Transition of fertilizer application and agricultural pollution loads: A case study in the Nhue-Day River basin

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Abstract
Rapid socio-economic development in suburban areas of developing countries has induced changes in agricultural waste and nutrient management, resulting in water pollution. The study aimed at estimating agricultural nutrient cycles and their contribution to the water environment. A material flow model of Nitrogen (N) and Phosphorus (P) was developed focusing on agricultural activities from 1980 to 2010 in Trai hamlet, an agricultural watershed in Nhue-Day river basin, Vietnam. The model had focus on the change in household management of human excreta and livestock excreta, and chemical fertilizer consumption. The results showed that the proportion of nutrients from compost/manure applied to paddy fields decreased from 85% to 41% for both N and P between 1980 and 2010. The nutrient inputs derived from chemical fertilizer decreased 6% between 1980 and 2000 for both N and P. Then, these nutrients increased 1.4 times for N and 1.2 times for P from 2000 to 2010. As of 2010, the total inputs to paddy fields have amounted to 435 kg-N/ha/year and 90 kg-P/ha/year. Of these nutrient inputs, 40% of N and 65% of P were derived from chemical fertilizer. Thirty percent (30%) of total N input was discharged to the water bodies through agricultural runoff and 47% of total P input accumulated in soil.

Keywords
Chemical fertilizer; compost; excreta; manure; nutrient; paddy fields.

INTRODUCTION

For many decades, crop-livestock systems, which involved the intensive application of human/livestock excreta as nutrient sources, were traditional and well-practiced in Asia (Amir *et al*., 1989; Devendra, 2002; Allen *et al*., 2007). However, recent rapid economic growth has induced changes in waste management practices, and subsequently in the nutrient flows. Chemical fertilizers were produced significantly and have become a more preferable source of nutrients than human/livestock excreta. The amount of chemical fertilizers applied to paddy fields has been dramatically increasing (Heffer, 2010). Excessive nutrient inputs to paddy fields from chemical fertilizers may be a potential source of water pollution due to agricultural leaching or runoff. In addition, a huge amount of human/livestock excreta unused for agriculture now flows into fish cultivation ponds, or is directly discharged to the nearby water environment. Consequently, environmental pollution in agricultural watersheds is increasing. Moreover, the loss of valuable nutrients due to this discharge is a concern.

To deal with these problems, the changes of farming systems and their corresponding waste management practices as well as the dynamics of fertilizer application have to be understood. Nutrient balances in paddy fields, which are likely affected by these changes, and the contribution of paddy fields to water pollution are necessary information for a designing sound nutrient management interventions at a watershed level. Recently, several researchers have conducted this kind of research using material flow analysis (MFA) in developing countries such as Thailand (Whitbread *et al*., 2003), China (Chen *et al*., 2008), and Vietnam (Montangero *et al*., 2007; Nga *et al*., 2011). MFA is a systematic tool used to understand the levels of flow and the stocks of materials within a system defined at a particular point in space and time (Brunner, 2004). Although nutrient cycles of farming activities have likely changed in developing countries due to the rapid socio-economic development, previous studies did not address historical changes in the role of the paddy fields on nutrient management. Previous researches also did not discuss how the changes in this role lead to changes of interaction between agricultural activities and the environment.

This study aimed at understanding the historical changes of agricultural activities; including the practices of waste management and fertilizer application for a typical agricultural situation in the context of a river basin in Vietnam. The Nhue-Day River basin, where agriculture has been actively conducted in its downstream, has long been a platform for exchanging irrigation water with paddy fields. The basin is one of three important basins in Vietnam and has been experiencing an alarming level of nutrient pollution (Environmental Report of Vietnam, 2006). One potential source of pollution is diffuse agricultural pollution in the basin. To understand the pollution loads contributed in this manner, the study also aimed at estimating nutrient cycles in paddy fields and their contribution to watershed environment by developing a material flow model of N and P.

MATERIALS AND METHODS

Study site

The study area is the Trai hamlet, a suburban district of Hanoi, the capital of Vietnam. The hamlet is located on the bank of the Nhue River, 40 km from the river's upstream (**Figure 1**). General information regarding this hamlet is summarized in **Table 1**. Farming is the major occupation of the residents and rice is the dominant crop. The area of paddy fields, which has not changed between 1980 and 2010, covers more than 90% of the area. Human and livestock excreta are applied to paddy fields together with chemical fertilizers here as in several other agricultural communities in the basin (Nga *et al*., 2011), as well as in Indonesia (Harashina *et al*., 2003), and China (Chen *et al*., 2009). Water from rivers in the watershed is utilized for irrigating paddy fields. Agricultural wastewater from paddy fields is pumped back to the river after harvesting seasons.

