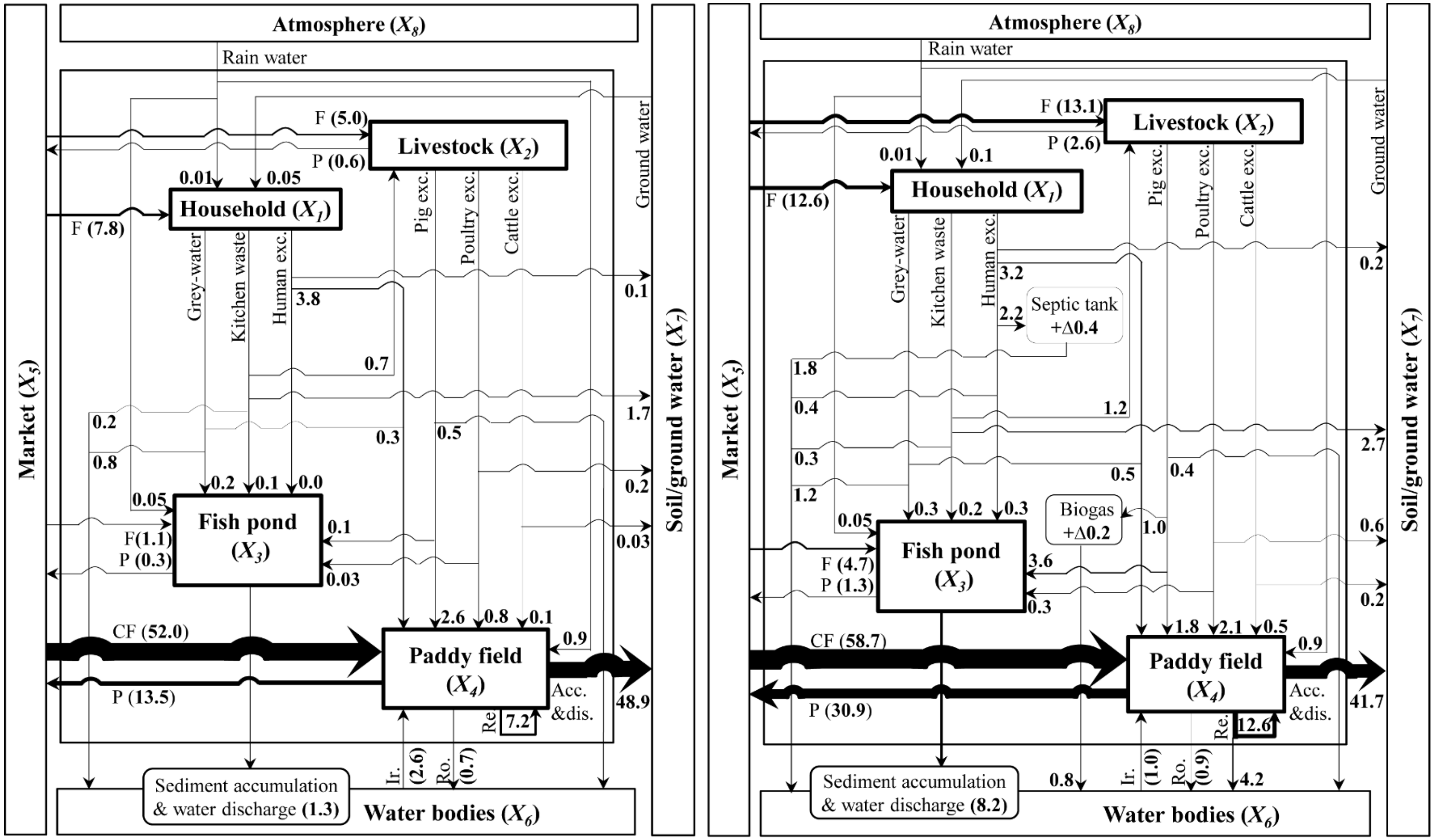

Figure 4 Flow of phosphorus in 1980 (left) and 2010 (right) (kg·ha^{-1}·year^{-1}). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff.

