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Nutrient budgets (N and P) for the Nui Coc reservoir catchment (North Vietnam)

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ABSTRACT

The Nui Coc reservoir (water surface: 25.2 km^2; catchment area: 567 km^2), typical of medium sized reservoirs in Vietnam and in South East Asia, was built in the 1970s to stimulate social and economic development in the surrounding area. The nitrogen and phosphorus budgets were established in this typical reservoir catchment to determine the degree of human-induced alteration of nitrogen and phosphorus cycles. The results showed that both nitrogen and phosphorus inputs are higher than their outputs in the agricultural soil system, indicating the excess of fertilizer utilization in the catchment. The budget of the hydrosystem revealed that the nitrogen and phosphorus fluxes from agricultural and forest soils accounted for 50% and 51% of the total inputs to the hydrosystem, respectively. About 66% of the annual total nitrogen and 79% of the annual total phosphorus inputs to the hydrosystem were deposited/eliminated in the reservoir.

1. Introduction

The impact of natural processes and human activities on the environment is a matter of great concern on both local and global scales. Indeed, over the last centuries human activities have considerably altered nitrogen (N), phosphorus (P) and carbon (C) biogeochemical cycles (Galloway and Cowling, 2002; Howarth et al., 1996; Van Drecht et al., 2003; Seitzinger et al., 2010). The role of changing nutrient concentrations and their relative molar ratios, the principle cause of anthropogenic eutrophication in freshwater including lakes, reservoirs and rivers and the coastal zone has been well documented (Winter et al., 2002; Langenberg et al., 2003; Bechmann et al., 2005; Kuo et al., 2006). The contamination of freshwater systems by excess nutrients results in many negative effects on the ecosystem, including anoxia, fish deaths and the development of toxic algal blooms (Smith, 1998; Carpenter et al., 1998, 1999). These algal blooms can cause severe water quality problems such as unpleasant odors, dissolved oxygen depletion, increased pH and dissolved organic carbon concentrations and reduced transparency (Kuiper-Goodman et al., 1999; Shen et al., 2003). Moreover, several of the bloom forming species (e.g. *Microcystis* sp.) can release harmful toxins that can have adverse impacts on livestock, wildlife, and human health (Duong et al., 2012; Falconer, 1996).

Obtaining a good understanding of the global natural and human impact to freshwater requires that processes be examined on a regional scale. As only in this way can the various climatic and socio-economical constraints be taken into account. On a regional scale, the role of natural and anthropogenic processes in environmental quality can be determined through the calculation of nutrient budgets. Indeed, this type of calculation over a large spatial scale (e.g. the Red River basin: 156,000 km^2 (Le et al., 2005) can provide important information necessary for the maintenance of sustainable agricultural production as well as playing a fundamental role in aiding deciders with the management of environmental issues (Wassmann and Olli, 2004; Luu et al., 2011).

Numerous studies have dealt with the construction of N and/or P budgets in lake and reservoirs of the United States and Europe (Redshaw et al., 1988; Dolan, 1993; Boggess et al., 1995; Winter et al., 2002; Hiscock et al., 2003). However, and despite their ecological and economic importance few such budgets have been

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established for reservoirs and lakes in Asia and the West Pacific regions (Wei et al., 1992; Hart et al., 2002).

In Vietnam, the construction of multi-purpose lakes and reservoirs has multiplied since the 1970s and at present it is calculated that there are more than 3500 such water bodies in Vietnam. However, the water quality of these lakes and reservoirs is under severe threat because of the high amounts of non-treated wastewater that they receive from the catchments. Indeed, this degradation of water quality has led to the appearance of algal blooms of some potentially toxic species in many water lakes and reservoirs in Vietnam (Dang et al., 2002, 2005; Nguyen et al., 2007; Dao et al., 2010; Duong et al., 2011).

The Nui Coc reservoir was built in 1973. One of the main roles of this multi-purpose reservoir is to supply fresh water for the domestic requirements of 200,000 people (about 40–70 $Mm^3\,y^{-1}$) due to the very low groundwater level in this region (Thai Nguyen center for TDI, 2002; Le, 2005). The reservoir is also used for the irrigation supply system of 13,000 ha in Thai Nguyen and Bac Giang provinces (Vietnam). It is also used for aquaculture, tourism, transportation, generation of electric power (provides 8.0 MWh), and flood control in the downstream rivers and plains (IMHE, 2006).

The water and ecological quality of the Nui Coc reservoir has recently declined and blooms of toxic cyanobacteria have been reported in several recent studies (Thai Nguyen center TDI, 2002; Dang et al., 2006; Duong et al., 2010a,b, 2011). Several preliminary investigations (e.g. Vu et al., 2010; Thai Nguyen center for TDI, 2002) have revealed that the reservoir receives large amounts of untreated domestic and agricultural wastewater. This is further compounded by the increasing tourism pressure in the area and the associated wastewater from restaurants and hotels. Industrial activity in Vietnam has rapidly increased however, the majority of industrial factories have no or insufficient wastewater treatment systems, resulting in serious pollution problems in surface waters (MONRE, 2006; Nguyen, 2009). Industry is much less developed in the Nui Coc reservoir catchment and Vu et al. (2010) reported that there were about eight factories for tea processing, one factory for mechanics and six ore exploitation mines. These factories are small in size, are unevenly distributed in the area and lack wastewater treatment systems. Therefore waste of industrial origin discharged from these factories and mining exploitations may also influence water quality of the reservoir.

The Nui Coc reservoir is a typical example of the more than 3500 lakes and reservoirs that are subject to multiple uses in Vietnam alone and it can be considered characteristic of those found across the uplands of South East Asia. We provide N and P budgets in order to contribute to the decision making process of the local government and to fulfill the present data gaps for sub-tropical reservoirs and their catchments on global scale. To do this we consider the contribution of different nutrient sources to the Nui Coc reservoir water and provide an estimate of the nutrient budgets of the catchment.

2. Materials and methods

2.1. Description of the Nui Coc reservoir catchment

2.1.1. Geomorphology

The Nui Coc reservoir catchment is located in Thai Nguyen province (North Vietnam) (Latitude 105°46′ E, Longitude 21°34′ N) and drains an area of 567 km^2. The catchment is located in a mountainous region, with an average elevation of 312 m and a mean slope of 41.3% (Vu and Nguyen, 2009). The reservoir has a water surface area of 25.2 km^2 and an effective storage capacity of $168.10^6\,m^3$ and has a mean depth of 23 m (Thai Nguyen center TDI, 2002; Duong et al., 2012).