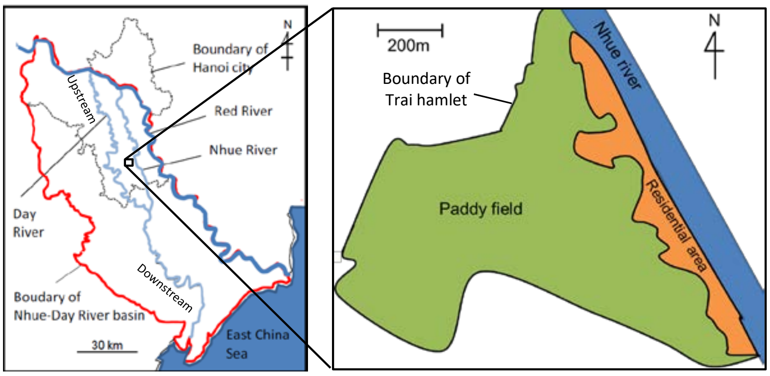

Figure 1 Map of Nhue-Day River basin and Trai hamlet

Table 1 General information of the study area (Local report, 2010; HSO, 2010; GSO, 2004, 2008, 2010)

Information	Symbol	Unit	Data	
			1980	**2010**
Population	P_o	People	505	800
Household number	N_{hh}	Household	-	240
Livestock number				
1. Pig	N_{pi}	Head	49	103
2. Poultry	N_{po}	Head	1094	3026
3. Cattle	N_{ca}	Head	2	16
Paddy field area	S_a	ha	52.6	52.6
Total area	$\sum S$	ha	56.1	56.1

Material flow model development

A mass flow model, shown in **Figure 2**, was developed based on Giang *et al*., 2012, which focused on nutrient balances in paddy fields. This model was applied for the hamlet. **Table 2** summarized reaction processes present in the paddy field component through matrix expression. All of the components in the system are listed across the top of the table with symbols. The model is composed of eight components labeled ($X_{1\text{-}8}$). (X_1) represents households, (X_2) represents livestock, (X_3) represents fishponds, (X_4) represents paddy fields, all of which are within the boundary. (X_5) represents a market, (X_6) represents water bodies, (X_7) represents both soil and ground water, and (X_8) represents the atmosphere. ($X_{5\text{-}8}$) are outside of the boundary.

Most of flows was calculated by unit value method:

$$I_i = \sum(U_k \times C_k \times R_k) \quad \text{(Eq.1)}$$

$$O_j = \sum(U_l \times C_l \times R_l) \quad \text{(Eq.2)}$$

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

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

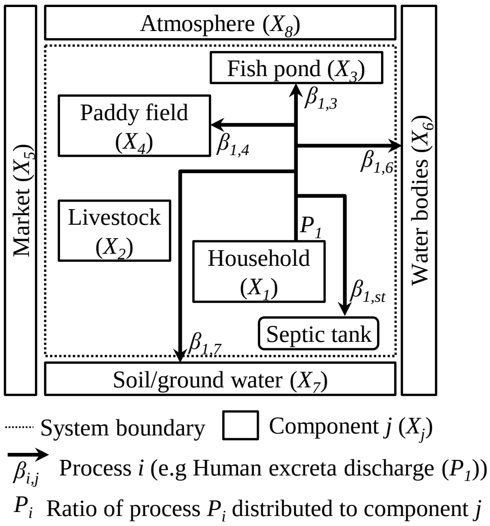

Figure 2 Material flow model

Table 2 Matrix expression on the description of reaction processes (adapted from Harada *et al*., 2010 and Giang *et al*., 2012)

