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Nitrogen, phosphorus and potassium flows through the manure management chain in China

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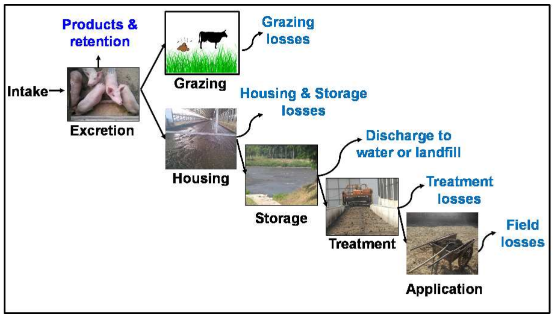
Abstract:

China is the biggest livestock production and largest fertilizer user country in the world. However, quantification of nutrient flows through the manure management chain and their interactions with management-related measures is lacking. Here, we present a detailed analysis of nutrient flows and losses in the “feed intake – excretion – housing – storage – treatment – application” manure-chain, while considering differences between livestock production systems. We estimated the environmental loss from the manure-chain in 2010 to be up to 78% of the excreted nitrogen, and over 50% of excreted phosphorus and potassium. Greatest losses occurred from housing and storage stages, via NH_3 emissions (39% of total nitrogen losses), and direct discharge of manure to water bodies or landfill (30-73% of total nutrient losses). There are large differences between animal production systems, where the landless system has the lowest manure recycling. Scenario analyses for the year 2020 suggest that significant reductions of fertilizer use (27%-100%) and nutrient losses (27-56%) can be achieved through a combination of prohibiting manure discharge, improving manure collection and storages infrastructures, and improving manure application to cropland. We recommend that current policies and subsidies targeted at the fertilizer industry should shift to reduce the cost of manure storage, transport and application.


Products &
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Storage
Treatment
losses
Treatment
Field
losses
Application

INTRODUCTION

Intensive livestock production systems have large impacts on water and air quality through emissions of greenhouse gases (GHG) and nutrients (mainly nitrogen (N) and phosphorus (P)[1-4]. The N and P emissions originate mainly from livestock excrements. Total livestock excretion in the world is about 80-130 Tg N per year, from which only 20-40% is efficiently utilized for fertilizing cropland[5-6]. The remainder of the manure N excreted is emitted to the atmosphere, groundwater or surface waters. However, there are large differences in manure management throughout the world, depending on livestock production system, environmental conditions and governmental policy measures. For example, on average 65% of excreted N in animal housing is recycled back to agricultural land in the Europe Union (EU), which is in part a result of strict regulations[7]. At the farm level, there can be large differences. A survey in Africa showed that 6-99% of collected manure is recycled cropland[8]. In China, a large proportion of manure N from pig production is lost via direct discharge into water bodies or is landfilled[9-10].

Recent studies have used material flow and nutrient footprint approaches to quantify N and/or P losses and use efficiencies for whole livestock production systems at global level[11], regional level (EU[12,13]) and national level (United States, USA[14]). Several models have been developed to estimate the nutrient flows and losses in livestock production, e.g. MITERRA-Europe[15], NUFER (NUtrient flows in Food chains, Environment and Resources use)[16], and GAINS (Greenhouse Gas–Air Pollution Interactions and Synergies)[17]. Some other models have been developed to estimate single pollutant losses from livestock systems, e.g. ammonia (NH_3) losses emission from manure management[18]. However, there are no models available yet that can calculate N, P and potassium (K) flows and losses in detail for each step in the "feed intake – excretion – housing – manure storage – manure treatment – manure application" chain in a consistent way for the different animal categories and production systems, at the regional level. A further understanding of the manure nutrient flows and losses is important, because previous studies showed that the effects of feeding regimes and manure management practices strongly differ between livestock production systems[10,19]. For example, N losses from traditional dairy production systems in China, mainly occur through NH_3 emissions, and in the industrial dairy feedlots mainly through direct discharge of manure to water bodies or landfill[10]. Information about the effects of management-related technical measures and their interactions on manure nutrient recycling and subsequent chemical fertilizer needs are still lacking. Such insights are needed for achieving low emission livestock production systems and sustainable agriculture in China[20].

China is a major contributor to world livestock production, and both extensive and intensive systems exist[21,22]. Industrial-scale livestock operations are rapidly increasing in their contribution to total livestock production, mainly because of their large production capacity and high feed use efficiency on the farm. However, most of these industrial systems are landless and have limited opportunity to recycle manure nutrients back to crop land. Recently, the Chinese government initiated a plan to stabilize fertilizer consumption by 2020, the so-called "Zero Fertilizer Increasing by

2020" goal[20]. The consumption of K fertilizers is large[22] and there are no studies in which the potential of replacing fertilizer K by manure K has been assessed.

The aim of this study was to estimate the manure N, P and K flows and losses in the "feed intake – excretion – housing – storage – treatment – application" chain for different animal categories and production systems in China for the year 2010, using a modified version of the NUFER model. We developed a 'K module' and included it in the NUFER model. The analyses were carried out for different animal categories (pigs, layers, broilers, dairy cattle, beef cattle, buffaloes and draught cattle, and sheep and goats) and different production systems (mixed, grazing and landless systems). In addition, five scenarios were explored to assess the potentials for reducing manure N, P and K losses and for replacing fertilizer inputs by manure nutrients for the year 2020.

MATERIALS AND METHODS:

The NUFER model[16] was further developed and used to estimate N, P and K flows and losses in each step of the manure management chain. This model uses a mass balance approach; it starts with an estimation of total feed nutrients intake rate for the different animal categories. The calculation methods and parameters used are presented in detail in the Supplementary Information (SI). Below a summary is given.