The reservoir catchment is in tectonically active area and is subject to high natural and agriculturally induced erosion rates, similar to other mountainous areas of the South East Asian region. Soils in the catchment are mainly ferrasols, ferric acrisols, fluvisols based on the FAO soil classification system (WRB, 1998). The geologic substratum of the catchment is dominated by consolidated paleozoic sedimentary rocks of complex lithology with variable contributions of mesozoic silicate or carbonated rocks (Le, 2005).

2.1.2. Administrative divisions

Administratively, the Nui Coc reservoir catchment is located in the Thai Nguyen province. Some of the data used for the budget calculation including land use, fertilization application, agricultural production, and livestock were taken from the recent official statistics from four districts of Thai Nguyen province (General Statistics Agency, 2006). The four districts/cities are Thai Nguyen city, and Dinh Hoa, Dai Tu and Pho Yen districts with areas in the Nui Coc reservoir basin of 17.3; 113.1; 414.3 and 22.4 km^2, respectively. This corresponds to a percentage of the district surface area located inside the catchment of 9.8%; 21.7%; 71.7% and 8.7%, respectively.

2.1.3. Meteorological and hydrological characteristics

The climate in the catchment is of the sub-tropical East Asia monsoon type characterized by two distinct seasons, rainy and dry seasons. The meteorological data recorded from 6 stations in the catchment over the period 1960–2006 showed that the average annual temperature was 22.8 °C and the average annual rainfall was 1848 $mm\,y^{-1}$ (IMHE, 1960–2006) with 85–92% of the total annual rainfall occurring during the rainy season (May–October). Relative humidity is high, varying from 82% to 87% (IMHE, 1960–2006).

The Nui Coc reservoir is located on the Cong River (Fig. 1) that has its source in the Pink Mountain (Nui Hong, Latitude 105°36′ E, Longitude 21°52′ N). The Cong River drains a total area of 957 km^2 with a drainage density of 1.2 $km\,km^{-2}$ on average and has a total length of 96 km. The mean water discharge of the upstream Cong River flowing directly into the Nui Coc reservoir was 15.1 $m^3\,s^{-1}$ during the period 1960–2006 (Vu and Nguyen, 2009; IMHE, 1960–2006).

2.1.4. Land use and population

Land cover and agricultural practices play an important role in determining nitrogen and, to a lesser extent, phosphorus concentrations in aquatic systems. As a whole, forest and meadows cover 42.5% and 4.8% of the catchment, respectively. Cultivated land (rice, dry cereals, and industrial crops) covers 34.7%, in which rice- and tea-cultured areas dominate other crop. Urban areas represented 5.7% of the total catchment area (Vu et al., 2010) (Table 1).

Population growth in the Nui Coc reservoir catchment is about 1.27%, slightly lower than the Vietnam national annual rate (1.53%). The population of the entire catchment was estimated to be 172,460 inhabitants in 2004. The population density is 304 $inhab\,km^{-2}$, slightly higher than the Vietnamese national average (252 $inhab\,km^{-2}$). Only 6% of the total population of the catchment lives in an urban area (Thai Nguyen City; General Statistics Agency, 2006).

2.2. Sample collection and analytical methods

2.2.1. Water sampling

2.2.1.1. Water sampling of the Cong River. Due to the lack of nutrient concentration data from the Cong River upstream and downstream of the reservoir, we carried out four sampling campaigns (two during the dry season, and two during the rainy season) from 2009 to 2010 at two points in the Cong River (Fig. 1). The data obtained were used for evaluating the nutrient inputs from the upstream