Component j → / Process i ↓		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Reaction rate of P_i, ρ_i (kg/yr)
P_1	Human excreta discharge	- 1		$\beta_{1,3}$	$\beta_{1,4}$		$\beta_{1,6}$ + $\beta_{1,st}$ × $\alpha_{N(P),6}$	$\beta_{1,7}$ + $\beta_{1,st}$ × $\alpha_{N(P),7}$		$C_{N(P),he} \times P_o \times 365 \times 10^{-3}$
P_2	Grey-water discharge	- 1		$\beta_{2,3}$	$\beta_{2,4}$		$\beta_{2,6}$			$C_{N(P),gr} \times P_o \times 365 \times 10^{-3}$
P_3	Kitchen waste discharge	- 1	$\beta_{3,2}$	$\beta_{3,3}$	$\beta_{3,4}$		$\beta_{3,6}$	$\beta_{3,7}$		$C_{N(P),kw} \times P_o \times 365 \times 10^{-3}$
P_4	Rain water supply	$\frac{S_{hh}}{\sum S}$		$\frac{S_P}{\sum S}$	$\frac{S_a}{\sum S}$				- 1	$C_{N(P),ra} \times Q_r \times \sum S \times 10^{-6}$
P_5	Pig excreta discharge	$\beta_{5,1}$	- 1	$\beta_{5,3}$	$\beta_{5,4}$		$\beta_{5,6}$	$\beta_{5,7}$		$C_{N(P),pi} \times N_{pi} \times 365 \times 10^{-3}$
P_6	Cattle excreta discharge		- 1		$\beta_{6,4}$			$\beta_{6,7}$		$C_{N(P),ca} \times N_{ca} \times 365 \times 10^{-3}$
P_7	Poultry excreta discharge	$\beta_{7,1}$	- 1	$\beta_{7,3}$	$\beta_{7,4}$			$\beta_{7,7}$		$C_{N(P),po} \times N_{po} \times 365 \times 10^{-3}$
P_8	Chem. fertilizer application				+ 1	- 1				$C_{N(P),cf} \times m_{N(P),cf} \times S_a$
P_9	Irr. water supply				+ 1		- 1			$C_{N(P),ir} \times Q_{ir} \times S_a \times 10^{-3}$
P_{10}	N fixation				+ 1				- 1	$337 \times e^{-0.0098 \times P_{2o}/S_a} \times S_a$ (*)
P_{11}	Agri. product harvesting		$\alpha_{re} \times \beta_{11,2}$		$-(1+\alpha_{re}) + \alpha_{res} \times \beta_{11,4}$	+ 1		$\alpha_{re} \times \beta_{11,7}$		$C_{N(P),ri/be} \times P_{rice/bean}$
P_{12}	Agricultural runoff				- 1		+ 1			$(P_1 \times \beta_{1,4} + P_2 \times \beta_{2,4} + P_3 \times \beta_{3,4} + \frac{S_a}{\sum S} \times P_4 + P_5 \times \beta_{5,4} + P_6 \times \beta_{6,4} + P_7 \times \beta_{7,4} + P_8 + P_9 + P_{10} + P_{11} \times \beta_{11,4} \times \alpha_{res}) \times R_{N(P)}$
P_{13}	N emission				- 1				+1	$(P_1 \times \beta_{1,4} + P_5 \times \beta_{5,4} + P_6 \times \beta_{6,4} + P_7 \times \beta_{7,4}) \times k_{N,ex} + P_8 \times k_{N,cf}$
P_{14}	Soil accumulation and discharge				- 1			+ 1		$(P_1 \times \beta_{1,4} + P_2 \times \beta_{2,4} + P_3 \times \beta_{3,4} + \frac{S_a}{\sum S} \times P_4 + P_5 \times \beta_{5,4} + P_6 \times \beta_{6,4} + P_7 \times \beta_{7,4} + P_8 + P_9 + P_{10} + P_{11} \times \beta_{11,4} \times \alpha_{res})(1 - R) - (1 + \alpha_{re}) \times P_{11} - P_{13}$
Net reaction rate for X_4 (kg/ha/yr)		$r_4 = [\sum_i(\nu_{i4} \times \rho_i)/\sum S] = 0$ (i = 1 ~ 14)								(*) Obtained from Berk and Zeki, 1997

U_k, U_l : unit composition data 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.

