




Nutrient flows in the crop-livestock system in an emerging county in China

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Abstract Understanding changes in nitrogen (N) and phosphorus (P) flows with the changes of crop-livestock systems is critical for sustainable agricultural development but has received little attention. This study presents a case study to estimate N and P flow changes in crop-livestock systems, of the dramatic agricultural transformation of Pinghe, an emerging county in Southeast China. The main nutrient inputs and outputs in the crop systems were fertilizer and soil accumulation, respectively. In the

livestock system, the main nutrient inputs and outputs were imported feed and recycled manure, respectively. From 1985 to 2015, the total N and P inputs into Pinghe's crop-livestock system increased from 11.0 and 1.2 Gg ($Gg = 10^9$ g) to 53.0 and 11.9 Gg, respectively. N and P use efficiency of the crop systems decreased from 24 and 42% to 10 and 6%, respectively; those in the livestock systems increased from 13 and 6% to 16 and 7%, respectively. The overall N and P use efficiency of the crop-livestock system decreased from 32 and 50% to 11 and 6%, respectively. The sharp increase in nutrient input and decrease in internal nutrient recycling are the main reasons for the decrease in system nutrient use efficiency. Scenario analyses indicated that there are large options for improving nutrient use efficiency and

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decreasing nutrient losses. We recommend a strong control of nutrient inputs, a tight coupling of crop and livestock production systems with effective manure recycling, and buffer areas between agricultural land and vulnerable water bodies, and with erosion control in hilly areas.

Keywords Agricultural systems · Nitrogen · Phosphorus · Nutrient use efficiency · NUFER model · Nutrient flow

Introduction

As essential nutrients, nitrogen (N) and phosphorus (P) play key roles in crop-livestock systems. To meet the growing consumer demand, N and P inputs into crop-livestock systems have dramatically increased in some emerging economies, such as China (Tilman and Clark 2014). However, the increasing rate of nutrient outputs has not kept up with nutrient inputs in crop-livestock systems, which not only has led to depletion of limited resources but also has led to vast amounts of environmental pollution in China (Vitousek et al. 2009; Chen et al. 2014; Chen and Graedel 2016; Jiao et al. 2018). At present, China consumes approximately 30% of the N and P fertilizers worldwide (FAO 2020), these fertilizers are overused within most crops, (Yan et al. 2013; Zhang et al. 2013), and excess fertilizers end up in the environment. For example, N is released into the atmosphere in the forms of ammonia (NH₃) and nitrous oxide (N₂O) and flows into the watershed in the form of nitrate (NO₃⁻). Losses of N can lead to pollution of groundwater acidification, haze climate change and eutrophication (Conley et al. 2009; Guo et al. 2010; Zhang et al. 2013).

Generally, farmers are more inclined to apply excessive amounts of fertilizer to cash crops (i.e., oil, sugar, tobacco, tea, fiber, vegetable and fruit crops) than to cereal crops (i.e., rice, wheat and maize) (Xin et al. 2012; Amenumey et al. 2014; Heffer et al. 2017; Chen et al. 2018). According to Chinese farmland surveys from 2000 to 2008, the annual fertilizer inputs into fruits and vegetables ranged from 388 to 555 kg N hm⁻² and from 66 to 261 kg P hm⁻², respectively, which were significantly greater than those in cereal crops (160–214 kg N hm⁻² and 27–55 kg P hm⁻²)

(Yan et al. 2013; Chen et al. 2018). Notably, the ratio of cereal crop cultivated area to cash crop cultivated area in China from the 1980s to the present has shifted from 8:2 to 7:3 (ECCS 2016; FAO 2020). Therefore, as the composition of crops change, the nutrient flow in crop systems change accordingly. In the livestock system, the number of livestock units (LUs) tripled in China from 1985 to 2015 (Bai et al. 2018). However, it is estimated that only one-third of the N and half of the P in animal manure are effectively recycled for crop use (Bai et al. 2014). This is different from that occurs in developed countries, such as the Netherlands and Denmark, where farmers have to comply with strict manure application limits (Willems et al. 2016). Changes in crop-livestock systems inevitably affect the characteristics of nutrient flow and cycling within farming systems, but few studies have focused on changes in nutrient flow characteristics with crop-livestock system change.

To determine mitigation measures for reducing N and P loss, quantifying N and P flow characteristics in crop-livestock systems is urgently needed. As such, the objectives of this paper are (1) to quantify the N and P flow characteristics in Pinghe County and (2) to explore appropriate nutrient management practices via scenario analysis. The ultimate goal is to provide policy recommendations for local governments and a reference for similar counties to achieve sustainable, green agricultural development.