Description of livestock production systems

In total, six animal categories and three typical (for China) production systems were distinguished. The six main animal categories include pigs, layers, broilers, dairy cattle, other cattle (beef cattle, buffaloes and draught cattle), and sheep and goats. Together these categories generate most of the manure in China[23]. For each animal category we distinguished three different production systems, according to the feeding regimes, manure management practices and available statistical data, i.e. mixed cropping-livestock system, grazing production system and landless production system (Table S1). Mixed cropping-livestock systems are basically the traditional production system; the solid part of excretion is collected and mainly applied to cereal crops, while the liquid fraction is only partly collected and the remainder is lost by leaching into the subsoil and wider environment. Grazing systems are mainly found in Gansu, Xinjiang, Ningxia, Tibet, and Inner-Mongolia provinces[16], see also Fig S1. Most of the excretion is directly dropped to grassland, during the grazing period. The solid part of the excretion is collected when the animals are kept in confinement; however, the liquid part is mainly leached to the subsoil. The industrial production systems are landless; a large fraction of the manure produced in landless systems is discharged into surface waters, with or without some treatment, or dumped into landfills. A part of the solid manure is exported to nearby farms growing vegetables and fruits following composting treatment. The livestock production structure (i.e. the percentage of each system per animal category) in 2010 was derived from national statistics[21]. Information about the definitions and animal population of each production system is listed in Tables S1 and S2 in the SI.

Feed and nutrient intake calculation

Total feed intake was calculated from the number of livestock for each category and the feed requirements per animal category. Feed intake was estimated on the basis of the energy requirements for maintenance, growth (live weight gain) and production (Bai et al. 2013; 2014)[9,10]. The number of animals per category was derived from MOA statistics[21] and the FAO database[22]. For pigs and broilers, the number of slaughtered animals was used, and for dairy and layers, the numbers of producing animals [22]. Stock numbers were used for beef cattle, buffaloes and draught cattle, and sheep and goat production[22]. Feed intake was estimated from energy requirements per animal category and feed supply according to data from the FAO database and farm surveys [16,22]. Feed-specific N, P and K contents were derived from literature (Table S9). The excretion of nutrients was calculated as the difference between feed nutrient intake and the nutrient retained in products (milk, eggs) and in body weight gain (meat, blood, bones and hides).

Nutrient retention by livestock

Nutrient (N, P and K) retention was calculated at the herd level per animal category (considering the breeding and backup animals). In a simple form (for one animal category, production system), the equation for estimating retention showed as below:

$$Oa_{\text{nutrient in products}} = (\text{Yield} + \text{BWG}) * \text{Animal number} * \text{Nutrient content} \qquad [1]$$

Where, $Oa_{\text{nutrient in products}}$ is the total amount of N, P or K in animal body weight gain, milk and egg, in kg per year; Yield is the yield of animal products (milk and eggs), in kg head^{-1} yr^{-1}; BWG is the body weight gain of animals, including meat, bones, blood and hides, in kg head^{-1} yr^{-1} (Table S5-7); Nutrient content is the N, P or K content of milk, eggs and BWG, in kg kg^{-1}. The N and P contents were derived from the NUFER database[16]. The K content was derived from literature (Table S8).

Nutrient excretion

Nutrient excretion was calculated as the difference between total nutrient intake and nutrient retention in milk, egg and BWG. In a simple form:

$$Oa_{\text{nutrient excretion}} = Ia_{\text{nutrient intake}} - Oa_{\text{nutrient in products}} - Oa_{\text{nutrient in dead animals}} \quad [2]$$

Where, $Oa_{\text{nutrient excretion}}$ is the amount of nutrient (N,P and K) excreted per animal category, in kg yr^{-1}; $Oa_{\text{nutrient in products}}$ is the amount of N, P and K output in milk, eggs and BWG per animal category and production systems, respectively, in kg yr^{-1}; and $Ia_{\text{nutrient intake}}$ represents the amount of N, P and K in feed intake per animal category and production system, in kg yr^{-1}. Corrections were made for animals that died during the production cycle ($Oa_{\text{nutrient in dead animals}}$); it was assumed that the nutrients in dead animals ended up landfill, possibly following incineration.

Nutrient use efficiency and manure nutrient recycling efficiency

The N, P and K use efficiencies and manure nutrient recycling efficiency were calculated at herd level as follows:

$$\text{Nutrient use efficiency} = (Oa_{\text{nutrient in products}} / Ia_{\text{nutrient intake}}) * 100\% \quad [3]$$

$$\text{Manure nutrient recycling efficiency} = (Oa_{\text{nutrient recycled}} / Oa_{\text{nutrient excretion}}) * 100\% \quad [4]$$

Manure nutrient recycling efficiency is the percentage of excreted N, P and K recycled to agricultural land per animal category and production system. $Oa_{nutrient\ recycled}$ is sum of the amounts of N, P and K deposited during grazing and applied to agricultural land per animal category and production system, in kg yr^{-1}.

Fertilizer replacement by manure

The potential to replace fertilizer by manure was calculated as follows:

$$\text{Fertilizer replacement} = \{(\text{Manure application} * \text{Fertilizer value}) / \text{Fertilizer application}\} * 100\% \quad [5]$$

Where, Fertilizer replacement is the amount of fertilizer N, P and K that can be replaced by manure N, P and K, in %; Manure application is the amount of manure N, P and K applied to cropland (excluding manure N, P and K deposited during grazing because essentially no fertilizer is applied to grassland in China), in kg yr^{-1}; Fertilizer value is the proportion of the manure N, P and K available to crops in the first season, in % (Table S13); Fertilizer application is the amount of fertilizer N, P and K applied to cropland in 2020, in kg yr^{-1}. Fertilizer values differ per animal manure type and nutrient. The total fertilizer application in 2020 was estimated from the total N, P and K fertilizer application in 2015[22], and the expected increase in fertilizer use during the period 2015- 2020[20].

Scenarios for 2020

A total of five future scenarios were considered to explore the potential for reducing nutrient losses from the manure management chain and the potential for replacing fertilizer nutrients by manure nutrients, The year 2010 was used as the reference year because of data availability, and 2020 was set as a target year, because of China's aim to achieve "Zero Fertilizer Increase Use" by the end of 2020[20]. According to the projections by FAO, the total demand for animal products in China will increase by 17% for pork and eggs, 33% for chicken meat, 24% for milk, 24% for beef, and 22% for mutton[24] between 2010 and 2020.

