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Full length article

Mitigation of nitrogen losses and greenhouse gas emissions in a more circular cropping-poultry production system

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ABSTRACT

There is a global need to improve the environmental performances and circularity of livestock production systems. This relates also to poultry production systems in China, however, the benefits of optimized, more circular systems have not been quantified. Here, we applied a substance flow analysis to estimate the reactive nitrogen (Nr) losses and greenhouse gas (GHG) emissions from housing, manure processing and manure application to cropland in a conventional decoupled and an optimized coupled crop-poultry system. We hypothesized that an optimized coupled system has lower Nr losses and GHGs emissions, and a higher economic return for farmers. We used data from experimental measurements, a farm survey, literature and local market prices to estimate the farm performance for both systems. In the conventional system the manure was only partly (58%) utilized and the remaining 42% was wasted and discharged into the environment. In the optimized system a series of emission mitigation measures was adopted, including low-protein feeding, manure composting with additives and a partial replacement of synthetic fertilizers by manure. The optimized system produced 24% more products per 100 units of N input, leading to a whole-system nitrogen use efficiency (NUE) increase from 33% to 50%. The Nr losses per unit of product-N decreased by 55%, whereas the GHG emissions (N_2O and CH_4) decreased by 35%. Moreover, the net economic benefit increased by 21%. Evidently, the optimized and more circular system had significant economic and environmental benefits compared to the conventional one. These benefits will be drivers for the transformation to more sustainable production systems, but governmental policy incentives will be needed to remove current cultural and institutional barriers.

Abbreviations
Nr, reactive nitrogen
GHG, greenhouse gas
C, carbon
N, nitrogen
NUE, nitrogen use efficiency
NCP, North China Plain
HCP, high crude protein
LCP, low crude protein
NS, natural storage
ZSP, zeolite and superphosphate
CF, chemical fertilizer
OF, optimized fertilizer

1. Introduction

The amount of reactive nitrogen (Nr) released into the environment has exceeded the safe planetary N boundary (De Vries et al., 2013; Steffen et al., 2015), resulting in huge adverse environmental and ecological impacts in for example China, US and Western Europe (Chang et al., 2021; De Vries, et al., 2021; Liu et al., 2020a). Crop and livestock production are the two most important drivers of the global N cycle (Uwizeye et al., 2020; Zhang et al., 2015). Global amounts of N excreted by livestock have exceeded global N fertilizer use since the start of the 21st century, which reflects the increasing livestock population due to

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the growing consumption of animal protein (Bouwman et al., 2013). For example, China experienced a 6-fold increase in total meat production during the last three decades. Poultry production (including chicken and duck) increased even 12 times and egg production 13 times between 1980 and 2019 (Fig. S1). During this period, livestock production has been rapidly transformed from small-scale extensive production to middle/large-scale intensive production, concomitant with a decoupling of crop-animal production systems; the traditional coupled crop-animal systems are disappearing rapidly (Jin et al., 2020), due to their lower productivity.

Livestock production has become one of the most serious N pollution sources in China (Chen et al., 2019). The manure N recycling ratio was only about 40% in 2017 (Zhu et al., 2022) indicating that 60% of N was lost into the environment and negatively affecting both air and water quality (Gu et al., 2014; Yu et al., 2019), increasing GHG emissions and biodiversity losses (Hamilton et al., 2018; Liu et al., 2011), and with impacts on human health (Erisman et al., 2013; Huang et al., 2019; Tian et al., 2019). Similarly, the overuse of chemical fertilizer in cropping systems caused that 30% – 60% of the N applied was lost to the environment, depending on crop production system and management (Ju et al., 2009). Crop and animal production systems together contributed 60% to the total Nr losses to water and 80% – 90% to the total ammonia (NH_3) emissions to air in China in 2010s (Yu et al., 2019; Zhang et al., 2018).

The poultry and egg production in China is one of the livestock production systems that needs further improvement of the nutrient use efficiency. China produced >40% of global eggs, with 50% of the production in the North China Plain (NCP) (FAO, 2020; National Bureau of Statistics of China, 2020), which is one of the global hotspots for Nr losses (Liu et al., 2019). Approximately half of the total amount of excreted N by the poultry sector was lost during housing and manure storage; this was more than in the cattle sector and slightly less than in the pig sector in 2017 (Zhu et al., 2022). Moreover, poultry manure application to cropland contributes 34% to the total NH_3 emission from manure application, thereby exceeding the contributions from cattle (29%) and pigs (29%) (Xu et al., 2015). The environmental impact of the poultry sector therefore demands for more efficient management practices leading to an increase in productivity and NUE on the one hand and a decrease in environmental costs on the other hand. This can be done by more manure recycling and the use of ammonia mitigation measures.