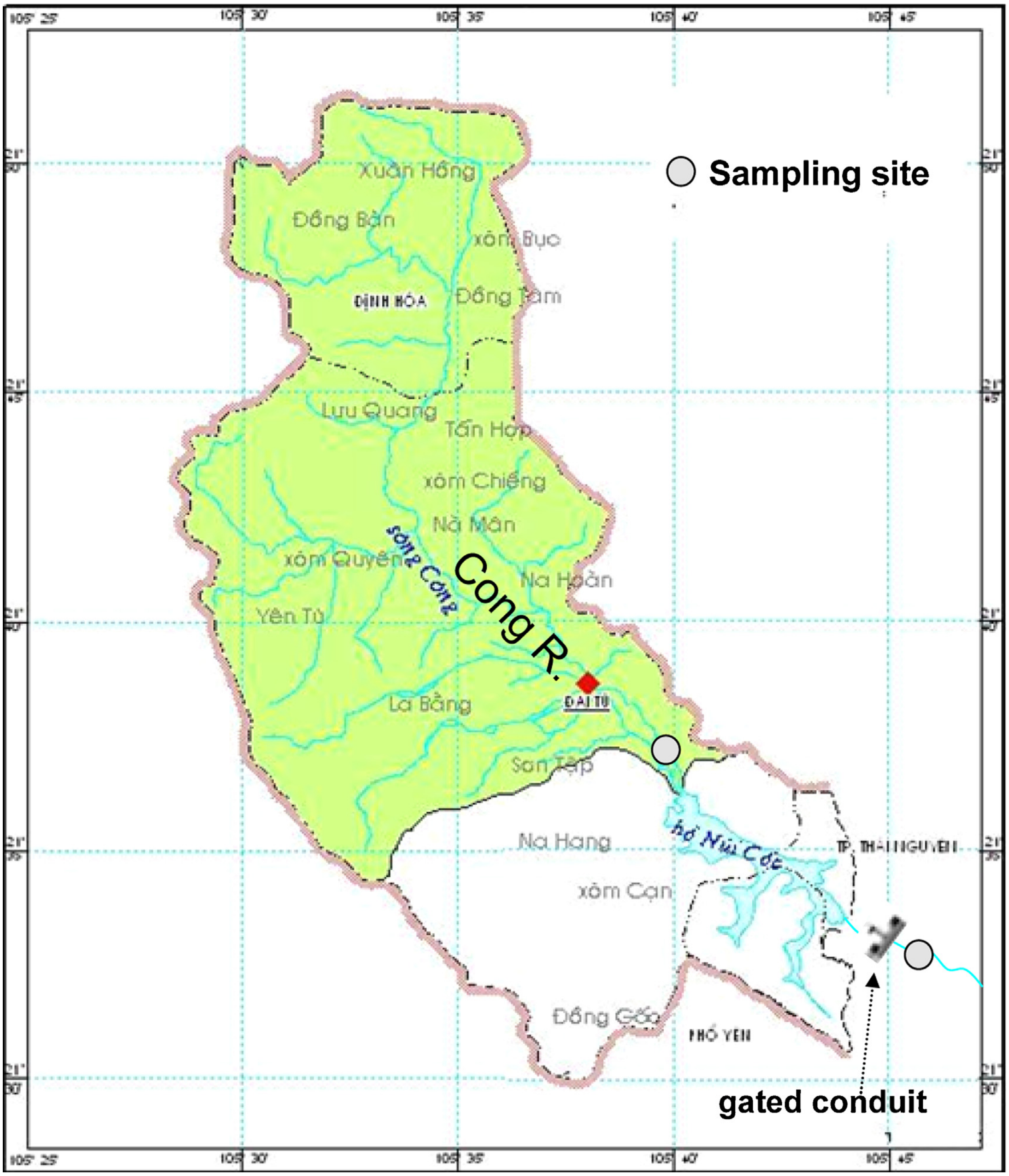

Fig. 1. The Nui Coc reservoir and the Cong River. The shaded area represents the upstream Cong River basin, the principal water source to the Nui Coc reservoir.

Table 1
Land use and fertilizer application rates in the Nui Coc reservoir catchment in 2004. Bold numbers are highlight numbers for the total area of each land-use item.

Land use		% Land area	Total area (ha)	N-fertilizer rate (kg N ha^{-1} y^{-1})	P-fertilizer rate (kg P_2O_5 ha^{-1} y^{-1})
Forest – total		**42.5**	**24,078**		
	Forest	42.5	24,078	–	–
Agriculture – total		**34.7**	**19,689**		
	Rice	20.8	11,783	120	60
	Dry cereals	7.5	4,258		
	Maize	*3.0*	*1,718*	*130*	*70*
	Potatoes	*2.7*	*1,558*	*120*	*80*
	Cassava	*0.7*	*418*	*120*	*60*
	Peanut	*0.6*	*320*	*30*	*70*
	Soybean	*0.4*	*245*	*20*	*200*
	Industrial plant culture	6.4	3,648		
	Sugarcane	*0.1*	*44*	*180*	*70*
	Tea	*6.3*	*3,604*	*130*	*40*
Urban – total		**5.7**	**3,224**	–	–
Grassland		**4.8**	**2,739**	–	–
Other		**12.31**	**6,982**	–	–

Cong River into the reservoir and the nutrient outputs from the reservoir toward the downstream Cong River.

2.2.1.2. Wastewater sampling of diffuse nutrient loss. To characterize non-point source inputs of nutrients, 18 water samples from the small streams draining agricultural areas were collected during both seasons from January 2009 to December 2010. The samples were collected from two kinds of plantations: from rice and other vegetables such as cabbage and salad greens and from industrial plantations of tea, soybean, peanut, and maize. Three other water samples were collected from small streams that drain forested lands.

2.2.1.3. Wastewater sampling of the industrial sources. Information concerning the location, production and effluent discharge of the industrial plants and ore exploitation mines in the catchment is well documented (Thai Nguyen center for TDI, 2002; Vu et al., 2010). However, the wastewater quality of these sources is unknown. For this reason, 9 wastewater samples from a mechanics factory, 4 tea processing factories and 4 ore exploitation mines were collected and analyzed.

2.2.2. In situ measurements and sample analyses

The water quality probe model WQC-22A (TOA, Japan), was used in situ to measure physico-chemical variables (pH, DO, conductivity and turbidity). After collection, water samples were kept in an ice box at 4 °C during transportation to the laboratory on the day of sampling (3–4 h). In the laboratory, all samples were immediately filtrated by vacuum filtration (Whatman GF/F filter).

Nitrite, ammonium and nitrate were determined spectrophotometrically (DRELL 2080 spectrophotometer (HACH)) on filtered water according to Rodier (1984), Slavyck and McIsaac (1972) and Jones (1984); total phosphorus and total nitrogen was evaluated on non-filtered samples according to APHA (1995).

2.3. Calculation of nutrient budgets

2.3.1. Nutrients cycling in the soil system

The terrestrial soil system of the watershed was divided into a forested area sub-system and an agricultural soil sub-system based on their respective surface areas in the watershed. In the forested subsystem, inputs from atmospheric nitrogen fixation and nitrogen and phosphorus from wet and dry atmospheric deposition are subject to losses through soil leaching and erosion. In the agricultural area, nutrient cycling was described in more detail. Inputs from chemical fertilizer and manure application, atmospheric deposition and from nitrogen fixation and outputs from the export of agricultural goods and whether or not they are consumed by human and animals in the watershed or are commercially exported outside the limits of the system were taken into account. The soil nutrient balance is defined as the difference between nutrient inputs and exports: if the balance for a particular nutrient is positive, nutrient accumulation in the soil will occur; and in contrast, if the balance is negative nutrients will depleted and soil fertility status may deteriorate (Le et al., 2005; Luu et al., 2011). In this calculation, internal nutrient cycling (microbial uptake and decomposition) is not considered. The commercial import of food and feed from outside the region should also be taken into account, which requires the complete balance of food to be established for the whole system.

2.3.2. Nutrient budgets in the hydrosystem

Nutrient inputs to surface water are from diffuse and point sources in the watershed. The diffuse sources include nutrients leached and eroded from forested and agricultural land. Here, diffuse sources are estimated from the total annual water flux and nutrient in runoff from different land use types evaluated from our direct measurements. The point sources were estimated from population data, tourist data, industrial census, and aquaculture production. The outputs of nutrient from the hydrosystem represent the nutrient fluxes exported from the catchment as calculated by the product of the annual water discharge and nutrient concentration at the outlet of the catchment.

The difference between total inputs and total outputs from the hydrosystem allows the calculation of retention processes relating either to elimination processes, such as denitrification, or retention processes, such as sedimentation and storage in reservoir sediments.