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

$$I_i = \sum_1^m O_j - (\sum_1^{i-1} I_i + \sum_{i+1}^n I_i) \qquad \text{(Eq.3)}$$

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

The rows in Table 2 show 14 reaction processes that occur within each paddy field component (P_1–P_{14}). The reaction rate (ρ_i) for each process (P_i) is in the rightmost column of the matrix. The main text of the matrix conveys the proportion (ν_{ij}) of a process that occur in each component. Therefore, the net reaction rate of a single component is affected by a number of different processes, which can be seen by moving down the column representing a component. Based on the law of mass conservation, the net reaction rate r_4 for component X_4 was considered in the mass balance:

$$r_4 = [\sum_i(\boldsymbol{\nu_{i4}} \times \boldsymbol{\rho_i}) / \sum \boldsymbol{S}] = \mathbf{0} \text{ (kg/ha/year)} \qquad \text{(Eq.4)}$$

where *i* is the process (*i* = 1–14) and $\sum S$ (ha) is the total area of the study site.

Data collection

The necessary data for flow calculation appears in **Table 3**. Structured questionnaire surveys were used to acquire data on waste management including human excreta, livestock excreta, kitchen waste, grey water, and agricultural waste (Giang *et al*., 2012). The data of waste composition data, *e.g* N and P amount in human excreta or in chemical fertilizers were collected from literature. It was assumed that waste composition data had not changed from 1980 to 2010, except for the N and P concentration in the Nhue River. This is because the water quality of the river is substantially affected by the rapid socio-economic development occurring in the area. Although data in 2010 was available, the oldest available data of TN and TP concentrations in Nhue River were those in 2007 by VEA (2012). Despite accelerated socio-economic growth in the area from the middle of 2000s, the authors assumed that the concentrations had not changed significantly from 1980 to 2007. The concentration data in 2007 were used as those in 1980, 1990 and 2000, as the impact of TN and TP concentrations in 2007 was limited on the flows to paddy fields.

RESULTS AND DISCUSSION

Historical changes of compost/manure application to paddy fields

Figure 3 shows historical changes of nutrient amounts derived from human/livestock excreta. As shown in **Figure 3**, the total nutrients from human/livestock excreta double increased from 1980 to 2010, for both N and P, due to population growth. The human population increased 1.6 times, and the livestock population increased 2.7 times in this period. However, the proportion of N and P from compost/manure coming to paddy fields sharply decreased after 2000. As a custom in Vietnam, the application of compost/manure to paddy fields has a long history. In 1980, 35 kg N/ha/year and 7 kg P/ha/year were applied to paddy fields, which accounted for 85% of both total N and P from human/livestock excreta in this year. The use of compost/manure as nutrient sources for paddy fields was popular. Recently, when chemical fertilizers became more preferable, the traditional practice of human and livestock excreta recycling has gradually decreased. Only 41% of total N (37 kg N/ha/year) and total P (7 kg P/ha/year) from human/livestock excreta coming to paddy fields in 2010. This result corresponds to the findings of a relevant study in an agricultural watershed in China (Chen *et al*., 2009). Instead of being intensively applied to paddy fields, human and livestock excreta flows were directed into septic tanks/biogas systems and to fish ponds.