Recycling manure to cropland is a well-established approach for improving soil fertility, reducing chemical fertilizer use and mitigating manure discharge (Gong et al., 2009; Guo et al., 2020; Han et al., 2021), and has been identified as an effective way for increasing NUE and decreasing N surplus at whole-system levels (Castillo et al., 2021; Denardin et al., 2020; Guo et al., 2020). Moreover, there are many emission mitigation measures that are effective for decreasing Nr losses at the livestock housing stage, e.g. use of low crude protein feed, improved floor systems, and air scrubbers (Boggia et al., 2019; Van Emous et al., 2019), and at the manure storage and processing stages, e.g. leak-tight and covered manure storages, use of additives (Cao et al., 2019; Wang et al., 2019). However, the aforementioned studies examined these measures mainly on specific parts of the crop-livestock production system, without considering the carry-over effects. Ignoring these effects causes pollution swapping and evaluated measures might fail to achieve the overall mitigation goal. The integrative effects of recoupling crop production with livestock production, improvements in housings, manure processing and the use of efficient application technologies on the Nr losses are essential, but have rarely been evaluated for poultry systems at farm level in China.

Recoupling cropping systems with livestock systems may increase NUE and decrease Nr losses (Castillo et al., 2021; Denardin et al., 2020) via direct and indirect reduction of N_2O emissions and leaching/runoff, as well via increased crop production from soil carbon (C) sequestration. However, few studies have evaluated the synergies and trade-offs between total Nr losses and total GHG emissions from these systems. Although the effects of emissions mitigation measures on GHG emissions and Nr losses have been studied at individual process levels (Chen et al., 2018; Cao et al., 2019; Wang et al., 2017, 2018), well-integrated experimental studies and systematic evaluations which examine the inherent interactions among stages of the manure management chain are still lacking.

To explore the potentials for Nr losses and GHG emissions mitigation and for improving NUE at whole crop-poultry production system in NCP, a typical poultry production farm and typical cropping systems (summer maize-winter wheat) were selected. Next, we designed a more circular and optimized cropping-poultry production system, i.e. a poultry system coupled to local cropping systems, combined with Nr mitigation measures at housing, storage and field application stages. The aim of this study was to quantify the benefits and trade-offs of the more circular and optimized poultry-cropping system, compared to the conventional system, in terms of NUE, Nr losses, GHGs emission, as well as farm income.

2. Material and methods

2.1. System description and design

To investigate the mitigation potential for the reduction in Nr losses and GHGs emission, a circular system was designed with mitigation measures applied at housing, manure processing and local field application stages. We defined this more circular system as an optimized system, versus a conventional system without mitigation measures and local manure cycling (Fig. 1 and Table 1). Thus, two similar poultry farms were selected. Both poultry farms accommodated approximately 7000 chicken in a three stair cages system (the prevailing system in China) with a density of 25 chickens per m^2. For the manure application to cropland, the summer maize and winter wheat double cropping system was selected, these crops accounted for 85% of the crop cultivation area in Quzhou, a typical county in NCP (Quzhou Statistic Year Book, 2017). Detailed information about the poultry farms and the crop management can be found in He et al. (2022). The conventional system had a common high-crude protein (HCP) ration, storage of manure in a soil pit (natural storage, NS) and used chemical fertilizers (CF) in the summer maize-winter wheat rotation system (named as local cropping system). To estimate the use of manure from poultry farms, a farm survey was conducted among 53 farmers within Quzhou county. On the basis of the interviews with farmers and managers of organic fertilizer treatment plants, we estimated that 58% of the poultry manure was used by various crop production system (maize, wheat, rice, vegetable or fruit trees; here named as non-local cropping systems) (Table 1), and that the remaining 42% was being wasted and/or discharged into the environment directly following housing stage (because of insufficient storage capacity). The optimized system used a low crude protein (LCP) ration, and all manure was composted with additives of zeolite and superphosphate (ZSP), following the housing stage. Further, chemical fertilizer N was partly replaced by processed (composted) manure N, while the total N application rate was optimized (OF) in the local summer maize-winter wheat rotation system (Table 1).

Thus, N entered the system via chemical fertilizers and animal feed, and left the system via crop and animal products, including manure, and losses to air and water (Fig. 1). Crop and poultry production were considered as an integrated system in the coupled and optimized system, while crop and poultry production were only loosely interacting in the conventional system. The winter wheat-summer maize double cropping system provides wheat for human consumption and maize for poultry. Other components of the animal rations (e.g., soybean, roughages, supplements) were imported from other regions and abroad, and the amount were calculated on the basis of the maize yield and it's proportion in feed.