Table 2
Nitrogen and phosphorus budgets for the Nui Coc reservoir catchment.

	Nitrogen ($Mg\,N\,y^{-1}$)	Phosphorus ($Mg\,P\,y^{-1}$)
Soil system		
Atmospheric deposition		
Forest	120	14
Agriculture + grass	112	12
Nitrogen fixation		
Forest	120	–
Agriculture + grass	797	–
Fertiliser application	2365	522
Human manure application	706	85
Cattle farming		
Meat and dairy production	337	43
Excretion	1907	409
Grazing and feed consumption	2244	452
Agriculture and food balance		
Agricultural production	4501	619
Human consumption	942	113
Tourist consumption	3	0.3
Aquacultural feeding	21	7
Hydrosystem		
Inputs to hydrosystem		
Domestic waste water release	235	28
Leaching from agricultural soil	247	36
Leaching from forest soil	129	14
Input from the upstream Cong River	123	13
Waste from the aquaculture food	15	5
Industrial waste water release	3	1
Tourist-service waste water release	3	0.3
Total load to hydrosystem	755	98
Outputs from the hydrosystem (toward the Cong River)		
Output to the downstream Cong River	260	20
Total output	260	20
Retention in hydrosystem	495	78
%	66	79

3. Results

3.1. The budget of the soil system

3.1.1. Atmospheric deposition

To estimate the nutrient atmospheric deposition in the Nui Coc reservoir catchment, we assumed that the atmospheric N and P deposition rates of this catchment were the same values used for the Red River catchment (Le et al., 2005) as they are both located in North Vietnam. Therefore, the values used were 500 $kg\,N\,km^{-2}\,y^{-1}$ for nitrate-N deposition rate and 60 $kg\,P\,km^{-2}\,y^{-1}$ for phosphorus deposition rate. Taking into account these rates and the Nui Coc reservoir catchment area, we estimate that the total N and P inputs from the atmospheric deposition were 232 $Mg\,N\,y^{-1}$ and 26 $Mg\,P\,y^{-1}$ for the whole catchment (Table 2).

3.1.2. Atmospheric nitrogen fixation

The calculation of atmospheric nitrogen fixation was based on the specific fixation rates corresponding to the main land use

Table 3
Livestock census and excretion in the Nui Coc reservoir catchment in 2004.

	Livestock census (1000 capita)	N excretion ($Mg\,N\,y^{-1}$)	P excretion ($Mg\,P\,y^{-1}$)
Bovines	22.7	1135	218
Pigs	72.1	556	162
Poultry	719.0	216	29
Total		1907	409

classes in the Nui Coc reservoir catchment. The specific fixation rates, compiled from previous studies, were: 105 $kg\,N\,ha^{-1}\,y^{-1}$ for N_2 fixation by soybean and peanut; 50 $kg\,N\,ha^{-1}\,y^{-1}$ for paddy rice; 5 $kg\,N\,ha^{-1}\,y^{-1}$ for forest soil; 5 $kg\,N\,ha^{-1}\,y^{-1}$ for other cultures, and 15 $kg\,N\,ha^{-1}\,y^{-1}$ for grassland (Luu et al., 2011; Le et al., 2005; Boyer et al., 2002; Xing and Zhu, 2002). The calculated total nitrogen fixation rates are given in Table 2.

3.1.3. Chemical fertilizers

The estimation of total chemical fertilizer utilization is dependent upon the types of crops in the catchment. According to the report of the Vietnam Fertilizer Association (2005), fertilizer application rates used for different crops in the Nui Coc reservoir catchment varied between 20 and 180 $kg\,N\,ha^{-1}\,y^{-1}$ for nitrogen, and 40 and 200 $kg\,P\,ha^{-1}\,y^{-1}$ for phosphorus (Table 1). The total annual fertilizer inputs were calculated from these rates and the main kinds of plantation area in the whole catchment. In the catchment, rice and tea are main crops and these two cultures have the highest fertilizer application rates. They therefore play a key role in the nutrient budget.

3.1.4. Feed consumption, food production, and excretion by domestic animals

Manure production from domestic animals is considered as a nutrient input into the agricultural soil system while grazing and feed consumption are considered as outputs. The relative concentrations of nutrients in manure were weighted as a function of the type of livestock. According to the livestock census from 2004 the catchment has: poultry (719,000), pigs (72,100) and cows and buffalo (22,700). The rates of manure production per capita livestock, as well as the rates of meat and dairy products utilized are taken from Le et al. (2005). The sum of excretion and food production was used to estimate total feedstuff consumption by livestock (Table 2). Pigs and bovines were responsible for more than 80% of the total fluxes of domestic animals excretion in the Nui Coc reservoir catchment (Table 3).

3.1.5. Nutrient export from crop harvesting and grazing

Nutrients exported by harvested crops are important in that they represent a nutrient loss from the soil. The crop production in the Nui Coc reservoir catchment is divided into 8 types: rice, starchy roots (cassava and potatoes), maize, soybean, peanut, vegetables, sugarcane, and tea (Table 4). The rice and tea are main harvested crops of this region. Nutrient outputs from harvested crops were determined from agricultural production in the catchment and the N and P contents of harvested crops (Table 4).

3.1.5.1. Pasture of domestic animals. Grass production represents a large portion of domestic animal feed. As data on grass production is scarce for this region, we utilized the overall yield value of 8000 $kg\,ha^{-1}\,y^{-1}$, proposed by Stevenson and Cole (1999), with a nutrient content of 2% N and 0.25% P. This resulted in nitrogen and phosphorus uptake by pasture in the whole catchment of 438 $Mg\,N\,y^{-1}$ and 57 $Mg\,P\,y^{-1}$.

3.1.6. Domestic and industrial P, N loadings

3.1.6.1. Domestic wastewater in cities and villages. Le et al. (2005) determined the average per capita diet of the Vietnamese people and the N and P contents of harvested crops. Based on these figures, the yearly per capita nutrient loading was 5.46 $kg\,cap^{-1}\,y^{-1}$ for N and 0.65 $kg\,cap^{-1}\,y^{-1}$ for P (Table 4).