S0 – Business as usual (BAU). Production of animal products was based on linear extrapolations of the projections of FAO between 2010 and 2020[24]. In this scenario, we assumed that the increase in the demand for livestock products would be produced in land-less systems. We also assumed that the productivity, feed composition and manure management practices of each system would be the same as in 2010, which may provide a conservative estimate of manure nutrient production, flows and losses. Changes in animal numbers between 2010 and 2020 are shown in Table S2.

S1 – Prohibit the discharge of manure. This scenario builds on S0, but includes an adoption of stricter manure management regulations[25]. We assumed that the discharge of manure to surface water or landfill will be prohibited in the industrial animal production systems.

S2 – Improving manure collection and nutrient preservation in housing and storage systems. This scenario builds on S0, and assumes in addition that the N losses (in % of excreted N) from animal housing and storage systems will decrease to current mean levels in the European Union (EU), i.e., the average N losses via NH_3,

N_2O and N_2 emissions to air and via N leaching will decrease to 5%, 1%, 5% and 0% of the amount of manure N excreted, respectively[26]. Further, there will be no losses of manure P and K from industrial production system due to improved containment of manures.

S3 – Improving manure application. This scenario builds also on S0. Current crop production in China does not account for nutrients supplied by manure, especially in cash crop production (e.g. in greenhouse vegetables and orchards) in which the amounts of nutrient applied with fertilizer and manure far exceed the nutrient demand of the crop[27]. We assume that the available nutrients in manures applied to cropland replace fertilizer nutrients, using manure-specific fertilizer nutrient replacement values. Further, we assumed that low ammonia emission manure application methods will be adopted, i.e. slurry injection and rapid incorporation of solid manures, by which the N fertilizer replacement value of manures will increase to 55% for cattle slurry, 75% for pig slurry and 85% for poultry manure (Table S13).

S4 – Combination of S1-S3. In this scenario, the technologies assumed for S1, S2 and S3 are combined. Further, we assumed that the technologies can be applied as complements to each other.

RESULTS

Nutrient flows through the whole manure chain

The N, P and K flows in the manure chain for the year 2010 are presented in Fig 1. Total feed N intake amounted to 26.0 Tg, from which 22.8 Tg N was excreted (3.5 Tg

N was deposited in the field during grazing and 19.3 Tg N was excreted in housing systems). Total N losses via NH_3 emission, denitrification, and leaching from housing amounted to 8.3 Tg. In addition, a significant amount (5.4 Tg N) was lost via discharge to water bodies or landfill. The collected manure (5.6 Tg N) was treated (by composting, digestion or separation), which led to another N loss of 1.6 Tg. In total, only 4.0 Tg manure N was applied to cropland, i.e., 68% to cash crops and 32% to cereals crops. Total N losses via gaseous emissions, leaching, runoff and erosion during grazing and after manure application were estimated at 1.5 Tg. The remaining manure N was either taken up by crops or accumulated in the soil. In total 78% (17.8 Tg N, including field losses) of the excreted N was lost to the environment from the different stages of the manure management chain. The highest losses occurred from housing and manure storages (47% of total N loss), followed by discharge of manure to water bodies or landfill (30%), losses during treatment (9%) and losses following manure application (8%) and grazing (6%).

About 50% of the total amount of excreted P (4.6 Tg) and 53% of the total amount of excreted K (16.2 Tg) were recycled in pastures and cropping systems. Similar to N, cash crops received the highest amount of manure P. However, the applied manure K was more evenly distributed between grassland, cereals and cash crops, as most of the K came from other cattle, and sheep and goat production (Fig 2, 3)

Contributions of different animal categories and production systems

Fig 2 presents the relative contributions of different production systems and animal categories to total manure nutrient flows and losses. Clearly, the manure nutrient flows were largest in the mixed production systems, accounting for 53%-57% of total nutrient excretion. Nutrient excretion was smallest in grazing systems. Nutrient recycling was smallest in the landless production system and largest in grazing systems. The P losses were relatively low in grazing systems (3% of total manure P losses), and high in mixed and landless production systems. Manure production was highest for the category beef cattle, buffaloes and draught cattle, followed by sheep and goats and then pigs. Pigs excreted two times more P than sheep and goats. The contributions of layers, broilers and dairy cattle to manure nutrient flows were relatively small (Figure 2).

Nutrient use efficiencies at herd level

The average feed nutrient use efficiency at herd level, across all livestock categories, was 11% for N (NUE), 14% for P (PUE), and 2.7% for K (KUE). The low KUE was related to the low K contents of meat, milk and egg. The landless production systems had much higher nutrient use efficiencies than the other two production systems (Figure 3a). For example, the NUE of landless systems was 21%, almost six times that of grazing systems. The mixed production system was more efficient than the grazing system to convert feed N and K into products (Figure 3a), but the grazing system had a higher PUE than the mixed system.

The NUE at herd level was highest for broilers (40%) and lowest for beef cattle, buffaloes and draught cattle (2.3%). Similar results were found for PUE and KUE.

The monogastric animals (broilers, layers and pigs) were more efficient than the ruminant livestock categories (dairy cattle, beef cattle, buffaloes and draught cattle, sheep and goats) in utilizing feed nutrients (Fig 3b).

Manure nutrient recycling efficiency

The manure N recycling efficiency decreased in the order of grazing (54%) > mixed (34%) > landless (19%) production system. Similar trends were found for manure P and K recycling efficiencies (Figs. 3c and 3d). The manure nutrient recycling efficiency of grazing systems was about two times greater than that of the landless system (Fig 3c). The manure nutrient recycling efficiency ranged from 20 to 40% for N, 30 to 62% for P, and 30 to 65% for K, depending on animal category and production system. The manure nutrient recycling was higher for ruminant animals than for monogastric animals (Fig 3).

Losses of nutrients from the manure management chain

Total N losses from the whole manure management chain amounted to 17.8 Tg in 2010 (Fig 4). Emission of NH_3 (6.9 Tg; 13 kg N ha^{-1} agricultural land) and discharge of manure to surface waters or landfill (5.4 Tg, 11 kg N ha^{-1} agricultural land) were the major N losses pathways. Losses via leaching, runoff and erosion (L&R&E) amounted to 3.4 Tg N (6.6 kg N ha^{-1} agricultural land). Losses via denitrification and N_2O emissions were 1.8 (3.5 kg N ha^{-1} agricultural land) and 0.3 Tg (0.5 kg N ha^{-1} agricultural land, respectively. Direct discharge of manure to water bodies or landfill contributed 78% to the total manure P losses and 61% to the total manure K losses. The total average N loss was 35 kg N ha^{-1} cropland. Average P and K losses were 5.0kg P ha^{-1} and 16 kg K ha^{-1} cropland, respectively.