Table 3 Data collection

Symbol	Explanation	Unit	1980	1990	2000	2010	Ref.
$\beta_{1,3}$	Ratio of human excreta go to fish ponds	-	0	0	0	0.05	1)
$\beta_{1,4}$	Ratio of human excreta go to paddy fields	-	0.97	0.97	0.93	0.52	1)
$\beta_{1,6}$	Ratio of human excreta go to water bodies	-	0	0	0	0.07	1)
$\beta_{1,st}$	Ratio of human excreta go to septic tank	-	0	0	0	0.36	1)
$\alpha_{N,6}$	N transfer coefficient in septic tank (leachate)	-	0.90	0.90	0.90	0.90	2)
$\alpha_{P,6}$	P transfer coefficient in septic tank (leachate)	-	0.81	0.81	0.81	0.81	2)
$\alpha_{N,7}$	N transfer coefficient in septic tank (sludge)	-	0.10	0.10	0.10	0.10	2)
$\alpha_{P,7}$	P transfer coefficient in septic tank (sludge)	-	0.19	0.19	0.19	0.19	2)
$\beta_{2,3}$	Ratio of greywater go to fish ponds	-	0.16	0.16	0.16	0.16	1)
$\beta_{2,4}$	Ratio of greywater go to paddy fields	-	0.25	0.25	0.25	0.25	1)
$\beta_{2,6}$	Ratio of greywater go to water bodies	-	0.59	0.59	0.59	0.59	1)
$\beta_{3,2}$	Ratio of kitchen waste go to livestock	-	0.27	0.27	0.27	0.27	1)
$\beta_{3,3}$	Ratio of kitchen waste go to fish ponds	-	0.04	0.04	0.04	0.04	1)
$\beta_{3,6}$	Ratio of kitchen waste go to water bodies	-	0.07	0.07	0.07	0.07	1)
$\beta_{3,7}$	Ratio of kitchen waste go to soil/groundwater	-	0.62	0.62	0.62	0.62	1)
$\beta_{5,1}$	Ratio of pig excreta go to households (biogas)	-	0.01	0.01	0.01	0.15	1)
$\beta_{5,3}$	Ratio of pig excreta go to fish ponds	-	0.04	0.04	0.15	0.53	1)
$\beta_{5,4}$	Ratio of pig excreta go to paddy fields	-	0.96	0.95	0.84	0.32	1)
$\beta_{6,4}$	Ratio of cattle excreta go to paddy fields	-	0.67	0.67	0.67	0.67	1)
$\beta_{6,7}$	Ratio of cattle excreta go to soil/groundwater	-	0.33	0.33	0.33	0.33	1)
$\beta_{7,1}$	Ratio of poultry excreta go to households (biogas)	-	0	0	0	0.01	1)
$\beta_{7,3}$	Ratio of poultry excreta go to fish ponds	-	0.03	0.04	0.07	0.09	1)
$\beta_{7,4}$	Ratio of poultry excreta go to paddy fields	-	0.76	0.75	0.73	0.70	1)
$\beta_{7,7}$	Ratio of poultry excreta go to soil/groundwater	-	0.21	0.21	0.20	0.20	1)
$\beta_{11,2}$	Ratio of agri.residue go to livestock	-	0.03	0.03	0.03	0.03	1)
$\beta_{11,4}$	Ratio of agri.residue go to paddy fields	-	1	1	1	0.73	1)
$\beta_{11,7}$	Ratio of agri.residue go to soil/groundwater	-	0	0	0	0.27	1)
$\alpha_{re,rice}$	Ratio of agri.residue to agri.production (rice)	-	-	-	-	0.53	1)
$\alpha_{re,bean}$	Ratio of agri.residue to agri.production (bean)	-	-	-	-	1	1)
$C_{N,he}$	N amount in human excreta	g/cap/day	-	-	-	8.1	3)
$C_{P,he}$	P amount in human excreta	g/cap/day	-	-	-	1.2	3)
$C_{N,gr}$	N amount in grey water	g/cap/day	-	-	-	0.4	4)
$C_{P,gr}$	P amount in grey water	g/cap/day	-	-	-	0.4	4)
$C_{N,kw}$	N amount in kitchen waste	g/cap/day	-	-	-	0.65	5)
$C_{P,kw}$	P amount in kitchen waste	g/cap/day	-	-	-	0.83	5)
$C_{N,ra}$	N amount in rain water	mg/L	-	-	-	0.25	6)
$C_{P,ra}$	P amount in rain water	mg/L	-	-	-	0.06	6)
Q_r	Average rainfall	mm/year	-	-	-	1,612	7)
$C_{N,pi}$	N amount in pig excreta	g/head/day	-	-	-	20.33	1)
$C_{P,pi}$	P amount in pig excreta	g/head/day	-	-	-	4.59	1)
$C_{N,ca}$	N amount in cattle excreta	g/head/day	-	-	-	31.66	1)
$C_{P,ca}$	P amount in cattle excreta	g/head/day	-	-	-	5.13	1)
$C_{N,po}$	N amount in poultry excreta	g/head/day	-	-	-	0.36	1)
$C_{P,po}$	P amount in poultry excreta	g/head/day	-	-	-	0.08	1)
$C_{N,cf}$	N amount in chemical fertilizer	%	5 – 46% (depended on fertilizer types)				1)
$C_{P,cf}$	P amount in chemical fertilizer	%	10 – 16% (depended on fertilizer types)				1)
$C_{N,ir}$	N amount in irrigation water (Nhue river)	mg/L	2.6	2.6	2.6	7.7	8)
$C_{P,ir}$	P amount in irrigation water (Nhue river)	mg/L	0.17	0.17	0.17	0.66	8)
Q_{ir}	Irrigation water consumption	m^3/ha	-	-	-	16,200	9)
$C_{N,ri}$	N amount in rice	kg/kg	-	-	-	0.0114	10)
$C_{P,ri}$	P amount in rice	kg/kg	-	-	-	0.0026	10)
$C_{N,be}$	N amount in bean	kg/kg	-	-	-	0.0064	11)
$C_{P,be}$	P amount in bean	kg/kg	-	-	-	0.0019	11)
P_{rice}	Rice production	kg/year	292,143	342,446	570,744	630,720	12)
P_{bean}	Bean production	kg/year	0	0	0	50,400	12)
$k_{N,ex}$	N emission factor of excreta	-	-	-	-	0.2	13)
$k_{N,cf}$	N emission factor of chemical fertilizer	-	-	-	-	0.1	13)
R_N	Ratio of runoff in case of nitrogen	-	-	-	-	0.3	14)
R_P	Ratio of runoff in case of phosphorus						
	Rice	-	-	-	-	0.01	14)
	Bean	-	-	-	-	0.02	14)