In the reservoir catchment, 6% of the total population lives in the urban area, in a small part of the Thai Nguyen city (General Statistics Agency, 2006), and about 19% of total population in the whole

Table 4
Agricultural production and its destination (human and livestock consumption (cons.) or exportation) in the Nui Coc reservoir catchment in 2004.

	%N	%P	Production ($ton\,y^{-1}$)	Average human diet ($kg\,cap^{-1}\,y^{-1}$)	Human cons. ($ton\,y^{-1}$)	Tourist cons. ($ton\,y^{-1}$)	Animal cons. ($ton\,y^{-1}$)	Export/import ($ton\,y^{-1}$)
Rice								
Grain	1.1	0.22	57,635	164	28,283	82	11,313	17,955
Leaves	1.1	0.22	57,635		0	0	57,635	0
Wheat	1.8	0.38	0	6	1035	3	0	−1038
Sugarcane	2.1	0.08	1863	13	2242	7	0	−386
Leaves	2.1	0.08	932		0	0	296	635
Maize								
Grain	1.2	0.35	8236	5.6	966	3	7267	0
Leaves	1.2	0.35	16,472		0	0	13,430	3042
Starchy roots	0.9	0.12	13,105	35	6036	18	7051	0
Leaves	1.2	0.22	6553		0	0	4661	1892
Vegetables	1.1	0.06	28,010	70	12,072	35	6036	9867
Peanut	1.3	0.23	387	1.4	241	1	144	0
Fruits	2.4	0.09	546	25	4312	13	0	−3778
Tea, coffee, tobacco	2.9	0.15	20,911	0.5	86	0	0	20,825
Soybean	2.2	0.46	355	1	172	1	182	0
Meat & dairy productions	3.5	0.30	9634	25	4312	13	0	5310
Fish & sea food	3.5	0.30	774	17	2932	9	0	−2166
Grass	2.0	0.26	21,912		0	0	21,912	0
Other feed	2.0	0.23	46,930		0	0	46,930	0
Total in $ton\,y^{-1}$			291,344	364	62,689	183	176,858	52,158
Total in $ton\,N\,y^{-1}$			4501	5.46	942	3	2244	975
Total in $ton\,P\,y^{-1}$			619	0.65	113	0.3	452	94

Table 5
Industrial wastewater quality in the Nui Coc reservoir catchment (average values and standard deviation values, $n = 4$).

Number of samples	Industrial branches	Wastewater quality					
		pH	Turbidity NTU	DO (mg L^{-1})	Conductivity (μS cm^{-1})	N_{tot} (mg N L^{-1})	P_{tot} (mg P L^{-1})
1	Mechanics	7.4	60	3.5	705	1.49	0.58
4	Ore exploitation mining	6.7 ± 1.4	128 ± 98	6.5 ± 0.3	291 ± 110	1.98 ± 0.45	0.46 ± 0.23
4	Tea processing	7.7 ± 0.3	46 ± 8	5.8 ± 0.2	157 ± 23	1.50 ± 0.2	0.28 ± 0.11

catchment lives adjacent to the reservoir bank (People Committee of Thai Nguyen Province (2009) where domestic wastewater can run into the reservoir. Thus, the calculation of nutrient fluxes from domestic wastewater considered that only 25% (19% + 6%) of the total domestic loading is released as wastewater to the reservoir water, the remaining part being internally recycled in the agricultural soils. Thus, N and P fluxes from the domestic wastewater into the Nui Coc reservoir were 235 Mg N y^{-1} and 28 Mg P y^{-1} (Table 2).

3.1.6.2. Industrial wastewater input. Industrial wastewater quality in this catchment determined from the water sampling campaign showed that pH was around neutral whereas turbidity and conductivity were highly variable (Table 5). Total N and total P in the industrial wastewater averaged 1.66 mg N L^{-1} (range 1.30–2.43 mg N L^{-1}) and 0.44 mg P L^{-1} (range 0.17–0.69 mg P L^{-1}) respectively (Table 5). Total N and P loads from the wastewater discharge of the industrial sector (1095 × 10^3 m^3 y^{-1}) into the reservoir were 3 Mg N y^{-1} and 1 Mg P y^{-1} (Table 2).

3.1.7. Tourism-services wastewater release

According to the Thai Nguyen Provincial Department of Trade and Tourism (2010), the number of tourists increased rapidly, from 9000 persons in 1996, up to 840,000 persons in 2010. The stay duration per tourist in the Nui Coc reservoir catchment also increased from 0.67 to 1.5 day from 2004 to 2010 (Vu et al., 2010). In 2004, there were 273,638 tourists with the stay duration per tourist of 0.67 days, mainly during the summer months (Thai Nguyen Provincial Department of Trade and Tourism, 2010).

The total food consumption by tourists was calculated from the number of tourists in 2004, the stay duration per tourist and the human food consumption per capita of 5.46 kg cap^{-1} y^{-1} for nitrogen and 0.65 kg cap^{-1} y^{-1} for phosphorus. As a consequence of the short duration of their visits, total food consumption by tourists was much lower (3 Mg N y^{-1} and 0.3 Mg P y^{-1}) than total local human food consumption in the catchment. All of the hotels and guesthouses are located on or very near to the reservoir banks where wastewater can run directly into the reservoir. Thus, the calculation of nutrient fluxes from tourist wastewater supposed that all of the nutrients from this source reached the reservoir surface water.

3.2. Budget of the hydrosystem

3.2.1. Diffuse nutrient loss from forested soils to the hydrosystem

The content of N and P in runoff from planted and natural forest averaged 0.60 (range 0.38–0.77) mg N L^{-1} for total nitrogen and 0.05 (range 0.03–0.08) mg P L^{-1} for total phosphorus in the Nui Coc reservoir catchment. These mean values were combined with the total annual water flux for forested area (198 × 10^6 m^3 y^{-1}, (IMHE, 1960–2006)) to calculate total N and P diffuse loss from forest soils (Table 2).