Materials and methods

Study area description

Pinghe County (24°02′–24°35′ N, 116°54′–117°31′ E) is located in southwestern Fujian province, China (Fig. S1). Low-elevation mountains and hills constitute the main types of landforms in Pinghe County; these landforms are distributed mostly in the valleys and intermountain regions of the Huashanxi basin, accounting for 91.5% of the total area (www.pinghe.gov.cn). In 2010, the land area was determined to 230 × 10³ hm², which includes 24 × 10³ hm² of cultivated land and 180 × 10³ hm² of forest land. Pinghe County has a typical subtropical monsoon climate, with average amounts of rainfall ranging from 1600–2000 mm and temperature between 17.5 and 21.3 °C, which are suitable for various subtropical and

tropical crop species (PCLCC 2009). From 1985 to 2015, the scale and pattern of crop and livestock systems in Pinghe County changed dramatically (Fig. 1). The total sowing area increased from 56×10^3 to 100×10^3 hm^2 , the sowing area of cereal crops decreased from 42×10^3 (accounting for 75% to the total sowing area) to 10×10^3 hm^2 (accounting for 12% of the total sowing area), and the sowing area of cash crop (fruits, vegetables, tea, etc.) increased from 7.7×10^3 (accounting for 14% of the total sowing area) to 89×10^3 hm^2 (accounting for 88% of the total sowing area) (Fig. 1a). Moreover, in 1985, the main livestock animal was cattle, which constituted 55% of the total livestock; however, the main livestock animal changed to pigs, which accounted for 67% of the total livestock in 2015 (Fig. 1b).

Research system boundary

The research system boundary of the present study is the administrative region of Pinghe County. This area is inclusive of both crop and livestock systems. The crop systems include both cereal crop species (rice, wheat, and tuber crops) and cash crops (oil, sugar,

tobacco, tea, fiber, vegetable and fruit crops), and the livestock systems include monogastric animal species (pigs, broilers, layers and rabbits) and ruminant species (beef cattle, dairy cattle and sheep). The N and P flow pathways in crop-livestock systems were divided into input and output components (Ma et al. 2010). The input components included F^1 (fertilizer), F^2 (feed import), F^3 (deposition), F^4 (fixation), F^5 (local feed), F^6 (returned straw) and F^7 (recycled manure), and the output components included F^8 (accumulation), F^9 (runoff and erosion), F^{10} (leaching), F^{11} (discharged manure), F^{12} (denitrification), F^{13} (emission), F^{14} (crop produce), F^{15} (straw), F^{16} (meat, eggs and milk) and F^{17} (byproducts). The N and P flows were based on the following two assumptions (Ma et al. 2018): (1) the animals ate local feed first and then ate imported feed when local feed was insufficient, and (2) local manure resources were first applied to the field, while chemical fertilizer was applied when local manure resources were insufficient. In addition, owing to the small proportions of N and P wet deposition, dry matter accumulation in nonedible parts of crop plants and weight gain of un-slaughtered animals were not considered.

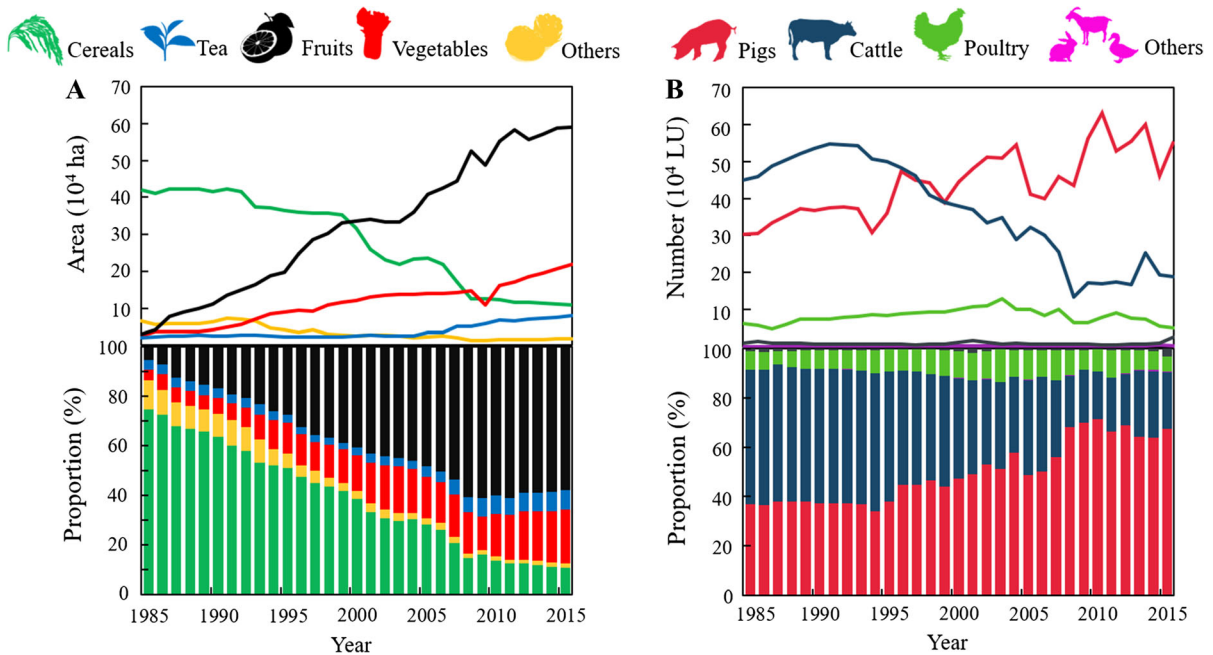


Fig. 1 Scale and pattern of crop (a) and livestock (b) systems in Pinghe County from 1985 to 2015. The data in these were obtained from ECPS (2016) and the different colors of the line

chart and the bar chart are the same as those of the corresponding crops and animals indicated above the graphs

Main formulas and data sources

In this study, the *NUtrient Flows in food chains, Environment and Resources use* (NUFER) model (Ma et al. 2010) was used to analyze nutrient (N and P) flow characteristics, nutrient losses and nutrient use efficiency (NUE and PUE) in the crop-livestock system of Pinghe County from 1985 to 2015. The main formulas and parameter descriptions are shown in Table 1 (see the supplementary materials for specific calculation details). The data used in this study are described in table S1, and include national statistical data (crop and livestock yields, planting areas and fertilizer consumption) (ECPS 2016), survey data (the proportion of crop products used in different ways and the proportion of animal manure discharged from storage, based on organizational field surveys and the NUFER model; Tables S3, S4, S5 and S7) and other published data (N and P contents of crop and livestock products or residues, and loss factors; Tables S2, S6, S8, S9 and S10).