Animal production systems differed in nutrient loss pathways (Fig 4). Most of the N losses via NH_3, N_2O and N_2 emissions to air, and via leaching, runoff and erosion to water bodies occurred in mixed production systems. Direct discharge of manure into watercourses or landfill represented the largest N loss pathways in landless production system, while there was no discharge of manure nutrient in grazing systems. Ammonia emissions were the largest N loss pathway in mixed systems. Highest P losses were found in pig and poultry production and in landless production systems. Monogastric animals contributed around 50% to the N losses via direct discharge, while ruminant animals were the dominant source of N losses via leaching, runoff and erosion.

Scenarios for 2020

In the S0-business as usual scenario, manure management contributed to reduce 1% of N fertilizer, 12% of P fertilizer, and 34% of K fertilizer (Fig 5). The changes in fertilizer replacement are relatively small in the scenario where direct discharge of manure was prohibited (S1). This is because most of the recycled manure was applied to cash crops; these crops are over-fertilized and more manure does not affect the fertilizer use. Also, a ban on direct discharge is not easy to implement, as it will require additional investments in manure storage, transportation and spreading infrastructure, thus increasing the cost. Improving manure collection in housing and storage systems (S2) has also little impact on fertilizer replacement rates, for similar reasoning (Fig S2). Improving manure application strategies (S3) seems more promising than the other two single options; it increases the N fertilizer replacement to 11%, the P fertilizer replacement to 43% and K fertilizer replacement to 76%.

In S0, the total N losses from the whole manure management chain will increase by 15% in 2020 compared with 2010. The total P and K losses will increase by 12% and 22%, respectively (Fig 5b). In all single options, S1 is more effective than S2 and S3 in reducing nutrient losses. The N losses can be reduced by 14%, P losses by 47% and K losses by 40% through the prohibition of direct discharges of manure to surface water or landfill and the application of manure to agricultural land. The integrated option (S4) is more effective than the single options, both in reducing fertilizer input and reducing manure nutrient losses. In the combination scenario (S4), 27% of the chemical N fertilizer, 86% of the chemical P fertilizer and all of the chemical K fertilizer can be replaced by optimizing the management of manure. At the same time, manure N losses can be reduced by 27%, P losses by 56% and K losses by 53%, compared with those in the S0 scenario (Fig 5).

DISCUSSION

This is the first study on N, P and K flows through the whole manure management chain of different livestock categories and production systems in China, that quantifies the impacts of management and technical measures to reduce N, P and K losses. In 2010, 33 % of the excreted N, 50% of excreted P and 53% of excreted K were recycled, with the rest being lost to the environment at different stages of the manure chain. In contrast to many other countries in the world, the greatest losses occurred via direct discharge of manure to watercourses and landfill. Highest nutrient losses occurred in mixed production systems with other cattle (beef and draught cattle and buffaloes). The results of this study indicate the key stages (animal housing and manure storages), production systems (landless systems) and livestock categories (other cattle and pigs) where policy and research on manure management should be focused in China in the future.

Through analysis of the impacts of management-related technical measures, we found that significant reductions of nutrient losses (27-56%) and inputs of fertilizers (27%-100%) could be achieved by 2020. To achieve such reductions, polices for prohibiting direct discharge of manures into watercourses and landfill, improving manure collection and storage infrastructure, and improving manure application methods should be coordinated in the future. The main uncertainties in the results of this study are related to the robustness of the statistical and literature data and the emission factors used. Additional farm level monitoring and measurements of nutrient losses are needed in the future to estimate the nutrient flows more accurately, e.g. gaseous emissions and leaching of nutrients from different livestock systems, and fertilizer replacement values of different manures.

Manure nutrient excretion, losses and recycling in China

Our estimate of total N excretion in 2010 (22.8 Tg) was higher than the net N excretion of some other studies, such as 16 Tg N in 2010[23], 17 Tg N in 2005[28], and 19 Tg N in 2005[16]. These other studies presented the net excretion only, i.e., they corrected the total excretion for gaseous N losses in housing and storages[16, 23, 28]. The average gross N and P excretions per animal category were rather similar to reported gross nutrient excretion rates for the EU[29] (Table S17). Total excretion was 4.6 Tg for P and 16.2 Tg for K in 2010, which is rather similar to those of previous studies, i.e. 5.2 Tg P in 2010[23], 4.4 Tg P in 2005[16], and 14 Tg K in 2005[28].

The estimated NH_3 emissions (6.9 Tg NH_3-N) and N_2O emissions (0.3 Tg N_2O-N) were higher than the estimates of other studies (5.3 Tg NH_3-N in 2006[30,] and 0.2 Tg N_2O-N in 2007[31]). These differences are partly because net N excretion (excluding gaseous N losses from housing) was used in one of the previous studies, and partly because N losses following manure application were not included in the other study[23].

In our study, 7.5 Tg manure N (representing 33% of excreted N) was either deposited in grassland by grazing livestock, or applied to cropland (Fig 1). This amount is similar to estimate provided in the study of Ma et al (2010) [16], who reported that 32% of the excreted N was recycled in 2005, but lower than that of Liu et al (2010)[28], who reported that more than 50% of the excreted N was recycled in 2002. The latter study did not consider N losses in all stages of the manure management chain and therefore overestimated the amount of manure recycled. About 50% of the excreted P was recycled, which is similar (45%) to that reported by Liu et al (2016)[32]. Our results suggest that around 8.7 Tg K was recycled, out of the 16 Tg K excreted in 2010.. A nearly similar amounts of K excreted was lost via direct discharge of manure to water bodies or landfill (61%) and leaching to the sub-soil (39%). Leaching coefficient for K were derived from composted manure (Table S12), and applied to the housing, storage and treatment sector for the other manure types of manure, due to lack of data. As composted manure contains relatively lower K in solution, our estimation for K leaching may be relatively low.