Losses of Nr and GHG emissions from the systems at housing, manure processing and local/non-local field application stages were quantified. Nr losses referred to NH_3 volatilization, N_2O emissions and N leaching/

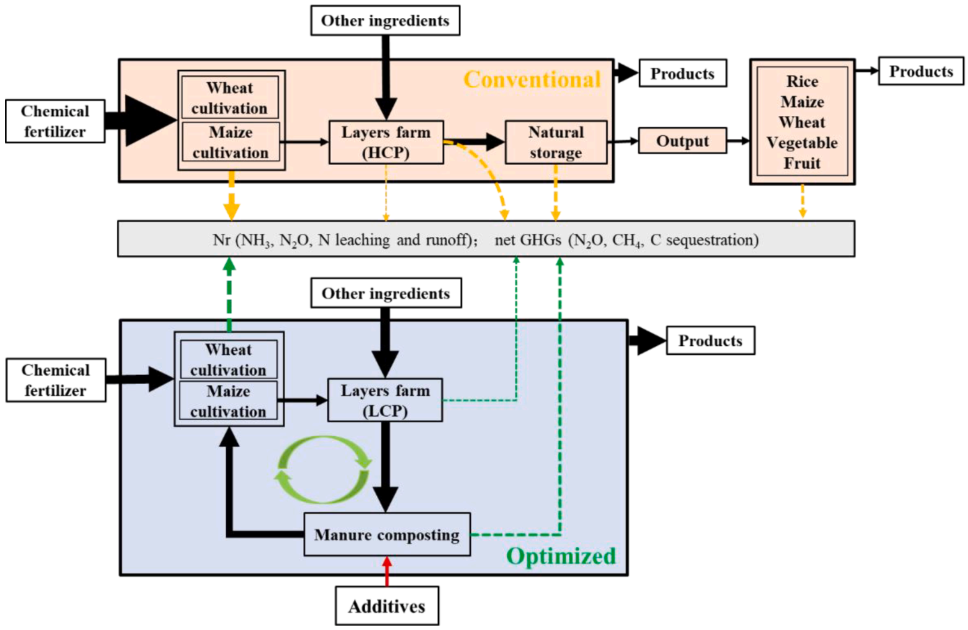

Fig. 1. Boundary for systematic analysis of cropping-poultry production in both the conventional and the optimized systems. The solid black arrows are the N flow, the dashed yellow and green arrows represent Nr losses or GHGs emission, and the solid red arrow shows the addition of additives during the composting period.

Table 1
The treatments at housing, manure processing, local cropping and manure output stages (non-local cropping)

Treatment	Housing	Manure processing	Local cropping	Non-local cropping
Conventional	HCP	NS	CF	MOP
Optimized	LCP	ZSP	OF-M	-

Housing: Where, HCP = High crude protein feed; LCP = Low crude protein feed.
Manure processing: Where, NS = Natural storage; ZSP = Composting with zeolite and superphosphate.
Local cropping: Where, CF = Conventional chemical fertilizer; OF = Optimized chemical fertilizer; M = Processed manure of ZSP.
Non-local cropping: Where, MOP = Manure output to non-local crop systems.

runoff; GHG emissions referred to N_2O and CH_4 emissions, as well as to soil C sequestration in the cropping systems introduced by manure recycling. It should be noted that dinitrogen (N_2) from denitrification was considered as a N output (losses), but was not included in the estimation of Nr losses, because N_2 is considered to be unreactive.

2.2. Data sources of Nr losses and GHG emissions

The Nr losses and GHG emissions at each stage were quantified via measurements in the crop-poultry system or derived from literature (Table 2). Detailed information and the experimental design of the housing, manure processing and field application stages are shown in Tables S1, S2 and S3, respectively. Briefly, in-situ monitoring results refer to NH_3 volatilization measurements at housing, manure processing and local field application stages. Emissions of N_2O and CH_4 from manure processing and local field application stages were also based on experimental measurements. Emissions of NH_3 were measured by passive samplers, dynamic chamber-acid capture system and Dräger-Tube methods at housing, manure processing and field application stages, respectively (He et al., 2022). The NH_3 emission factors derived from the measurements at housing, manure processing and field application stages are shown in Tables S4, S5 and S6, respectively. Emissions of N_2O and CH_4 were determined by static opaque chambers and gas chromatography techniques, at manure processing and local field application stages (Text S1) and can be found in Tables S5 and S6.