Future scenarios

Three scenarios were chosen to simulate changes in N and P loss, NUE and PUE in crop-livestock systems in the future (Table S11):

- (i) Business as usual (BAU): The growth rates of crop and livestock products in Pinghe County will equal to those of Asian countries, as predicted by the Food and Agriculture Organization of the United Nations. Chemical fertilizer consumption will increase by 6 and 22%, crop yield will increase by 8 and 28%, and livestock products will increase by 13 and 59% in 2030 and 2050, respectively, compared with 2015. (Alexandratos and Bruinsma 2012; ECPS 2016).
- (ii) Zero-fertilizer growth (ZF) from 2030: Chemical fertilizer consumption will maintain a growth rate of zero after 2030, and more organic fertilizer (60%) will be recycled from 2030 to 2050 (MOAC 2015).
- (iii) Improved nutrient management (INM) in 2050: This scenario assumes that the following nutrient management options will be adopted in 2050. Firstly, the use of N and P fertilizer will be reduced by 100% because

there will be enough nutrients in the soil in 2050 (Ma et al. 2012; Wang et al. 2017). Second, nutrients will be absorbed more efficiently by using improved animal feed (reduced N and P concentrations in feed) and by raising transgenic animals whose N and P excretion will be reduced by 20 and 30%, respectively (Oenema et al. 2009; Ma et al. 2012). Third, NH₃ emissions will be 50% lower than those in the ZF scenario, and the manure recycling rate will be increased to 90% because of improved manure management in 2050 (Ma et al. 2012).

Sensitivity and statistical analysis

In this study, N and P loss coefficients via runoff, erosion, leaching, emission and denitrification used were the average values of Fujian Province, China (refer to Ma et al. 2010). To judge the impact of these key regional parameters on the results, we reduced these coefficients by 35%, 50% and 65% without changing the other coefficients and then calculated the losses N and P and the N and P use efficiencies. This method of sensitivity analysis was borrowed from the methods of Wu et al. (2015) and Zhu et al. (2017). Statistical and Pearson correlation analyses were performed using the Statistical Product and Service Solutions (SPSS) software version 21.0 (IBM, Armonk, NY, USA).

Results

Farm N and P balance

In 1985, the major N and P inputs into the crop system were from fertilizer, these accounted for 75 and 77% of the total inputs, respectively (Fig. 2). Twenty-seven percent of the N was accumulated in soil, which constitutes the net storage of N in the topsoil. In addition, 20% of N was loss through emissions. In 1985, almost 42% of the P was output through crop products, the amount of which was larger than the proportion of N in the crop products. From 1985 to 2015, N and P inputs first increased but then decreased. The average N input increased from 398 to 808 kg·hm⁻² during 1985–2005 and then decreased

Table 1 Main formulas and corresponding explanations

Equations	Items	Description
$N(P)I_{crop} = N(P)I_{fer} + N(P)I_{am} + N(P)I_{st}$	$N(P)I_{crop}$	Total N or P input in the crop system (Gg or kg ha ⁻¹)
	$N(P)I_{fer}$	N or P fertilizer input (Gg or kg ha ⁻¹)
	$N(P)I_{am}$	N or P input from local animal manure (Gg or kg ha ⁻¹)
	$N(P)I_{st}$	N or P input from local crop straw (Gg or kg ha ⁻¹)
$N(P)UE_c = (N(P)O_{crop}/N(P)I_{crop}) \times 100\%$	$N(P)UE_c$	N or P use efficiency in the crop system (%)
	$N(P)O_{crop}$	N or P output in crop products (Gg or kg ha ⁻¹)
$N(P)UE_a = [N(P)O_{Animal}/(N(P)I_{fi} + N(P)I_{lf})] \times 100\%$	$N(P)UE_a$	N or P use efficiency of the livestock system (%)
	$N(P)O_{Animal}$	N or P output via animal products (Gg or kg LU ⁻¹)
	$N(P)I_{fi}$	N or P input from imported feed (Gg or kg LU ⁻¹)
	$N(P)I_{lf}$	N or P input from local feed (Gg or kg LU ⁻¹)
$N(P)UE_{(c+a)} = [(N(P)O_{crop} + N(P)O_{Animal})/(N(P)I_{fer} + N(P)I_{fi})] \times 100\%$	$N(P)UE_{(c+a)}$	N or P use efficiency in the crop-livestock system (%)
$N(P)O_{Accumulate} = N(P)I_{crop} - N(P)O_{crop} - N(P)O_{st} - N(P)O_{rf} - N(P)O_{le}$	$N(P)O_{Accumulate}$	Accumulated N or P in the soil (Gg or kg ha ⁻¹)
	$N(P)O_{st}$	N or P output via crop straw (Gg or kg ha ⁻¹)
	$N(P)O_{rf}$	N or P output via soil runoff and erosion (Gg or kg ha ⁻¹)
	$N(P)O_{le}$	N or P output via leaching (Gg or kg ha ⁻¹)
$N(P)L_{(c+a)per} = (N(P)O_{rf} + N(P)O_{le} + N(P)O_{Discharge} + NO_{Ammonia})/(N(P)O_{crop} + N(P)O_{Animal})$	$N(P)L_{(c+a)per}$	N or P loss per kilogram of crop-livestock product (kg kg ⁻¹)
	$N(P)O_{Discharge}$	N or P output via discharged manure (Gg or kg LU ⁻¹)
	$NO_{Ammonia}$	N output via NH ₃ and N ₂ O volatilized from fertilizer and manure (Gg or kg ha ⁻¹ or kg LU ⁻¹)
	$N(P)O_{Manure}$	N or P output via animal manure (Gg or kg LU ⁻¹)
$N(P)I_{am} = N(P)O_{Manure} \times MR$	MR	Proportion of recycled manure to total manure (%)
$N(P)I_{fi} = N(P)O_{Animal} + N(P)O_{ANB} + N(P)O_{Manure} - N(P)I_{lf}$	$N(P)O_{ANB}$	N or P output via animal byproducts (Gg or kg LU ⁻¹)
	UDL	Degree of utilization of local agricultural resources (%)
$UDL = (N(P)I_{lf} + N(P)I_{am} + N(P)I_{st}) / (N(P)O_{crop} + N(P)O_{st} + N(P)O_{Manure}) \times 100\%$		