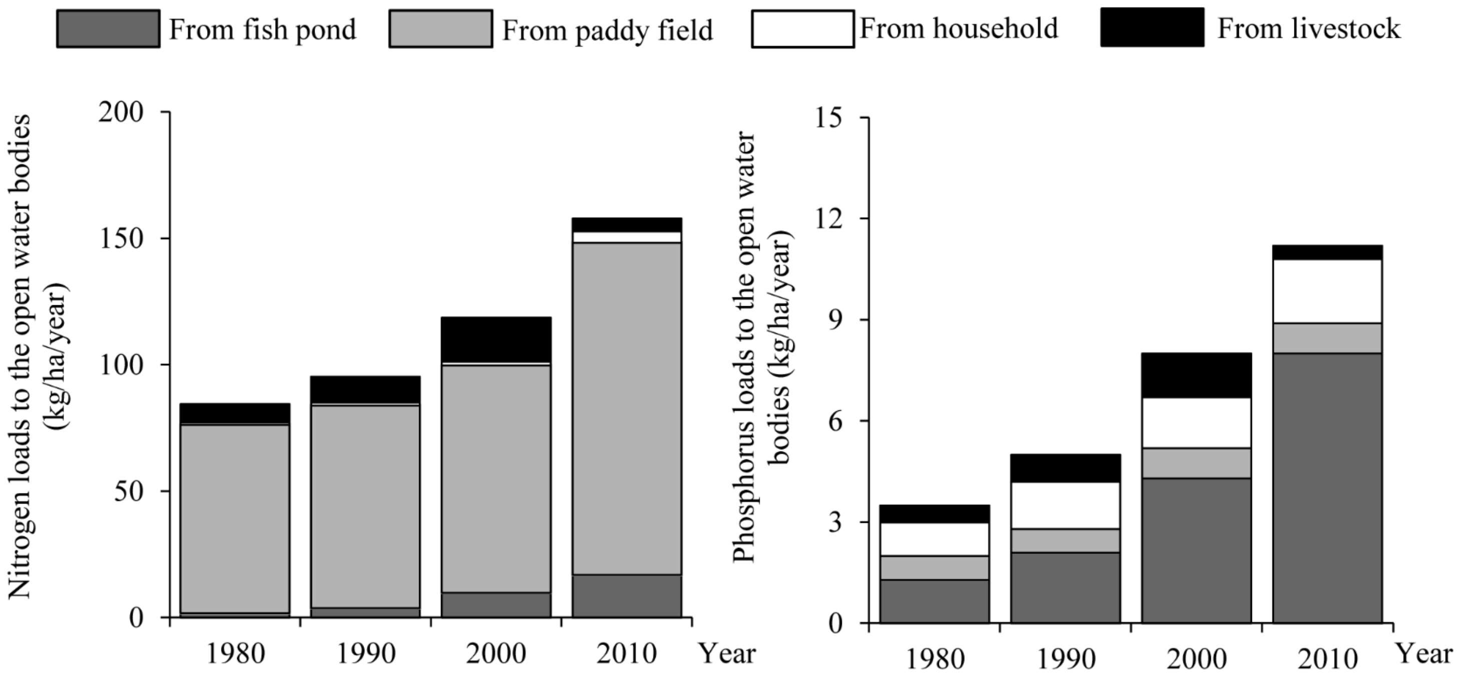

Figure 5 Nutrient input to open water bodies

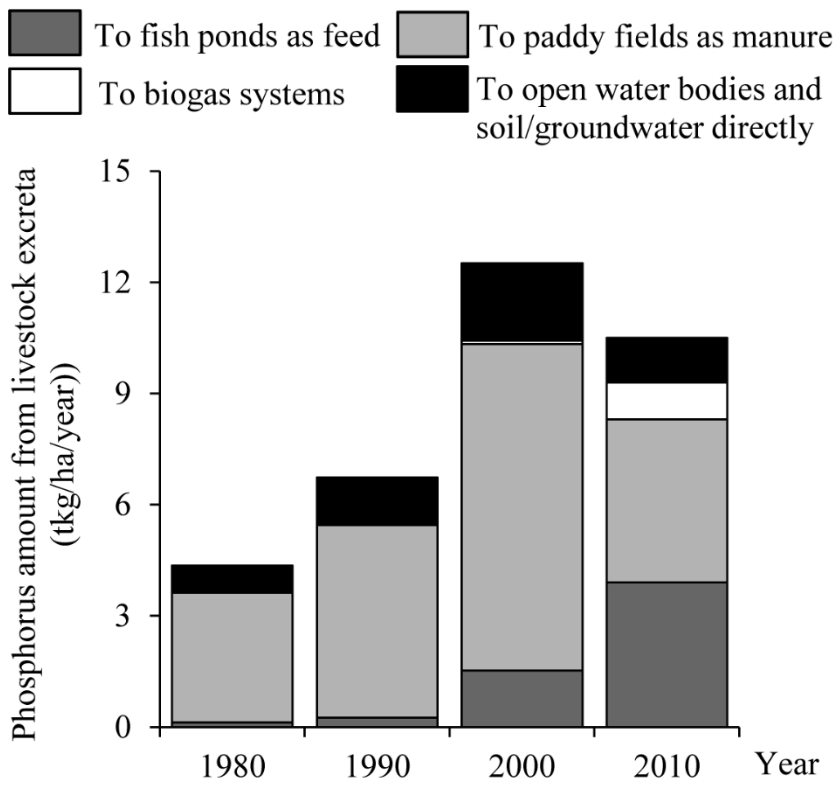

Figure 6 Phosphorous load derived from livestock excreta

List of tables

Table 1 General information in the study area

Information	Symbol	Unit	Data			
			1980	**1990**	**2000**	**2010**
Population	P_o	People	505	686	782	800
Number of household	N_{hh}	Household	240	240	240	240
Number of livestock						
Pig	N_{pi}	Head	109	152	293	229
Poultry	N_{po}	Head	2101	3342	6106	5810
Cattle	N_{ca}	Head	3	12	16	22
Residential area	S_{hh}	1,000 m^2	8	8	8	8
Paddy field area	S_a	1,000 m^2	526	526	526	526
Total area	$\sum S$	1,000 m^2	561	561	561	561

Table 2 Description of reaction processes of the material flow model via matrix expression

Component $[X_j]$ → Process$[P_i]$↓		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Reaction rate of $Pi[\rho_i]$ (kg-N/year or kg-P/year)
P_1	Human excreta discharge	$-1+\beta_{1,st}$		$\beta_{1,3}$	$\beta_{1,4}$		$\beta_{1,6}$	$\beta_{1,7}$		$C_{1,N(P)} \times P_o \times 365 \times 10^{-3}$
P_2	Greywater discharge	- 1		$\beta_{2,3}$	$\beta_{2,4}$		$\beta_{2,6}$			$C_{2,N(P)} \times P_o \times 365 \times 10^{-3}$
P_3	Kitchen waste discharge	- 1	$\beta_{3,2}$	$\beta_{3,3}$			$\beta_{3,6}$	$\beta_{3,7}$		$C_{3,N(P)} \times P_o \times 365 \times 10^{-3}$
P_4	Rain water supply	$\frac{S_{hh}}{\sum S}$		$\frac{S_p}{\sum S}$	$\frac{S_a}{\sum S}$				- 1	$C_{4,N(P)} \times Q_r \times \sum S \times 10^{-6}$
P_5	Ground water supply	+ 1						- 1		$C_{5,N(P)} \times Q_{gr} \times P_o \times 365 \times 10^{-6}$
P_6	Food supply to households	+ 1				- 1				$P_1 + P_2 + P_3 - \frac{S_{hh}}{\sum S} \times P_4 - P_5$
P_7	Pig excreta discharge	$\beta_{7,bio}$	- 1	$\beta_{7,3}$	$\beta_{7,4}$					$C_{7,N(P)} \times N_{pi} \times 365 \times 10^{-3}$
P_8	Cattle excreta discharge		- 1		$\beta_{8,4}$			$\beta_{8,7}$		$C_{8,N(P)} \times N_{ca} \times 365 \times 10^{-3}$