3.2.2. Diffuse nutrient loss from agricultural soils

Nitrate concentration in runoff from rice fields and other plant cultures averaged 0.78 mg N L^{-1} (0.16–2.13 mg N L^{-1}) and 0.66 mg N L^{-1} (0.10–1.65 mg N L^{-1}), respectively. Ammonium concentration in runoff from rice fields and other plant cultures averaged 0.45 mg N L^{-1} (0.10–1.27 mg N L^{-1}) and 0.51 mg N L^{-1} (0.05–2.57 mg N L^{-1}), respectively. Total phosphorus concentrations averaged 0.13 mg P L^{-1} (0.01–2.08 mg P L^{-1}) from the rice fields and 0.21 mg P L^{-1} (0.03–3.42 mg P L^{-1}) from the other fields. Due to the lack of nutrient concentrations in base flow, we assumed that for nitrogen, nitrate and ammonium contents are the same concentrations for both runoff and base flow components because as known, nitrogen leaching (mostly of nitrate and ammonium as they are highly soluble) is the process that brings most nutrients to both surface and underground water. For phosphorus, the process of transfer from soils to the river is different because phosphates are mostly absorbed on to particles. Hence, surface flow (and erosion) is the main mechanism bringing P to rivers. We therefore use a haft of total phosphorus concentrations in surface flow was applied for its in base flow.

The calculation of diffuse nutrient loss from agricultural soils was based on the total annual water flux for the agricultural area (184.5 × 10^6 m^3 y^{-1}, (IMHE, 1960–2006)) and respective nutrient concentrations in runoff from different land uses (Table 2).

3.2.3. Nutrient input from aquaculture

Truong (2007) reported that 10^6 Mg of excess food and residual wastes (including 29 × 10^3 Mg N and 9.5 × 10^3 Mg P) were released for an aquacultural area of 5600 ha with a fish production of 1.5 × 10^6 Mg. Thus, the yearly production of 774 Mg of fish in 2004 in the Nui Coc reservoir may have released 15 Mg N y^{-1} and 5 Mg P y^{-1}.

According to Le et al. (2006), only about 25–30% of the nutrients in aquaculture food are taken up, the rest (70%) is released to the reservoir. Based on this figure and on the yearly excess of nitrogen and phosphorus in aquaculture, we calculate that the total aquaculture feed used for fish production in the Nui Coc reservoir represented 21 Mg ton y^{-1} and 7 Mg P y^{-1}.

3.2.4. Input from the upstream Cong River

The nutrient input from the upstream Cong River was calculated based on nutrient concentrations in the Cong River upstream of the reservoir. We found mean concentrations of total N of 0.26 (range 0.21–0.29) mg N L^{-1} and of total P of 0.03 (range 0.02–0.04) mg P L^{-1} with no clear seasonal pattern (Fig. 2). Nutrient loads from the upstream part of the Cong River were calculated by multiplying the water flow of the upstream Cong River (15.1 m^3 s^{-1}) (Vu and Nguyen, 2009) with the nutrient concentrations obtained from our measurements. The contribution from the upstream Cong River to the reservoir budget was 123 Mg N y^{-1} and 13 Mg P y^{-1} (Table 2).

3.2.5. Nutrient discharged from the reservoir to the downstream Cong River

The output of nutrient fluxes of the Nui Coc reservoir to the downstream Cong River was calculated based on the mean value of the river water flow (1960–2006) and nutrient concentrations in the Cong River downstream of the reservoir as no values of discharge from the reservoir are available. It should be noted that the reservoir only provides water for irrigation and drinking water through a gated conduit which locates at the base of the reservoir (Fig. 1). Thus, we considered that the value of the input water discharge from the Cong River was equal to the output water discharge

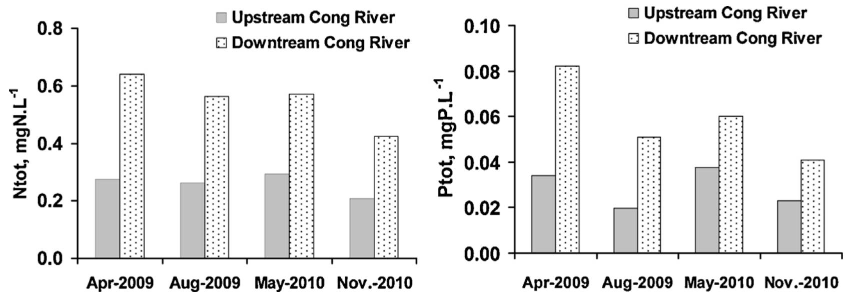

Fig. 2. Nitrogen and phosphorus concentrations in the Cong River, at the upstream and downstream of the Nui Coc reservoir.

of the reservoir. The nutrient concentrations in the Cong River, just downstream of the reservoir had mean concentrations of total nitrogen and total phosphorus of 0.55 (range 0.42–0.64) mg N L^{-1} and 0.059 (range 0.04–0.08) mg P L^{-1}, respectively; with no clear seasonal variation (Fig. 2). Thus, nutrient loads from the Nui Coc reservoir to the downstream Cong River were 260 Mg N y^{-1} and 20 Mg P y^{-1} (Table 2).

4. Discussion

Here, we present nutrient budgets for a typical medium sized reservoir catchment in Vietnam in order to evaluate the impact of human activities on natural nutrient cycling in this system. To our knowledge, this work is the first to address this subject in these upland reservoirs despite their ecological and economic importance in South East Asia. In these calculations, nutrient fluxes due to population increases and industrial and agricultural activities were taken into account. This was with the goal understanding the sources and loads from the different sources in order to provide a scientific basis to management decisions aimed at reducing eutrophication in the Nui Coc reservoir itself, as well as on a more general scale for other reservoirs or lakes in Vietnam.

4.1. Balancing nutrient budgets

Nitrogen and phosphorus fluxes in the Nui Coc reservoir catchment are presented in Fig. 3a and b. Nutrient budgets of the agricultural land showed that both nitrogen and phosphorus have an excess of inputs over outputs. This is probably a direct consequence of the high fertilizer utilization in the catchment. This is particularly the case for rice and tea, two main crops that have high rates of fertilizer application throughout the year (Vietnam Association of Fertilizer, 2005; Le et al., 2008; Vu et al., 2010). Despite large inputs of nutrients as fertilizers (estimated as 2365 Mg N y^{-1} and 522 Mg P y^{-1} based on data on agricultural practices) and manure (estimated as 2613 Mg N y^{-1} and 494 Mg P y^{-1} based on livestock census and population data) that are largely in excess of crop requirements (estimated to 4501 Mg N y^{-1} and 619 Mg P y^{-1} based on agricultural production), the export by leaching and erosion from the watershed appears low based on our estimates of runoff (estimated to 247 Mg N y^{-1} and 36 Mg P y^{-1}) (Table 2). Even considering that the measured runoff concentrations missed some peaks in N and P export we can conclude that a large fraction (1139 Mg N y^{-1} and 373 Mg P y^{-1}) of the nutrients applied in excess of crop uptake is stored in the soils. These rates of nutrient accumulation (51 kg N ha y^{-1} and 17 kg P ha y^{-1}) are lower than the values observed in the intensive agricultural area of the Red River Delta (North Vietnam), i.e. 28 kg P ha y^{-1} (Luu et al., 2011). However, the high amounts of nutrients accumulated in agricultural soils are a threat for future water quality in this region, as suggested by some previous studies (Sharpley et al., 2001; Ulen and Kalisky, 2005). Thus it is necessary to reduce external nutrient loading, e.g. careful management of fertilizer application will be important for the sustainable development of agriculture in the catchment.