1)Giang(2012) 2)Montangero (2007) 3)Montangero (2007) 4) Busser (2005) 5)Shouw (2002); World Bank (2004); Nakamura (2005); Kawai (2007)6)Khanh (2000); Huong (2007)7) HSO (2010) 8) VEA (2012)9) FAO (2013) 10) FAO (2003); FAO (2004); Thuy (1998); Nakamura (2005) 11) USDA (2014) 12)GSO (2010); GSO (2004)13)IPCC (2000)14)Takamura (1976); Takeuchi (1997)

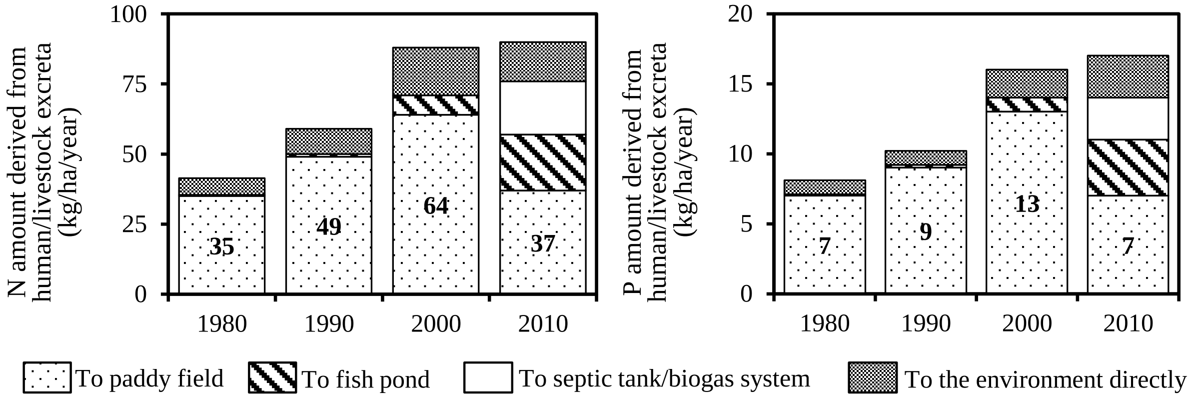

Figure 3 Nutrient amounts from compost/manure derived from human and livestock excreta

These transitions of N and P load may be results of the modernization process, which affected waste management and terminally the dynamics of nutrient cycling. Dry chamber toilets from which human excreta can be collected and reused for agriculture, have been gradually replaced by flush toilets. In 2010, 44% of households using flush toilets stopped using human excreta in agriculture. Instead, they discharged the human excreta to septic tanks or directly to the environment. In addition, biogas program for the Vietnam Livestock sector, especially for pigs, were implemented in 2003. The program was implemented in both suburban and rural Vietnam in an effort to increase farmers' income and reduce environmental pollution (Dung *et al.*, 2009). The project was introduced to the study site in 2006; however, only 16% of households raising pigs actually constructed biogas systems to treat pig excreta. About 53% of households discharged pig excreta into fish ponds. The amount of pig excreta that flows into fish ponds is expected to continuously increase since the farmers currently believe that fish in ponds fertilized with pig excreta grow faster than fish in ponds supplied with other feeds (Vu *et al.*, 2010). Thus, fish ponds have become a platform for receiving livestock excreta, gradually replacing paddy fields as recipients of the excreta in the study area.