P_9	Poultry excreta discharge	$\beta_{9,bio}$	- 1	$\beta_{9,3}$	$\beta_{9,4}$			$\beta_{9,7}$		$C_{9,N(P)} \times N_{po} \times 365 \times 10^{-3}$
P_{10}	Pig product		- 1			+ 1				$C_{10,N(P)} \times N_{pi} \times W_{pi}$
P_{11}	Poultry product		- 1			+ 1				$C_{11,N(P)} \times N_{po} \times W_{po}$
P_{12}	Cattle product		- 1			+ 1				$C_{12,N(P)} \times N_{ca} \times W_{ca}$
P_{13}	Food supply to livestock		+ 1			- 1				$P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{12} - \beta_{3,2} \times P_3 - P_{13} - \alpha_{res} \times \beta_{17,2} \times P_{23}$
P_{14}	Water filling in fish ponds			+ 1			- 1			$\sum[C_{14,N(P)} \times S_{Pk} \times D_{Pk} \times f_{Pk} \times 10^{-3}]$
P_{15}	Commercial feed for fish ponds			+ 1		- 1				$C_{15,N(P)} \times P_f \times FCR$
P_{16}	Water removal from fish ponds			- 1			+ 1			$\sum [C_{16k,N(P)} \times S_{Pk} \times D_{Pk} \times f_{Pk} \times 10^{-3}]$
P_{17}	Fish harvesting			- 1		+ 1				$C_{17,N(P)} \times P_f$
P_{18}	N emission from pond surface			- 1					+1	$(P_1 \times \beta_{1,3} + P_2 \times \beta_{2,3} + P_3 \times \beta_{3,3} + P_4 \times \frac{S_{P_i}}{\sum S} + P_7 \times \beta_{7,3} + P_9 \times \beta_{9,3} + P_{14} + P_{15}) \times k_{N,emis}$
P_{19}	Sedimentation & unintentional discharge from fish ponds			- 1			+ 1			$(P_1 \times \beta_{1,3} + P_2 \times \beta_{2,3} + P_3 \times \beta_{3,3} + P_4 \times \frac{S_{P_i}}{\sum S} + P_7 \times \beta_{7,3} + P_9 \times \beta_{9,3} + P_{14} + P_{15}) - P_{16} - P_{17} - P_{18}$
P_{20}	Chemical fertilizer application				+ 1	- 1				$C_{20,N(P)} \times m_{cf} \times S_a$
P_{21}	Irrigation water to paddy fields				+ 1		- 1			$C_{21,N(P)} \times Q_{ir} \times S_a$
P_{22}	N fixation				+ 1				- 1	$337 \times e^{-0.0098 \times P_{20}/S_a} \times S_a$
P_{23}	Agricultural product harvesting		$\alpha_{res} \times \beta_{23,2}$		$-(1+\alpha_{res}) + \alpha_{res} \times \beta_{23,4}$	+ 1		$\alpha_{res} \times \beta_{23,7}$		$C_{23,N(P)} \times P_a$