and stabilized at approximately 600 kg hm⁻² through 2015. Similarly, the average P input increased from 45 to 179 kg·hm⁻² during 1985–2003 and then remained at 150 kg·hm⁻² through 2015. Approximately 42 and 84% of N and P inputs, respectively, accumulated in the soil, which constituted the predominant output component in 2015.

At the same time, Pinghe County has become more dependent on imported feed. In 1985, imported N and P feed accounted for 53 and 63%, respectively, of the total amount of feed used; these values increased to 93 and 95%, respectively, in 2015. In addition, from 1985 to 2015, recycled manure decreased from 16 to 5.3 kg N LU⁻¹ and 13 to 3.6 kg P LU⁻¹, respectively (Fig. 2c and d); discharged manure increased from 1.5 to 9.5 kg N LU⁻¹ and 0.5 to 3.0 kg P LU⁻¹, respectively.

Production of meat, eggs and milk increased by approximately 1.5-fold (kilogram of N(P) LU⁻¹).

System N and P flow characteristics

The N and P flows changed from 1985 to 2015 (Fig. 3). The amount of N fertilizer input (F¹) changed from 8.8 Gg (Gg = 10⁹ g) in 1985 to 46.2 Gg in 2015. In addition, the accumulation of soil N (F⁸) increased from 3.2 to 21.7 Gg. The amount of N emitted as NH₃ and N₂O to the atmosphere (F¹³) increased from 2.6 to 12.5 Gg, and the amount of N lost as NO₃⁻ through runoff and erosion (F⁹) increased from 0.4 to 1.6 Gg; the amount of N leaching (F¹⁰) also increased from 0.9 to 6.2 Gg during the same period. Compared with those in the crop systems, the changes in N flow in the