In the forest soil, atmospheric deposition (primarily from the combustion of fossil fuel and from ammonia volatilization (Langenberg et al., 2003)) and from atmospheric nitrogen fixation were used as inputs whereas the outputs were calculated from nutrient losses through leaching or erosion into surface- or groundwater. Our estimates, 240 Mg N y^{-1} (996 kg km^{-2} y^{-1}) of nitrogen fixation and deposition onto forested soils, are far in excess of the nitrogen output from forest soil leaching and erosion, 129 Mg N y^{-1} (535 kg km^{-2} y^{-1}). Sadly, due to a lack of data on the total wood production in the catchment, wood export could not be calculated.

Of the different nutrient inputs into the reservoir hydrosystem, nitrogen and phosphorus fluxes leaching from agricultural and forest soils accounted for 50% and 51% of total nitrogen and phosphorus inputs to the hydrosystem, respectively. Inputs from domestic wastewater accounted for 31% and 29% of total nitrogen and phosphorus inputs, respectively. The upstream of the Cong River carried of about 16% and 13% of the total nitrogen and phosphorus inputs, respectively whereas, the aquaculture, industrial/mining exploitation, and tourist activities released a small proportion to hydrosystem (3% for nitrogen and 7% for phosphorus). Although inputs from aquaculture and tourism-sector activities into the hydrosystem were much lower than the other sources on an annual scale, particular attention has to be paid to these activities because the N and P inputs associated with these activities are directly discharged into the reservoir during a short period of the year, e.g. in the middle of summer (Thai Nguyen Provincial Department of Trade and Tourism, 2010). Indeed, the Nui Coc reservoir is an interesting eco-tourism destination which has led to a rapid increase in tourism in recent years. Moreover, it is probable that wastewaters related to tourism activities may be one of the factors causing cyanobacteria blooms as has been observed at several sites in the Nui Coc reservoir during the summer months (Duong et al., 2010a,b, 2011, 2012).

According to the People Committee of Thai Nguyen Province (2009), aquaculture and tourism are strongly encouraged in this catchment in order to accelerate the economic development of the Thai Nguyen province. Thus, it is necessary to develop nutrient management strategies for the whole reservoir catchment that take into account the economic development of the catchment in order to provide a sustainable exploitation of this ecosystem. Our results indicated that both point and non-point sources in the Nui Coc catchment should be controlled to reduce the cyanobacteria in the reservoir, like the case of the Chaohu Lake (Wei et al., 1992).

Regarding nutrient retention in the reservoir water, our estimates show that 66% of total nitrogen and 79% of total phosphorus inputs to the hydrosystem was deposited or eliminated in the