P_{24}	Agricultural runoff				- 1		+ 1			$(P_1\times \beta_{1,4} + P_2\times \beta_{2,4} + P_3\times \beta_{3,4}+\frac{S_a}{\sum S}\times P_4 + P_7\times \beta_{7,4} + P_8\times \beta_{8,4} + P_9\times \beta_{9,4} + P_{20} + P_{21}+ P_{22} + P_{23} \times \beta_{17,4}\times\alpha_{res}) \times R$
P_{25}	N emitted from paddy fields				- 1				+1	$(P_1\times \beta_{1,4}+P_7\times\beta_{7,4} + P_8 \times \beta_{8,4}+P_9 \times \beta_{9,4}) \times k_{N,ex}+ P_{20} \times k_{N,cf}$
P_{26}	Soil accumulation &discharge from paddy fields				- 1			+ 1		$(P_1\times \beta_{1,4} + P_2\times \beta_{2,4} + P_3\times \beta_{3,4} +\frac{S_a}{\sum S}\times P_4 + P_7\times \beta_{7,4} + P_8\times \beta_{8,4} + P_9\times \beta_{9,4} + P_{20} + P_{21}+ P_{22} + P_{23} \times \beta_{23,4}\times\alpha_{res}) (1 - R) - (1 + \alpha_{re}) \times P_{23} - P_{25}$
Net reaction rate (kg/yr)		$r_j = \sum_i(\nu_{ij} \times \rho_i) = 0$ (i = 1,2,…26)				$r_j = \sum_i(\nu_{ij} \times \rho_i)$ (i = 1, 2, …26)				

Note: Details of symbols are explained in Figure 2 and Table 1,3 and 4.