Table 2
The data sources of Nr losses and GHGs emission of each stage in cropping-poultry production system.

Category	Housing	Manure processing		Cropping	Manure output
		Storage	Composting		
NH_3	M	M	M	M	C
N_2O	C	M	M	M	C
N leaching and runoff	0	C	0	C	C
CH_4	C	M	M	M	C
SOC changes	/	/	/	C	C

Where, M = Measured in this study; C = Cited or calculated from published results; 0 means no N lost with leaching/runoff form in this study.

The N_2O and CH_4 emissions at housing stage were derived from a literature review of published results, including 35 studies related to CH_4 emissions and 14 studies related to N_2O emission factors. We used average emission factors to quantify GHG emissions from poultry farms (Table S4). The N leaching/runoff losses from the housing and manure storage and processing stages were calculated using N loss factors and a N mass balance approach. The N leaching/runoff factors for local field were derived from published results (Table S6).

Soil carbon (SOC) sequestration induced by manure application was estimated from the differences in SOC content between manure amended and control treatments (without manure, but with chemical fertilizers), which was derived from literature data. The relationship between the accumulative manure-C input and changes in SOC stock as established by Ren et al., (2018) was used.

The Nr losses and GHGs emission at the non-local field application stage induced by manure output in conventional system were estimated by emission factors derived from literature (Table S7). The target non-local cropping systems included vegetables, maize, wheat, rice and fruit trees.

2.3. Calculations

Total N inputs into the local cropping systems in the form of chemical fertilizer or/and manure were expressed in 100 units (kilograms) for both the conventional and the optimized systems, to facilitate comparison between the systems. The harvested maize in local field served as poultry feed, while the amount of other components of the animal rations was calculated on the basis of the maize's proportion in feed. The mass balance approach was applied to calculate the N flow, Nr losses and GHG emissions for two systems.

2.3.1. Calculations of NUE and Nr losses

NUE: the NUE in the animal system (NUE_{animal}) was calculated as the ratio of N retention in poultry and eggs to the total N inputs contained in feed according to Eq. (1):

$$NUE_{animal} = \left(N_{eggs} + N_{poultry}\right)/N_{feed} \times 100\% \tag{1}$$

Where N_{eggs} and $N_{poultry}$ refer to the total amount of N (kgN) embedded in eggs and poultry, respectively; N_{feed} is the total amount of N (kgN) in feed (including all ingredients in feed).

The NUE in the crop system (NUE_{crop}) was calculated as the ratio of N withdrawal in harvested maize, wheat and non-local crops to the total N inputs via chemical or/and manure fertilizer via Eq. (2):

$$NUE_{crop} = \left(N_{maize} + N_{wheat} + N_{non-localcrops}\right)/N_{fertilizer} \times 100\% \tag{2}$$

Where N_{maize}, N_{wheat} *and* $N_{non\text{-}local\ crops}$ refer to the total amounts of N (kgN) in harvested maize, wheat and non-local crops; $N_{fertilizer}$ means the total amounts of N in fertilizer and processed manure.

The NUE in the cropping-poultry system (NUE_{system}) was calculated as the ratio of N withdrawal in poultry meat, eggs, wheat and non-local crops to the total N inputs from chemical fertilizer, manure and imported feed, and was calculated according to Eq. (3):

$$NUE_{system} = \left(N_{eggs} + N_{poultry} + N_{wheat} + N_{non-localcrops}\right)/\left(N_{fertilizer} + N_{otheringredients}\right) \times 100\% \tag{3}$$

Where N_{eggs}, $N_{poultry}$, N_{wheat}, $N_{non\text{-}local\ crops}$ and $N_{fertilizer}$ have the same meanings as in Eqs. 1 and 2; $N_{other\ ingredients}$ is the amount of N (kgN) in feed (including all feed ingredients except maize, which was supplied by the local crop production system). Details of the parameters used to calculate NUE are shown in Tables S4–S7.

Nr losses: The total and unit Nr losses from the cropping-poultry system were calculated as follows:

$$Nr_{system} = Nr_{localfield} + Nr_{housing} + Nr_{manureprocessing} + Nr_{non-localfield} \tag{4}$$

$$unitNr_{system} = Nr_{system}/N_{products} \tag{5}$$

Where $Nr_{local\ field}$, $Nr_{housing}$, $Nr_{manure\ processing}$ and $Nr_{non\text{-}local\ field}$ refer to Nr losses from the local cropping system, poultry farm, manure processing and non-local cropping system (kgNr per 100 kg N input), respectively (See Text S2). The unit Nr losses from the cropping-poultry system were defined as the Nr losses from the produce of 1 kg N embedded in products (kg Nr per kg $N_{product}$, being the sum of wheat, eggs, meat and other crops from 100 kg N input into local cropping system).