Comparison with manure management in other countries

About 33% of the excreted N and 50% of the excreted P were utilized in China in 2010 (Fig 1). Table 1 shows that these percentages were smaller than those reported for USA (75% of the manure N and P is recycled[33,34], the EU (80% of the manure N and almost 100% of the manure P is recycled[12,35]), and Japan (70% of the manure N and 80% of the manure P is recycled[36,37]). The differences between China and these other countries are mainly related to environmental regulations. Manure storage and application to agricultural land is regulated in the EU (e.g. Nitrates Directive, Water Framework Directive, and National Emission Ceiling Directive)[7]. The Nitrates Directive regulates the use of N in agriculture, especially through designation of "Nitrate Vulnerable Zones" and establishment of Action Plans in these areas, e.g. the maximum N applied via livestock manure shall not exceed 170 kg^{-1} ha^{-1} yr^{-1}, and there are ‘closed periods’ for manure and fertilizer applications, and obligation for leak-tight manure storages with storage capacity per farm of 6-9 months[38]. The zero-discharge manure systems in USA regulate for manure storage, land application and whole-farm nutrient management planning, resulting in a higher manure recycle efficiency than in China[39,40] (Table 1). Incentives and taxes can have an important role within some of these policies; for example excess phosphate on farms in the Netherlands was taxed at 9.08 euro for each additional kilogram that exceeds a defined limit[42] until 2006However, until a new policy was initiated in 2014, to control the environmental problems resulting from industrial livestock production systems[25], there has been little in the way of manure regulations in China. Direct discharge of manure to water bodies is still a major loss pathway. Discharge of manure is forbidden in the EU and USA because of the implementation of the Nitrates Directive in EU[42] and specific member states resolutions[43] and USA federal regulations[39,40]. Current polices in China mainly focus on manure processing and treatment, to promote recycling of manure[44]. However, our results show that the amount of manure that is treated and subsequently applied to crops only represents a small part of the excreted amount of nutrients (Fig 1). Hence, the effectiveness of these policies is still low.

Implications for future manure management

Grassland is extensively managed in China, barely receiving any fertilizers. Hence, improved recycling of manure from animal confinement in grazing systems will not replace fertilizer, but yet may improve pasture production. In contrast, fertilizer and manure P application rates of 261 and 310 kg P ha^{-1} $year^{-1}$ have been reported for greenhouse vegetable production systems[27]. Although production is high in these systems, the high fertilizer applications rates suggest that manure applied to these cash crops did not replace much fertilizer. Only manure nutrients applied to cereal crops were considered to replace fertilizer nutrients in this study. Yet, there is a large potential for replacing fertilizer NPK by manure NPK.

In 2020, the total nutrient excretion will amount to 26 Tg N, 5.2 Tg P and 19 Tg K. Results presented in Fig 5 indicate that the objectives of “Zero Fertilizer Increasing by 2020” can be achieved, and that fertilizer use can be reduced by 27% for N, 82% for P and 100% for K if the integration of manure management options (S4) can be implemented successfully. Even more fertilizer can be saved if over-fertilization is decreased through the implementation of balanced fertilization[45].

Recycling of manure is not only environmentally beneficial, through the mitigation of nutrient losses, it is also economically profitable. The annual value of manure nutrient in China is equivalent to 190 billion Yuan (roughly 25 billion Euros), based on the prices of N, P, and K in fertilizers[23], and the availability of N, P and K present in animal manure. However, the cost to manure application to crop land is higher than the cost of fertilizer application. In 2015, around 100 billion Yuan of subsidies (equivalent to 13 billion Euros), was provided to the fertilizer industry in China. Redirecting these subsidies for the fertilizer industry towards manure storage infrastructure, manure transportation and manure application would promote more sustainable use of manure nutrients in the future.

There are also other barriers to recycling manures nutrients to agricultural land effectively and hence reduce losses, e.g. the lack of information about manure nutrient contents and their bioavailability, a shortage of machines to transport and apply manure, the in-efficient extension services[23], and poor infrastructure in terms of housing and storage systems. More studies are required to improve the accuracy of the estimations of nutrient losses and nutrient efficiency in the whole manure chain. In particular, information is needed on the fertilizer replacement value and nutrient availabilities of different manure types applied to the major crops in typical soil and climates in China, to provide the evidence base for a manure management recommendation system. Further investments are needed to improve the infrastructure and management of the farms.

Extensive livestock systems are generally found in remote areas in China, e.g. in Northwest where land degradation is serious, in part because of overgrazing[47]. Intensive livestock production tends to cluster in locations with cost advantages (often close to cities) where insufficient land is available for the recycling of waste from livestock. This may lead to an overload of manure nutrient in these regions. A regional specific analysis is needed to propose region-specific strategies, for effective manure use and mitigation of nutrient losses[48]. There are also other potential environmental problems related to manure management, e.g. antibiotics and heavy metals are of concern. Residues of veterinary antibiotics have been detected in manures and surface water around livestock production farms[49,50], and even in the urine samples of children[51]. These problems should also be considered through manure chain management strategies.

To conclude, only 33% of the excreted N is recycled, which is less than has been estimated in previous studies. Further, 78% of the excreted N by livestock in China is lost to the environment (including losses after manure application to land, accounted for 11% of total N excretion). Nutrient use efficiencies and manure recycling efficiencies differed greatly between systems and animal categories. There is considerable potential to reduce NPK losses from the manure management chain, and to increase the amount of manure applied to crop land and replace fertilizer NPK through adopting integrated options. However, to improve manure utilization, large changes and investments to livestock farm infrastructure, i.e. animal housing, manure storage, and facilities for manure transportation and application, are needed. An integrated manure and fertilizer nutrient recommendation system has to be developed that takes account of the total nutrient and available nutrient content of manures. Finally, the improved knowledge needs to be disseminated to farmers. .

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Table 1. Manure nitrogen (N) and phosphorus (P) excretion, utilization in crop land, and losses in United States of America (USA), Europe (EU), Japan and China.