Historical changes of chemical fertilizer consumption

Although it is a custom to use human and livestock excreta as agricultural inputs, chemical fertilizers are now widely applied to paddy fields. **Figure 4** illustrates the transition of nutrients derived from chemical fertilizers and compost/ manure over time. As can be seen in the figure, the nutrient inputs derived from chemical fertilizer decreased by 6% from 1980 to 2000 for both N and P. From 2000 to 2010, N and P then increased 1.4 and 1.2 times, respectively. Those changes were contrasted with the transitions of nutrient inputs derived from compost/manure, which peaked in 2000. This indicates that large amounts of compost/manure applied to paddy fields could reduce the usage of chemical fertilizers. Although the government has policies favoring expansion of livestock production (ACI, 2002), the nutrient inputs from manure have been gradually decreasing. Due to economic development, chemical fertilizers are now more preferable than compost/manure as a source

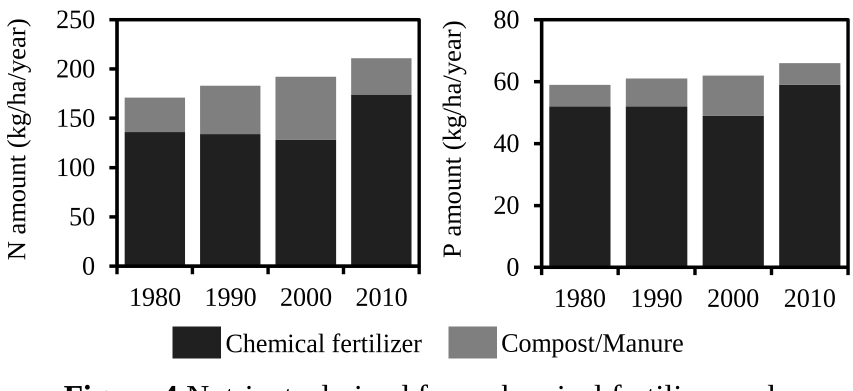

Figure 4 Nutrients derived from chemical fertilizer and compost/manure

of nutrients. As reported by UNEP in 2011, the chemical fertilizer consumption in East and Southeast Asia was 196 kg/ha. This value is higher than many regions in the world. It is expected to continuously increase in the near future.

Historical changes of nutrient balance in paddy fields

N and P balances in paddy fields in 1980 and 2010 are shown in **Figure 5 and 6**. The dominant flows of N were chemical fertilizer, irrigation, runoff, and production. The dominant flows of P were chemical fertilizer, production, and soil accumulation and discharge. The total inputs to paddy fields were 435 kg N/ha/year and 90 kg P/ha/year in 2010. These are 1.5 and 1.3 times higher, respectively, than those in 1980. Chemical fertilizer contributed to the 1980's and 2010's total inputs 47% and 40% in the case of N, respectively and 74% and 65% in the case of P, respectively. In 2010, 174 kg N/ha/year and 59 kg P/ha/year from chemical fertilizer were put into paddy fields. These results of N chemical fertilizer consumption were consistent with that consumed by a hamlet in a watershed in a study done in Indonesia (Harashina *et al*., 2003). The inputs from irrigation water in the area had a strong impact to the total nutrient inputs in 2010, which represented 29% of total N (125 kg N/ha/year) and 12% of total P (11 kg P/ha/year). The results were quite high compared to Mishima (2006), which indicated that Japanese irrigation water contributed 7% of N to agricultural input. Such differences could be explained by the quality of the irrigation source in the study area. The Nhue River is greatly contaminated by N and P in 2010 (VEA, 2012). In contrast, low concentrations of N and P in Nhue River in 1980 resulted in no significant impact of irrigation water to the total nutrient inputs in this period. The total inputs to paddy fields were estimated to exceed the recommended level, 200 kg N/ha/year and 52 kg P/ha/year (Bo *et al*., 2003), in both 1980 and 2010. The excessive application of N and P to paddy fields, especially due to large inputs of chemical fertilizers, caused the greater burden of N in the water bodies and of P in the soil. The differences between N and P load can be partly explained by the higher runoff coefficients of N to surface water, and by the larger fraction of P accumulating in soil (Carpenter, 1998).