Table 3 Secondary data used in the material flow model

Explanation		Unit	1980	1990	2000	2010	
$\beta_{1,3}$	Ratio of human excreta going to fish ponds	-	0.00	0.00	0.00	0.05	1)
$\beta_{1,4}$	Ratio of human excreta going to paddy fields	-	0.97	0.97	0.93	0.52	1)
$\beta_{1,6}$	Ratio of human excreta going to water bodies	-	0.00	0.00	0.00	0.07	1)
$\beta_{1,st}$	Ratio of human excreta going to septic tank	-	0.00	0.00	0.00	0.36	1)
$\beta_{2,3}$	Ratio of greywater going to fish ponds	-	0.16	0.16	0.16	0.16	1)
$\beta_{2,4}$	Ratio of greywater going to paddy fields	-	0.25	0.25	0.25	0.25	1)
$\beta_{2,6}$	Ratio of greywater going to water bodies	-	0.59	0.59	0.59	0.59	1)
$\beta_{3,2}$	Ratio of kitchen waste going to livestock	-	0.27	0.27	0.27	0.27	1)
$\beta_{3,3}$	Ratio of kitchen waste going to fish ponds	-	0.04	0.04	0.04	0.04	1)
$\beta_{3,6}$	Ratio of kitchen waste going to water bodies	-	0.07	0.07	0.07	0.07	1)
$\beta_{3,7}$	Ratio of kitchen waste going to soil/groundwater	-	0.62	0.62	0.62	0.62	1)
$\beta_{7,bio}$	Ratio of pig excreta going to biogas system	-	0.01	0.01	0.01	0.15	1)
$\beta_{7,3}$	Ratio of pig excreta going to fish ponds	-	0.04	0.04	0.15	0.53	1)
$\beta_{7,4}$	Ratio of pig excreta going to paddy fields	-	0.96	0.95	0.84	0.32	1)
$\beta_{8,4}$	Ratio of cattle excreta going to paddy fields	-	0.67	0.67	0.67	0.67	1)
$\beta_{8,7}$	Ratio of cattle excreta going to soil/groundwater	-	0.33	0.33	0.33	0.33	1)
$\beta_{9,bio}$	Ratio of poultry excreta going to biogas system	-	0.00	0.00	0.00	0.01	1)
$\beta_{9,3}$	Ratio of poultry excreta going to fish ponds	-	0.03	0.04	0.07	0.09	1)
$\beta_{9,4}$	Ratio of poultry excreta going to paddy fields	-	0.76	0.75	0.73	0.70	1)
$\beta_{9,7}$	Ratio of poultry excreta going to soil/groundwater	-	0.21	0.21	0.20	0.20	1)
$\beta_{11,2}$	Ratio of agricultural residue going to livestock	-	0.03	0.03	0.03	0.03	1)
$\beta_{11,4}$	Ratio of agricultural residue going to paddy fields	-	1.00	1.00	1.00	0.73	1)
$\beta_{11,7}$	Ratio of agricultural residue going to soil/groundwater	-	0.00	0.00	0.00	0.27	1)
α_{res}	Ratio of agricultural residue to production (rice)	-	0.53				1)
	Ratio of agricultural residue to production (bean)	-	1.00				1)
$C_{1,N}$	N amount in human excreta	g/cap/d	8.10				2)
$C_{1,P}$	P amount in human excreta	g/cap/d	1.20				2)
$C_{2,N}$	N amount in grey water	g/cap/d	0.40				3)
$C_{2,P}$	P amount in grey water	g/cap/d	0.40				3)
$C_{3,N}$	N amount in kitchen waste	g/cap/d	0.65				4)
$C_{3,P}$	P amount in kitchen waste	g/cap/d	0.83				4)
$C_{4,N}$	N amount in rain water	mg/L	0.25				5)
$C_{4,P}$	P amount in rain water	mg/L	0.06				5)
$C_{5,N}$	N amount in ground water	mg/L	4.60				6)
$C_{5,P}$	P amount in ground water	mg/L	0.40				6)
Q_{gr}	Ground water consumption	L/cap/d	60.00				1)
Q_r	Average rainfall	mm/year	1,612				7)
$C_{7,N}$	N amount in pig excreta	g/head/d	20.33				1)
$C_{7,P}$	P amount in pig excreta	g/head/d	4.59				1)
$C_{8,N}$	N amount in cattle excreta	g/head/d	31.66				1)
$C_{8,P}$	P amount in cattle excreta	g/head/d	5.13				1)
$C_{9,N}$	N amount in poultry excreta	g/head/d	0.36				1)
$C_{9,P}$	P amount in poultry excreta	g/head/d	0.08				1)
$C_{10,N}$	N amount in pig	kg/kg	0.022				8)
$C_{10,P}$	P amount in pig	kg/kg	0.0018				8)
$C_{11,N}$	N amount in poultry	kg/kg	0.0248				8)
$C_{11,P}$	P amount in poultry	kg/kg	0.0016				8)
$C_{12,N}$	N amount in cattle	kg/kg	0.024				8)
$C_{12,P}$	P amount in cattle	kg/kg	0.01				8)
W_{pi}	Pig meat product	kg/head	96				9)
W_{po}	Poultry meat product	kg/head	1.6				9)
W_{ca}	Cattle meat product	kg/head	410				9)
$C_{15,N}$	N amount in commercial feed for fish	kg/kg	0.04				10)
$C_{15,P}$	P amount in commercial feed for fish	kg/kg	0.01				10)
$C_{17,N}$	N amount in fish	kg/kg	0.03				10)
$C_{17,P}$	P amount in fish	kg/kg	0.0045				10)
P_f	Fish production	kg/year	3,875	6,200	9,900	15,850	11)
FCR	Feed conversion ratio	-	1.65				10)