	USA		EU		Japan		China**	
Year	2002[33]	2007[34]	2000[12]	2000[35]	2005[36]	2005[37]	2010	2010
	N	P	N	P	N	P	N	P
Excretion (Tg)	6.8	1.7	10.4	4.2	0.73	0.19	22.8	4.6
Utilization (Tg)	5.0	1.3	8.4	4.2	0.51	0.15	7.5	2.3
Losses (Tg)*	1.8	0.4	2.0	0.01	0.23	0.04	15.3	2.3

*Not including losses after manure application to crop land.

**This study.

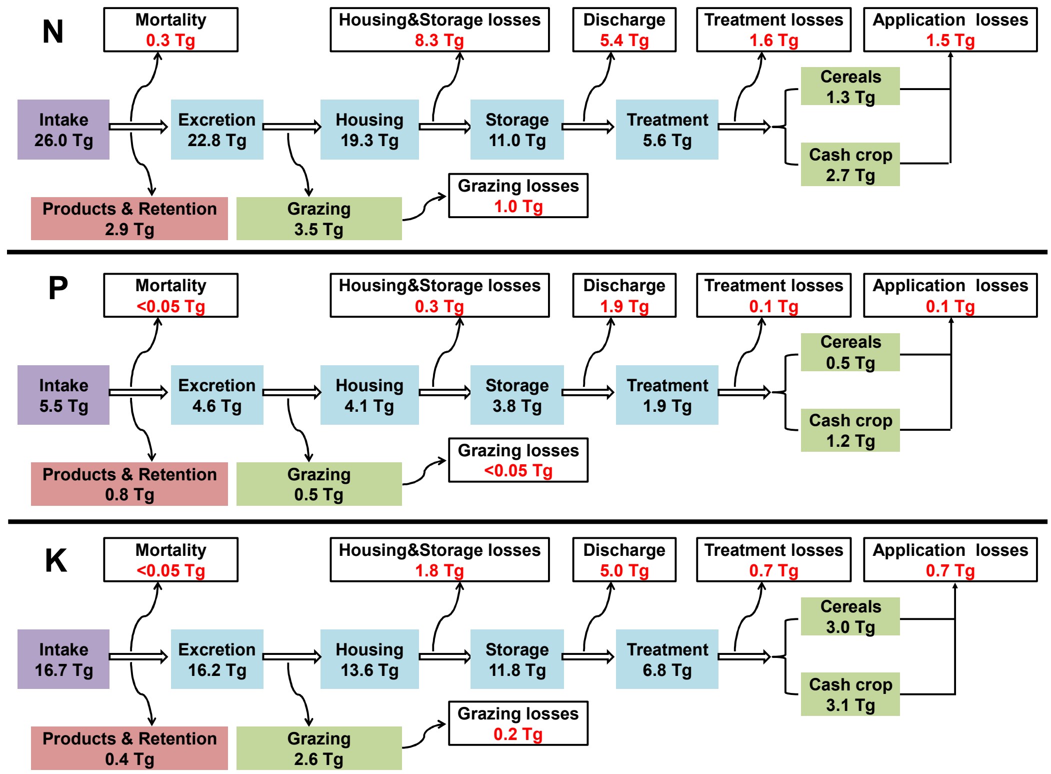

Figure 1. The nitrogen (N), phosphorus (P) and potassium (K) flows through the manure management chain in China in 2010.

Discharge, direct discharge of manure to water body or landfill.