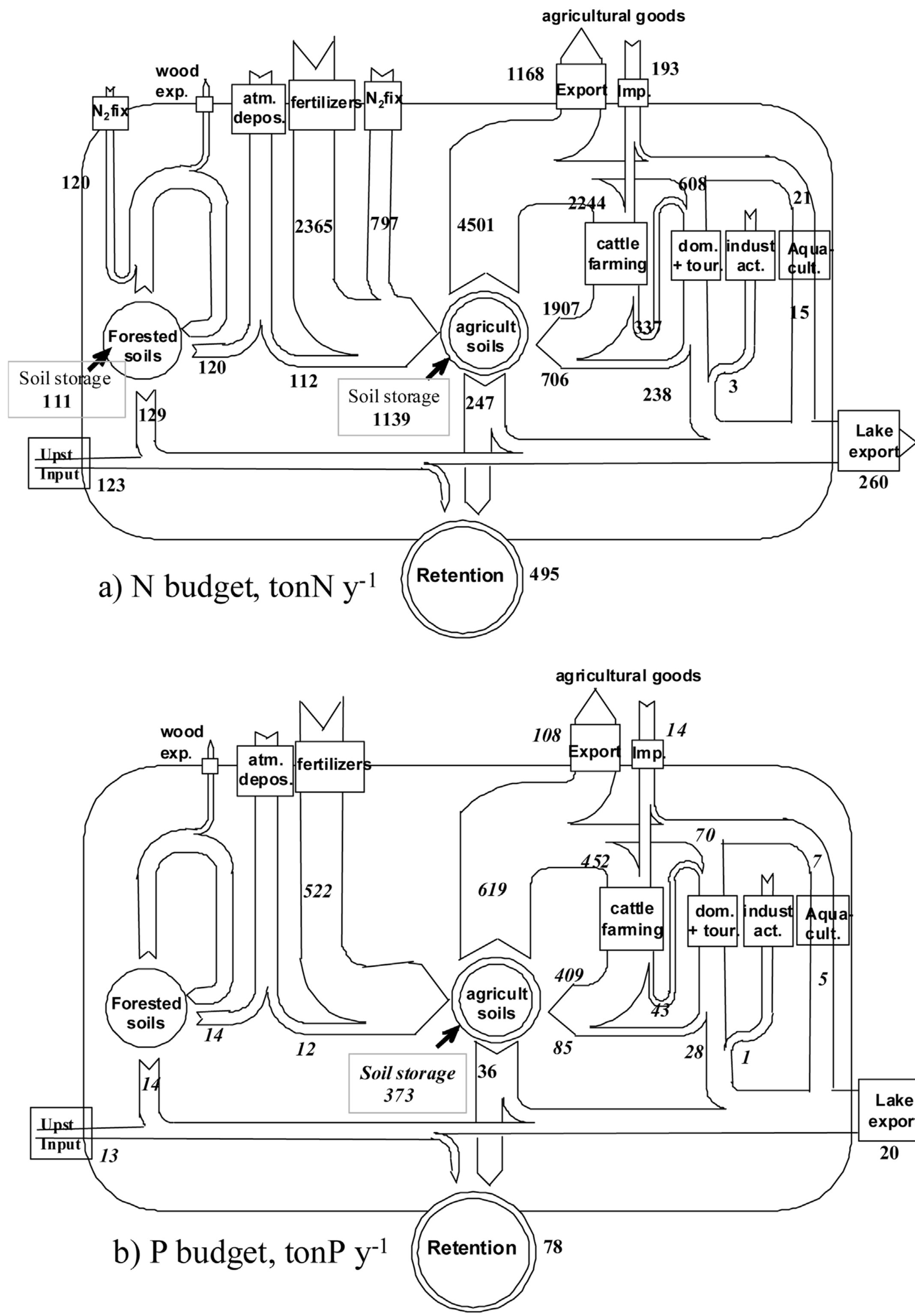

Fig. 3. Nutrient budgets for the Nui Coc reservoir catchment for the year 2004. (a) Nitrogen budget (in ton N y^{-1}); (b) phosphorus budget (in ton P y^{-1}).

reservoir. Thus it is clear that a large amount of nitrogen and phosphorus brought into the reservoir surface water from the upstream Cong River and human activities in the whole catchment is eliminated or retained in the reservoir before reaching the downstream Cong River, and hence reducing the eutrophication risk in the downstream of the Cong River. This is similar to other work on reservoirs that has shown the integral role they play in nutrient retention (e.g. Hart et al., 2002; Garnier et al., 1999).

The molar ratio of N:P retained in the reservoir water was used to evaluate the nutrient status of the water body of the Nui Coc reservoir. Hart et al. (2002) assumed that a waterbody is phosphorus deficient if the molar N:P ratio is greater than 16:1 and it is nitrogen deficient if the molar N:P ratio lower than 16:1. The N:P molar ratio of the Nui Coc reservoir water over the year averaged 14.1. An N:P ratio less than 16:1 may favor the growth of certain cyanobacteria, including nitrogen-fixing cyanobacteria in the reservoir water

(Hart et al., 2002; Havens et al., 2003). This could explain the predominance of cyanobacteria in the reservoir, as revealed by previous studies (Duong et al., 2010a,b, 2012). These authors noted that in the reservoir, cyanobacteria were the major contributor to phytoplankton composition with a relative abundance that ranged from 27% to 84%. The most abundant cyanobacteria in this reservoir were *Microcystis* spp. which are the most common toxic cyanobacterial genera in freshwater (Carmichael, 1992; Codd et al., 2005). Thus, the presence of cyanobacteria and their toxins in the water column of the Nui Coc reservoir may pose a health risk to people and to domestic animals. This is a potentially serious public health problem because one of main purposes of the Nui Coc reservoir is to supply fresh water for the domestic demand of 200,000 people in the region. Therefore, monitoring the frequency and abundance of toxic cyanobacteria and their toxins and understanding the factors (mainly nutrients) influencing their proliferation are integral to effective lake and reservoir management and the minimization of health risks concerned with cyanotoxins.

The nutrient budget calculations in this study rely on a wide variety of different data sources such as previous studies in the Red River catchment (Luu et al., 2011; Le et al., 2005). This data is of course subject to a number of possible biases. Additionally we do not have monthly values of water discharge from the Cong River. We therefore used a mean value for the period 1960–2006 of river water discharge for the upstream Cong River. This value was also used for the discharge from the reservoir to the Cong River. In addition, no water discharge data is available for minor rivers and creeks which drain into the reservoir. Obviously these could be sources of error in the nutrient fluxes calculations of the river input to the reservoir and for reservoir output to the river. In this study, we did not take into account nitrogen fixation by aquatic plants and algae in the reservoir water or nitrogen loss from the hydrosystem via denitrification as we do not have rates for these processes in the reservoir. Moreover, our estimations of atmospheric deposition may be overestimates as we used values for the Red River basin. Finally, the frequency of collection of the field samples will also be a source of potential error. For example, our phosphorus calculations are based on data from only 4 dates and none of these occurred during storm flow. Therefore it is probably that our calculations underestimate the amount of total phosphorus coming into the reservoir from the Cong River during high flow. Nevertheless, despite these potential errors, the budgets presented here show the importance of agriculture and, probably in the future, tourism as factors influencing nutrient supply to the reservoir.

4.2. Biogeochemical functioning of the catchment

Ecosystem function is classically described by the equilibrium between autotrophy and heterotrophy (Odum, 1971). An ecosystem is regarded as net autotrophic if the primary production of an ecosystem exceeds its consumption; conversely, the system is net heterotrophic if respiration exceeds production. In terms of nutrients (N and P), a regional watershed is defined as in anthropogenic autotrophy when its food and feed production (harvested and grazed products), expressed as N and P content is greater than the consumption of its agricultural products by human and livestock. In the opposite case, it is considered as in anthropogenic heterotrophy (Billen et al., 2010).

The Nui Coc reservoir catchment is greatly autotrophic when agricultural production (4501 $\mathrm{Mg\,N\,y^{-1}}$ and 619 $\mathrm{Mg\,P\,y^{-1}}$) is compared with the consumption of human and livestock (2873 $\mathrm{Mg\,ton\,y^{-1}}$ and 529 $\mathrm{Mg\,P\,y^{-1}}$) (Table 2). This watershed can therefore be considered as a net exporter of agricultural products and their contained nutrients (Fig. 3). This is similar to what has been observed in several other sub-catchments in North Vietnam (Le et al., 2005; Luu et al., 2011). The situation of these sub-catchments is similar in that the population density is not so high and that the agricultural production is greater than the local consumption of agricultural products by human and livestock in each sub-catchment. Conclusions similar to ours can be deduced from Billen et al. (2010) that is, that urban areas, where food is consumed but not produced, or rural regions characterized by intensive animal farming sustained by imported feed, are purely heterotrophic whereas rural regions specialized in crop production are autotrophic and export nutrients as food and/or feed.

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