For a sound material cycle, chemical fertilizer consumption needs to be reduced, and the usage of

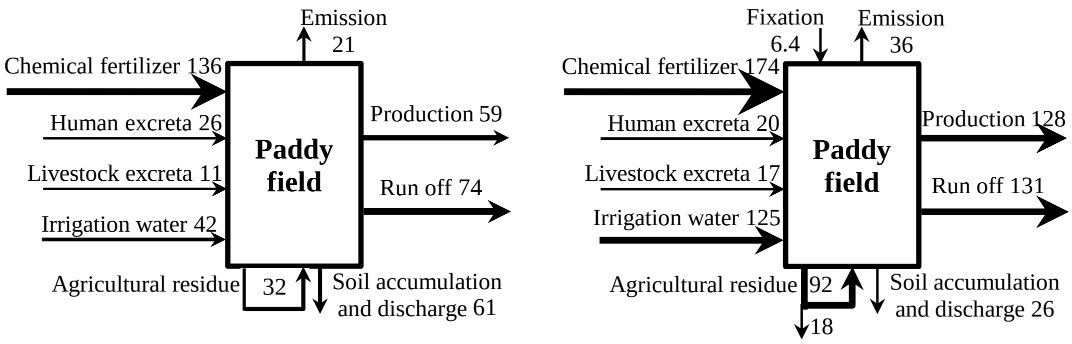

Figure 5 N balance in paddy fields: 1980 (left) and 2010 (right) (kg/ha/year)

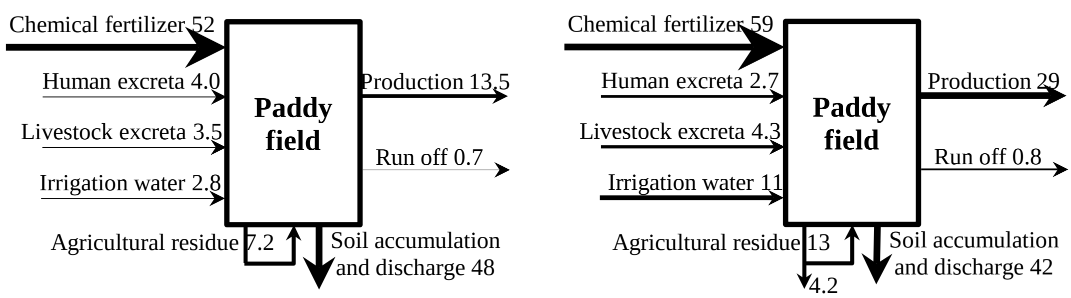

Figure 6 P balance in paddy fields: 1980 (left) and 2010 (right) (kg/ha/year)

human and livestock excreta in agriculture should be promoted. There were 33 kg N/ha/year and 5 kg P/ha/year from human/livestock excreta discharged directly or *via* septic tank/biogas systems to the environment in 2010. If those amounts were applied to paddy fields, the chemical fertilizer could be reduced by 19% for N and 8% for P. This might not only contribute to a better nutrient management, but also help to improve the water environment on the watershed scale.

CONCLUSIONS

N and P flows of an agricultural watershed area in the Nhue-Day River basin were examined together with the corresponding historical flows. Recently, the traditional waste recycling practices have been decreasing and chemical fertilizers have become a more preferred source of nutrients than human and livestock excreta. The total inputs for agriculture in 2010 were 435 kg N/ha/year and 90 kg P/ha/year. This is 1.5 and 1.3 times higher, respectively, than those in 1980. As of 2010, the largest input flow to paddy fields was from chemical fertilizers. It contributed 40% of N and 65% of P out of the total input. The total input of N and P to paddy fields was estimated to exceed the recommended level by 2.0 and 3.5 times, respectively. Excessive application of N resulted in the huge N burden to the water environment through runoff. Excessive application of P resulted in excess accumulation in soil and/or contamination of the ground water.

The study provided basic information for understanding the contribution of paddy fields to pollution in agricultural watershed environment. This study hence provides information relevant to formulate interventions for better waste and nutrient management on a watershed scale. A proper measure to reduce chemical fertilizer consumption and to promote human and livestock excreta use for agriculture should be proposed for a sound nutrient cycle not only in the Nhue-Day River basin but also in other agricultural watersheds in Asia. Instead of discharging human/livestock excreta directly, or *via* septic tank/biogas systems, these wastes could be applied to paddy fields. In the study area, if the wastes were applied to paddy fields, the chemical fertilizer consumption could be reduced by 19% for N and 8% for P. It may not only contribute to better nutrient management, but also help to improve the water environment in the whole watershed.

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