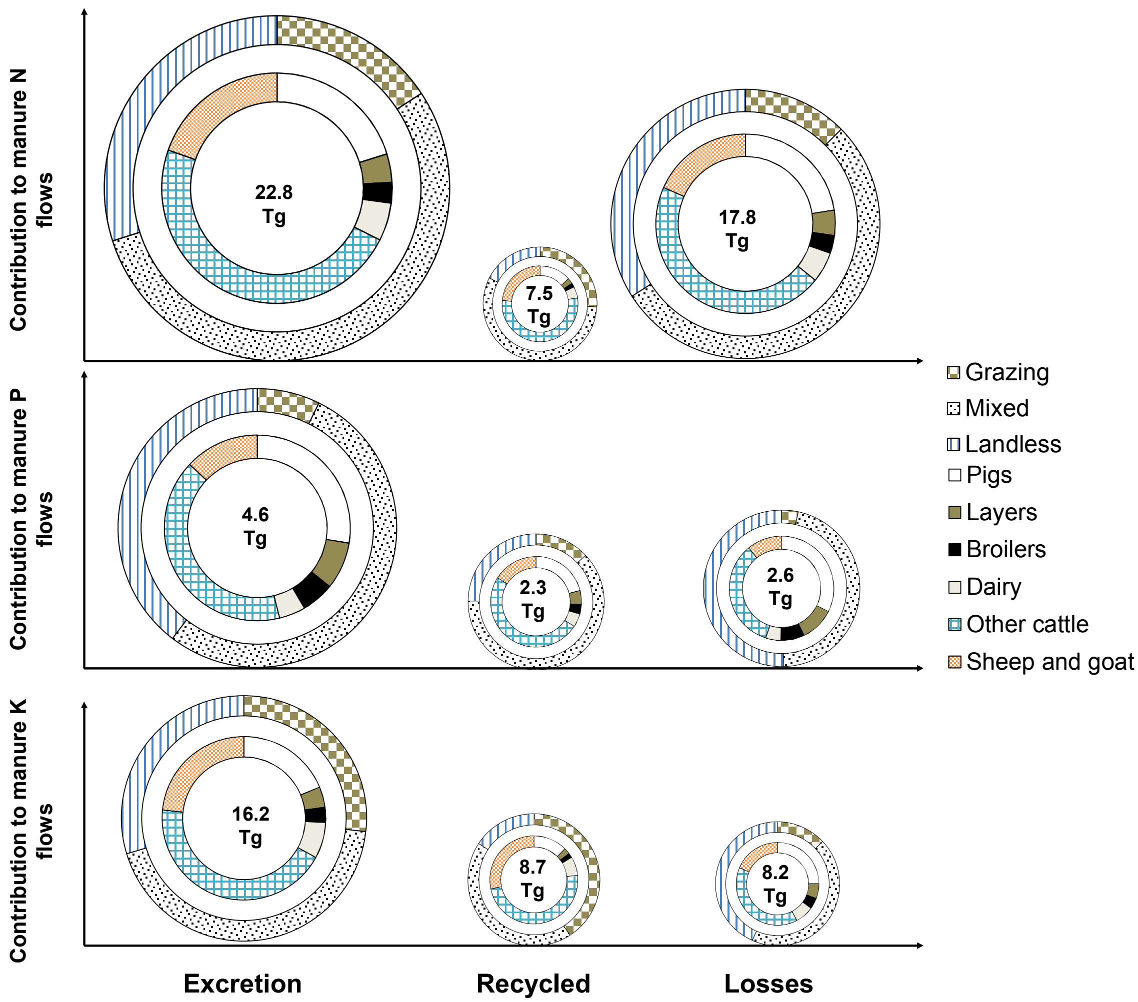

Figure 2. The relative contribution of different animal production systems (outside circle) and animal categories (inner circle) to the total manure nitrogen (N), phosphorus (P) and potassium (K) excretion, recycling to agriculture land and losses to the environment from livestock production in China in 2010.

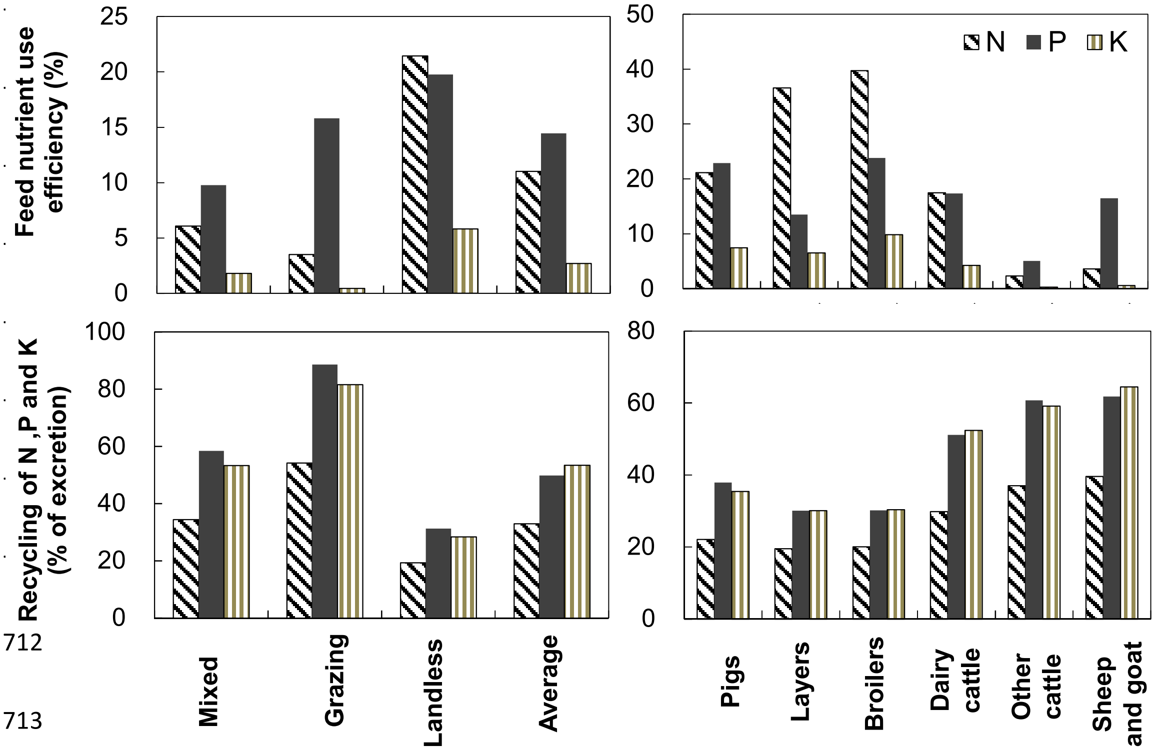

Figure 3. The nitrogen (N), phosphorus (P) and potassium (K) use efficiencies at the herd level for different production systems (a), and animal categories (b), recycling rate of excreted N, P and K for different production systems (c), and animal categories (d).