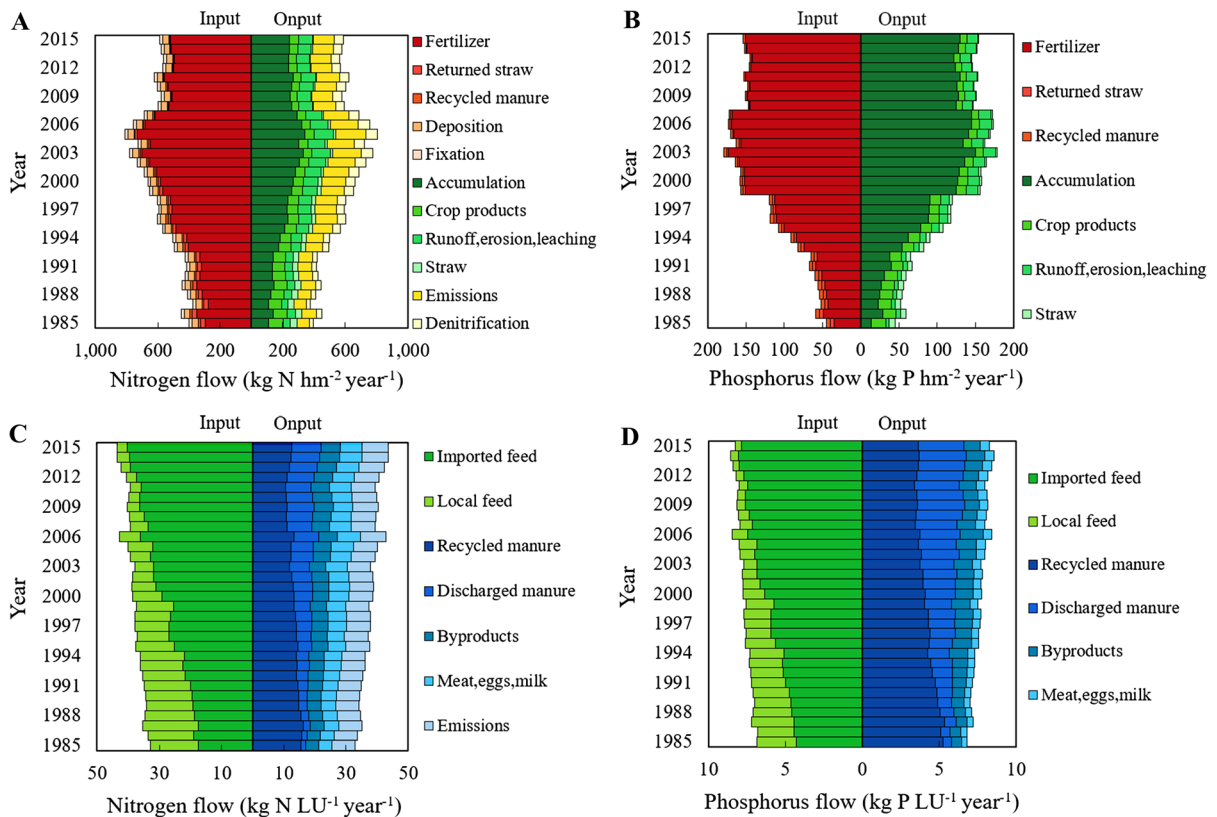


Fig. 2 Historical changes in nitrogen and phosphorus balances in crop (a, b) and livestock (c, d) systems in Pinghe County from 1985 to 2015

livestock system were relatively small: the amount of recycled manure N (F^7) increased from 0.4 to 0.5 Gg, and the amount of discharged manure N (F^{11}) increased by fourfold. At the same time, P fertilizer input (F^1) and the accumulation of soil P (F^8), the main components of P flow, increased by approximately 13- and 29-fold, respectively. Overall, the flux of P flow in livestock systems changes at the same rate as that in crop system.

N and P use efficiency

N use efficiency of the crop system (NUE_c) decreased from 24 to 7% during 1985–2003 but then slightly increased to 10% in 2015, and P use efficiency of the crop systems (PUE_c) decreased from 42 to 6% from 1985 to 2015. (Fig. 4). At the same time, N use efficiency of the livestock systems (NUE_a) increased from 13 to 16%, while P use efficiency of the livestock systems (PUE_a) was always less than 8%. The N and P use efficiency values of the crop-livestock system

($NUE_{(c+a)}$ and $PUE_{(c+a)}$, respectively) exhibit changes similar as those in NUE_c and PUE_c , which peaked at 42 and 50%, respectively, in 1985 and then decreased to 8 and 6%, respectively, in 2006, while $NUE_{(c+a)}$ increased to 11% and $PUE_{(c+a)}$ remained at 6% in 2015.

Scenario analysis

In the BAU scenario, NUE and PUE will remain at relatively low levels in 2030 and 2050, but N and P losses will be greater (Fig. 5). In the BAU in 2030 scenario, N emissions (loss of N as NH_3 or N_2O) will increase by 5%, an N losses through runoff, erosion and leaching will increase by 3% compared with that in 2015. NUE , PUE and nutrient losses in the ZF scenario will slightly increase compared with those in the BAU scenario. Specifically, when the BAU and ZF scenarios in 2050 are compared, both $NUE_{(c+a)}$ and $PUE_{(c+a)}$ will increase by 1%, N loss will decrease by 13% and P loss will decrease by 21%. In the 2050 INM