$k_{N,emis}$	N emission from surface water	-	0.2				10)
$C_{20,N}$	N amount in chemical fertilizer	%	5–46% (depended on fertilizer types)				1)
$C_{20,P}$	P amount in chemical fertilizer	%	10–16% (depended on fertilizer types)				1)
$C_{21,N}$	N amount in irrigation water (Nhue river)	mg/L	2.60	2.60	2.60	7.7	12)
$C_{21,P}$	P amount in irrigation water (Nhue river)	mg/L	0.17	0.17	0.17	0.66	12)
Q_{ir}	Irrigation water consumption	m^3/ha	16,200				13)
$C_{23,N}$	N amount in rice	kg/kg	0.0114				14)
	N amount in bean	kg/kg	0.0064				14)
$C_{23,P}$	P amount in rice	kg/kg	0.0026				15)
	P amount in bean	kg/kg	0.0019				15)
P_a	Rice production	ton/year	292	342	571	631	11)
	Bean production	ton/year	0	0	0	50	11)
$k_{N,ex}$	N emission factor of excreta	-	0.2				16)
$k_{N,cf}$	N emission factor of chemical fertilizer	-	0.1				16)
R_N	Ratio of runoff in case of N	-	0.3				17)
R_P	Ratio of runoff in case of P						
	Rice	-	0.01				17)
	Bean	-	0.02				17)

[1]Giang *et al.*,2012 [2]Montangero *et al.*,2007 [3]Busser *et al.*,2006 [4]Shouw *et al.*, 2002; World Bank, 2004; Nakamura and Yuzuyama, 2005; Kawai, 2007 [5]Khanh, 2000; Huong *et al.*,2007[6]Anh and Toda, 2005 [7]HSO, 2010 [8]MEXT, 2008 [9]GSO, 2008; Harada *et al.*, 2008 [10] Nga *et al.*, 2011 [11]GSO, 2010; GSO, 2004 [12]VEA, 2012[13]FAO, 2013 [14]FAO, 2003; FAO, 2004; Thuy *et al.*, 1998); Nakamura and Yuzuyama, 2005 [15]USDA, 2014 [16]IPCC, 2000[17]Takamura *et al.*,1976.

Table 4 Characteristics of fishponds in the study area

Characteristics	Unit	Data
Total area of fish pond	1,000 m^2	27 (S_p)
Surface area	1,000 m^2 (avg. ± s.d.)	1.5± 1.0
Depth	m (avg. ± s.d.)	1.04 ± 0.10
Frequency of water exchange& fish harvesting	times/year	0 (Prior to 2010) 2 ± 1 (After 2010)

Table 5 Nutrient balances of fish ponds in the study area

		N				P			
		1980		2010		1980		2010	
		kg/ha	**(%)**	**kg/ha**	**(%)**	**kg/ha**	**(%)**	**kg/ha**	**(%)**
Input	Commercial feed	4.6	(79)	18.6	(45)	1.1	(69)	4.7	(48)
	Livestock excreta	0.7	(12)	17.3	(41)	0.1	(6)	3.9	(40)
	Household waste	0.3	(5)	2.5	(6)	0.3	(19)	0.8	(8)
	Water filling	-	-	3.1	(7)	-	-	0.3	(3)
	Precipitation	0.2	(3)	0.2	(1)	0.1	(6)	0.1	(1)
	Total input	**5.8**	**(100)**	**41.7**	**(100)**	**1.6**	**(100)**	**9.8**	**(100)**
Output &Accumulation	Fish production	2.1	(36)	8.5	(20)	0.3	(19)	1.3	(13)
	N release	1.7	(29)	8.7	(21)	-	-	-	-
	Water removal	-	-	7.5	(18)	-	-	0.5	(5)
	Sediment accumulation &Unintentional discharge	2.0	(34)	17.0	(41)	1.3	(81)	8.0	(82)
	Total output &Accumulation	**5.8**	**(100)**	**41.7**	**(100)**	**1.6**	**(100)**	**9.8**	**(100)**