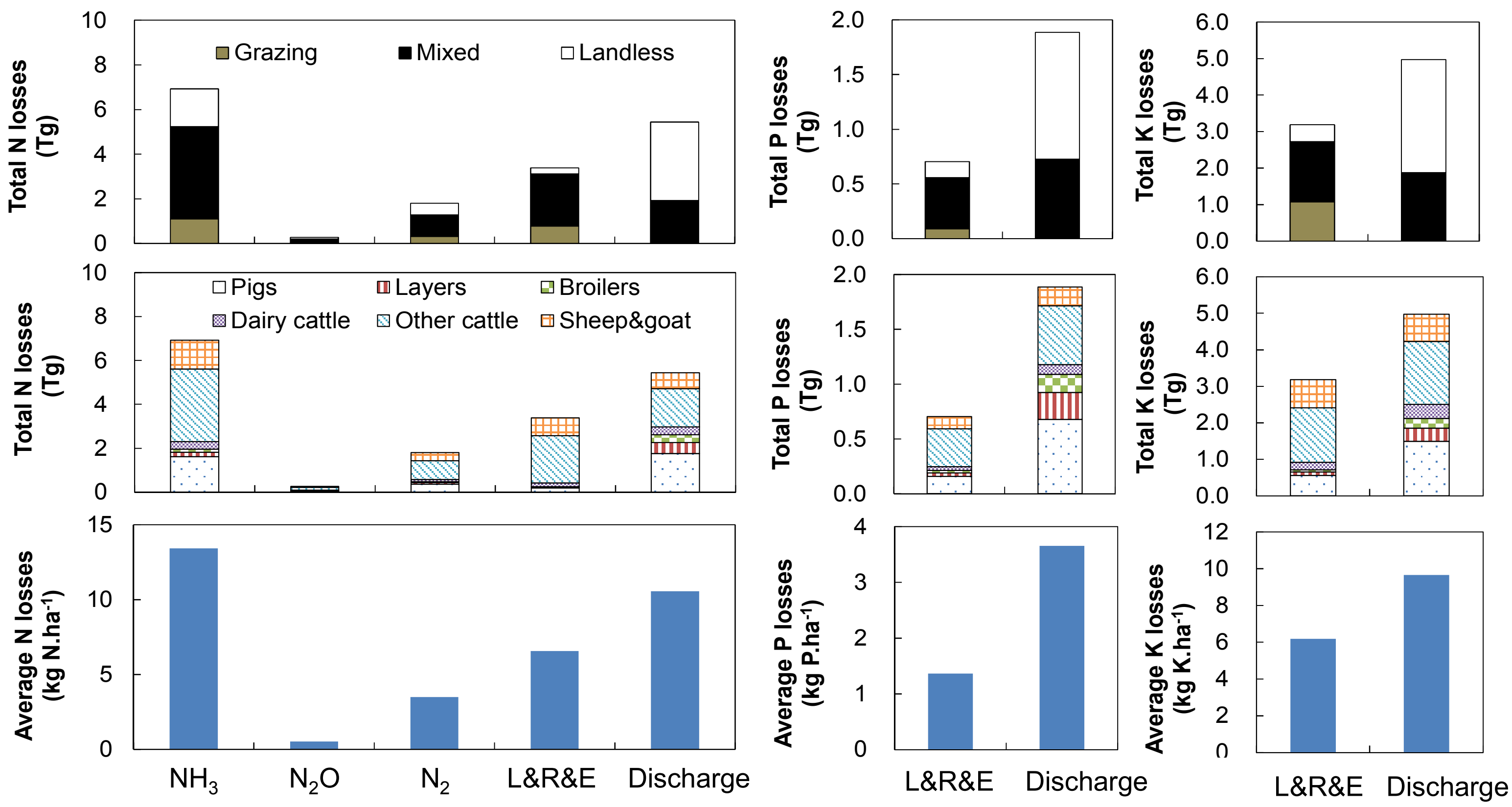

Figure 4. The contribution of the different animal categories and production systems to the total nitrogen (N), phosphorus (P) and potassium (K) losses through the manure management chain in China in 2010, and different scenarios in 2020. ***L&R&E are losses by, leaching, runoff and erosion.***

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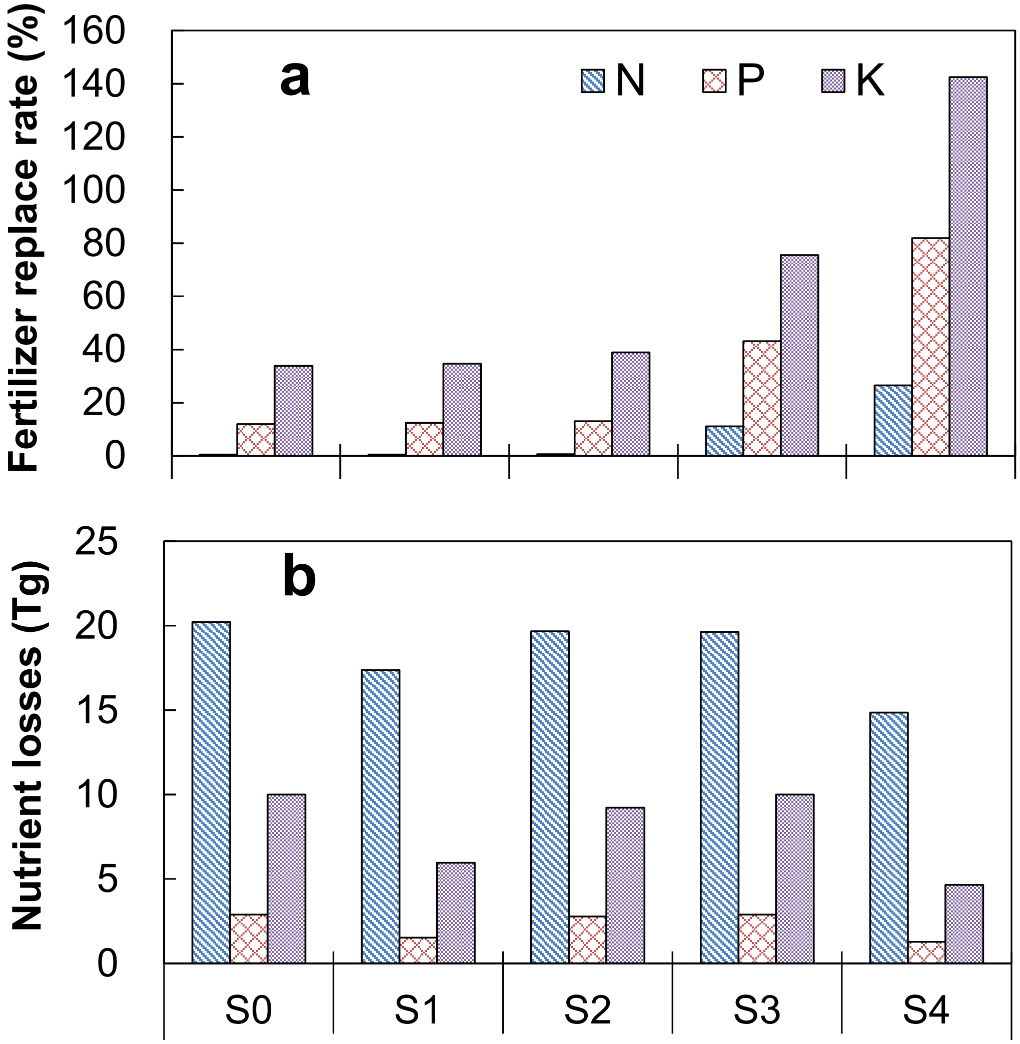

Figure 5. The chemical nitrogen (N), phosphorus (P), and potassium (K) fertilizer replacement by manure (a), and N, P and K losses in the manure management chain (b) in different scenarios in 2020.

S0, business as usual in 2020; S1, promote application of manure and prohibit discharge of manure; S2, improving manure collection in the housing and storage; S3, improving manure application; S4, Combination of S1-S3.