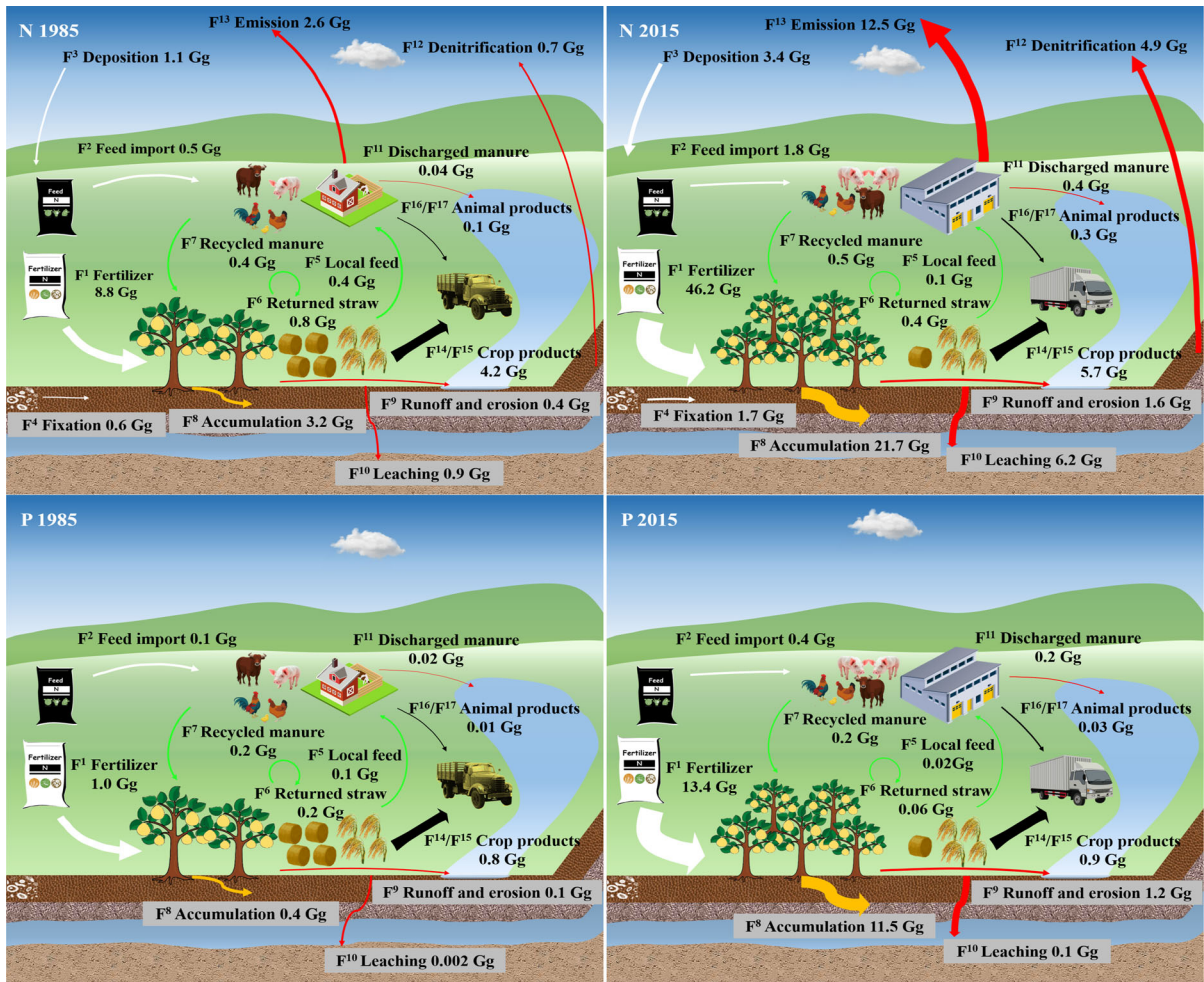


Fig. 3 Historical changes in nitrogen and phosphorus flows in crop and livestock systems in Pinghe County. N1985 and N2015 indicate nitrogen flow in 1985 and 2015, respectively, and P1985 and P2015 indicate phosphorus flow in 1985 and 2015, respectively. The white arrows represent the input nutrients, the green arrows represent nutrient cycling, the orange arrows

represent the storage nutrients, the red arrows represent the nutrient losses, and the black arrows represent the nutrient outputs. The thickness of each arrow is positively related to the size of the flow. A superscript letter F plus a number indicates the corresponding series number of each nutrient flow

scenario, NUE_c and PUE_c will greatly increase compared with those in 2015 (NUE_c will increase from 10 to 105%, and PUE_c will increase from 6 to 72%), NUE_a and PUE_a will slightly increase (NUE_a will increase from 21 to 24%, and PUE_a will increase from 7 to 8%). Moreover, N and P losses will be reduced by 94 and 93%, respectively, in 2050 compared with those in 2050 BAU scenario. Taken together, these results indicate that nutrient management under the INM scenario is highly advantages for improving nutrient use efficiency and reducing nutrient loss.

Relationships between nutrient use efficiency and crop system and livestock system patterns

At the county level from 1985 to 2015, the proportion of cash crop sowing area out of the total crop area was significantly positively correlated with both N and P fertilizer inputs and N and P losses from crop system, respectively, and significantly negatively correlated with NUE_c and PUE_c (Table 2). The results also revealed significant positive correlations between the proportion of monogastric animals to total animals to

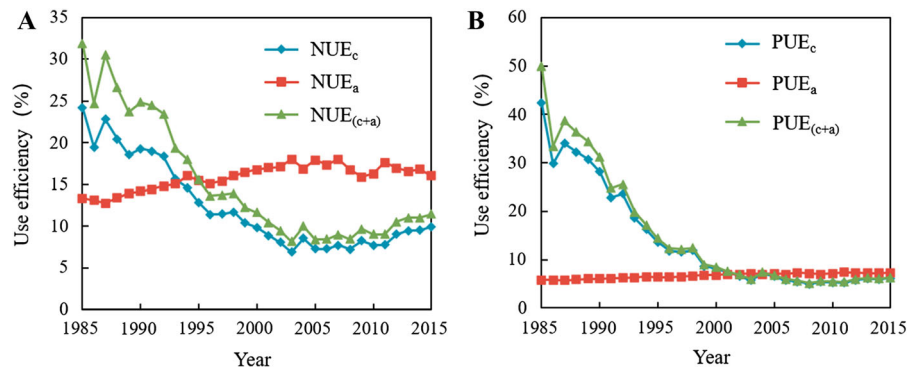


Fig. 4 Nitrogen (N; A) and phosphorus (P; B) use efficiency in crop and livestock systems in Pinghe County from 1985 to 2015. NUE_c and PUE_c indicate N and P use efficiency in crop systems, respectively, NUE_a and PUE_a indicate N and P use efficiency in

livestock systems, respectively, and $NUE_{(c+a)}$ and $PUE_{(c+a)}$ indicate N and P use efficiency in crop and livestock systems, respectively

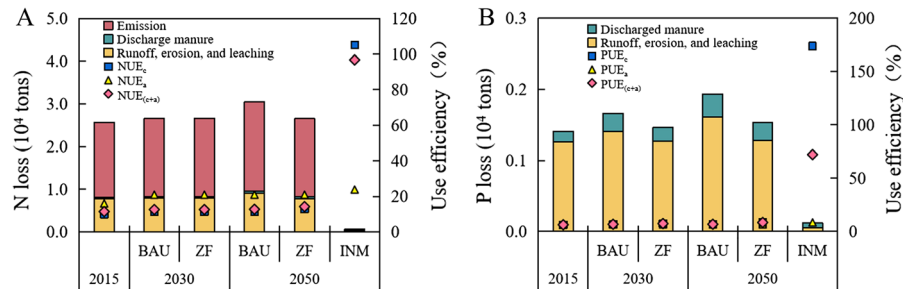


Fig. 5 Nitrogen (a) and phosphorus (b) use efficiency and loss characteristics in Pinghe County under different scenarios. The scatter plots represent the nutrient use efficiency and the cumulative bar charts represent the nutrient losses for different components

the N and P feed input, N and P loss from livestock system and NUE_a and PUE_a .

Discussion

N and P flows in crop-livestock systems and environmental impacts

Synthetic fertilizer input increased to 519 kg N hm^{-2} and $139 \text{ kg P} \cdot \text{hm}^{-2}$ in Pinghe County in 2015. This was 1.9- to 1.5-fold greater than the average inputs in China (MOAC 2016). In some developed countries such as Netherlands, the manure N application rate is limited to 170 kg N hm^{-2} , and organic manure and mineral fertilizer together were limited to $40 \text{ kg P} \cdot \text{hm}^{-2}$ in 2015 (Schröder and Neeteson 2008). In addition, the PUE_c in Pinghe County was only approximately 6% in 2015, while the average PUE_c was more than 60% in several European countries (e.g.

the Netherlands, Germany, France, Ireland, Spain, and Denmark), which have limited P rock reserves (Fageria and Baligar 2005; Oenema et al. 2012; Quemada et al. 2020). In Pinghe County, large amounts of N and P accumulated in soil during the period 1985–2015, which increased soil nutrient levels, and the average soil available P concentration increased from 4 to 124 mg kg^{-1} P (Olsen-P) (PCLCC 2009), which was sixfold greater than the average level in China (NATSC 2015). Of course, these increases in soil fertility are not beneficial to the ecosystem, especially in hot and rainy areas.

Owing to the abundant rainfall in and hilly terrain of Pinghe County, excess N and P can be easily washed away by rainwater, which increase the risk of environmental problems such as excessive NO_3^- levels and eutrophication in water bodies (Ervinia et al. 2019; Wu et al. 2017). Eutrophication is a common phenomenon in major lakes and rivers in Pinghe County. In addition, rapid NO_3^- leaching from

Table 2 Correlation analysis of both the proportion of cash crops and the proportion of monogastric animals and nutrient input, loss, and use efficiency in Pinghe County from 1985 to 2015

Pattern factor	Nutrient use components	Correlation coefficient	R ²
Proportion of cash crops (%)	N fertilizer input	0.961	0.92**
	NUE _c	-0.895	0.80**
	N loss from the crop system	0.940	0.88**
	P fertilizer input	0.983	0.98**
	PUE _c	-0.906	0.81**
	P loss from the crop system	0.983	0.97**
Proportion of monogastric animal (%)	N feed input	0.940	0.88**
	NUE _a	0.507	0.21**
	N loss from the livestock system	0.941	0.88**
	P feed input	0.928	0.86**
	PUE _a	0.887	0.86**
	P loss from the livestock system	0.969	0.94**

The numerals in the table refers to the square of the correlation coefficients. *, $P < 0.05$; **, $P < 0.01$

the soil may lead to the loss of positive ions, resulting in soil acidification (Guo et al. 2010); the soil pH in Pinghe County has decreased from 5.7 to 4.3 during the past three decades (Li et al. 2015).

Although there was a steady increase in NUE_a and PUE_a in Pinghe County from 1985 to 2015 and the NUE_a was close to the average levels in China in 2005 (both 16%), but PUE_a was less than the average levels in 2005 (7% in Pinghe County and 17% in China) (Ma et al. 2012). Moreover, the reported NUE of dairy production reached 19–40% in some leading production countries (Ledgard et al 2004; Hristov et al 2006; Eckard et al. 2007), and the average NUE of broiler production systems worldwide can be as high as 34% (Van der Hoek 1998). Thus, there is still great potential to improve NUE_a and PUE_a. These gaps may be related to the different nutrient contents of animal feed. The USA emphasized reducing protein and P levels in animal feed to protect the environment; however, the P concentrations in China's feed for dairy cattle and poultry were 26–74% and 2–28% greater, respectively, than those in the USA (Guo et al. 2018).

Influence of crop and livestock structure changes on N and P flows

There was a strong correlation between the proportion of cash crop sowing area and nutrient use efficiency in

Pinghe County (Table 2). This may be related to farmer's fertilization habits and crop's economic benefits. According to reports, as much fertilizer as possible was applied to ensure crop yields in the county (Zhang et al. 2020), average N and P fertilizer inputs for cash crops (which, in this study, was mainly pomelo) were 6- to sevenfold higher than those for cereal crops (Chen et al. 2018, 2020; Xu 2019), and the profit from pomelo was approximately 11.6×10^3 USD (\$) hm^{-2} , while the average profit for rice was only 0.9×10^3 USD hm^{-2} in China (Xu 2019). To regulate nutrient inputs, Pinghe County could adopt several policies from European countries, especially in those within "nitrate vulnerable zones" (Oenema et al. 2009).

There was a strong correlation between the proportion of monogastric animals and nutrient use efficiency (Table 2). Monogastric animals are usually present in relatively large proportions on large farms, and compared with chemical fertilizer, manure produced by these animals was used less by farmers in Pinghe County. This may be related to the lower labor costs associated with applying chemical fertilizer (Li et al. 2021). At the same time, there can be harmful germs, unpleasant odors, antibiotic residues, and even heavy metals in manure (Liu et al. 2020b), all of which further reduced the willingness of farmers to apply manure produced in the county in the past (Liu et al.

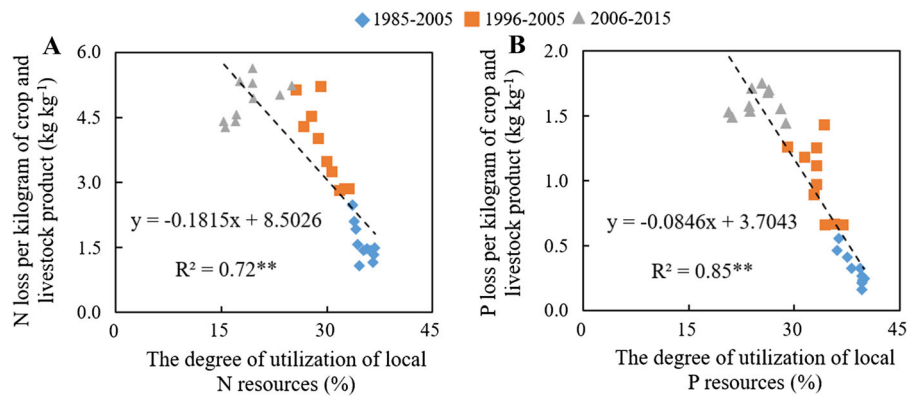


Fig. 6 Relationships between the degree of utilization of local nitrogen (a) and phosphorus (b) and nutrient loss per kilogram of crop and livestock product. ** $P < 0.01$

2020a). In conclusion, this situation may further intensify the decoupling of crop and livestock systems.

Implications for nutrient management

After combining our data with those of previous studies, we propose the following suggestions to improve nutrient management:

- (i) *Control total nutrient inputs.* In Pinghe County, there has been a downward trend of nutrient loss since 2006 in crop systems (Fig. 2a and b), which indicates that the national soil testing and fertilizer recommendation project launched in 2005 has been successful (Chen and Zhang 2006). In addition, the scenario analysis also proved that we can reduce nutrients losses in the future via balanced fertilization (Fig. 5). At the national scale, when the N fertilizer input was reduced by 30% in 2011, N emissions could be reduced by up to 16% (Chen et al. 2016b). At the same time, the results in Pinghe County showed that pomelo yield did not decrease when N and P fertilizer inputs decreased by 43 and 45%, respectively (Xu 2019).
- (ii) *Increase the degree of coupling of crop-livestock systems.* The data showed that when the degree of use of local agricultural resources decreased from 40 to 15%, the amount of N loss per kilogram of product increased by approximately fourfold, while the P loss increased by approximately

ninefold (Fig. 6). In addition, improved manure management could further reduce N and P losses by nearly one-third through precision feeding (Ma et al. 2014).

- (iii) *Adjust the planting structure.* The results show that an excessive proportion of economically important crops can lead to excessive nutrient input (Figs. 1 and 2). From the perspective of market demand and environmental carrying capacity, adjusting the planting structure is good for sustainable agricultural development, which was verified in the research of Yu et al. (2021).
- (iv) *Design a reasonable layout for crops.* The use of remote sensing (RS) and geographic information systems (GIS) to design a reasonable layout for crops could make full use of the altitude gap and the different nutrient requirements of crops to minimize nutrient runoff loss and achieve a reasonable distribution of nutrients (Yousaf et al. 2021)
- (v) *Return additional manure to the field.* Developing a mechanized application of manure or improving the portability of manure can further promote farmers' willingness to recycle manure and indirectly improve nutrient use efficiency in agricultural production systems (Franco et al. 2020).

Limitations and uncertainties

Although this study used a very mature model (NUFER) to quantify the flow characteristics of N

and P in Pinghe County, owing to the lack of relevant research and data, the key nutrient loss parameters are not; therefore, there is still some uncertainty associated with the results. Table S12 shows that when the N and P loss parameters were reduced by 35–60%, the total N and P loss decreased by 0.3–20% and 3.4–54%, respectively. However, the crop-livestock system nutrient use efficiency values changed little.

Conclusion

This study used the NUFER model to estimate the nutrient (N and P) flows in crop-livestock systems in an emerging county in China. The results show that the N and P inputs in the crop-livestock system increased sharply (from 11.0 to 53.0 Gg and from 1.2 to 11.9 Gg, respectively), and that the system nutrient use efficiency decreased (from 32 to 11% for N and 50 to 6% for P) during the period from 1985 to 2015. The main direct reasons for the decrease in system nutrient use efficiency were the sharp increase in nutrient input and the decrease in the internal nutrient recycling rate. The indirect reasons may be due to changes in crop and animal type composition, i.e., the proportion of cash crops and monogastric animals continued to increase. Reducing chemical fertilizer inputs, improving both the feed conversion rate and manure management, and increasing the utilization of recyclable nutrients will maximize the N and P use efficiency of crop-livestock systems. Therefore, to achieve sustainable development of agricultural systems, it is necessary to rationally allocate the types and scale of crops and animals while improving nutrient management.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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