2.3.2. Calculation of net GHG exchanges

The net GHG exchange (in CO_2 equivalents) was calculated as the difference of the emissions of N_2O and CH_4 and the CO_2 sink due to SOC sequestration, according to Eq. (6):

$$GHG\,exchange = N_2O \times 298 + CH_4 \times 34 - -SOC\,sequestration \times 44/12 \tag{6}$$

Where 298 and 34 are the conversion coefficients of N_2O and CH_4 relation to the global warming potential of CO_2 over a one 100-year time horizon according to the IPCC (2021). 44/12 is used for transformation of C to CO_2 sequestration. *SOC sequestration* is the soil organic carbon sequestration induced by manure application compared to the chemical fertilizer treatment and was calculated with the empirical model established by Ren (2018) about the relationship between SOC stock difference and accumulative manure-C input (Text S3). Due to the relatively low N losses and the addition of straw during composting in the optimized systems, the C/N of composted manure (C/N = 17) in the optimized system was higher than the C/N of the raw manure (C/N = 12) in the conventional system. We calculated that a total of 850 kg and 180 kg of accumulative C had been applied with manure into local field and non-local field for the optimized and conventional system, respectively, per 100 kg N input into the local cropping system. Details of the used methodology can be found in Text S3.

2.3.3. Calculation of costs and revenues

The difference between allocated costs and revenues in the two systems were calculated based on 100 kg N input into local cropping system. It was calculated as follows:

$$Cost = Cost_{localfield} + Cost_{housing} + Cost_{manureprocessing} + Cost_{non-localfield} \tag{7}$$

$$Revenue = Revenue_{wheat} + Revenue_{eggsandchicken} + Revenue_{non-localcrops} \tag{8}$$

$$Net\,Benefit = Revenue - Cost \tag{9}$$

Where $Cost_{local\ field}$ refers to the cost of the local cropping system, including fertilizer, seed, pesticide, machinery and labor inputs; $Cost_{housing}$ is the cost of the poultry production system, including feed, chicks, medicine, electricity, diesel, water and labor input; $Cost_{manure\ processing}$ represents the costs of the manure processing stage, including additives, diesel, film and labor inputs; $Cost_{non\text{-}local\ field}$ represents the cost of non-local cropping system referring to manure output in other regions, including fertilizer, seed, pesticide, machinery and labor inputs. $Revenue_{wheat}$, $Revenue_{eggs\ and\ chicken}$ and $Revenue_{non\text{-}local\ crops}$ refer to the revenues from the products of wheat, eggs and chicken meat and non-local crops. All the cost and revenues were in unit of RMB Yuan. Detailed information is shown in Text S4 and Tables S8-1– S8-3.

3. Results

3.1. NUE and Nr losses

The N flows for both the conventional and the optimized cropping-poultry systems are presented in Fig. 2. For the conventional system, 39 units (kilograms) of N were harvested from the local cropping production with local 100 units N fertilizer input; A total of 17 units N embedded in maize and 42 units N in other feed ingredients entered into the poultry system, producing 19 units N in eggs and meat, with a NUE of 32%. An average of 6.0 units of N were harvested from non-local cropping production systems with 15 units manure N input. In total, the NUE of the conventional system ranged from 29% to 35%. For the optimized system, 50 units of chemical fertilizer N plus 50 units of manure N (from which 12 units are being include from external sources) were applied to the cropping system, which produced 57 units of N in the form of cereals. The egg production system had inputs of all the maize produced plus additional 53 feed N, which produced 23.8 units of N in eggs and meat, respectively. Thus, the NUE_{crop} increased from 39% in the conventional system to 57% in the optimized system. There was no difference of NUE_{animal} between the two systems. However, the NUE of the whole system substantially increased from 33% to 50%, mainly because the local recycling of the composted manure reduced the N input in the form of the chemical fertilizer.

The Nr losses in the conventional system ranged from 41 to 54 units, while it was only 25 units in the optimized system (Fig. 3, Fig. S2 and Fig. S3). The cropping process and manure management were the main contributors to the Nr losses in both the conventional and the optimized systems. At housing stage, 4.6 N units were lost to the environment in the optimized system, At manure processing stage, 8.1 N units were lost into the environment in the optimized system. In the conventional

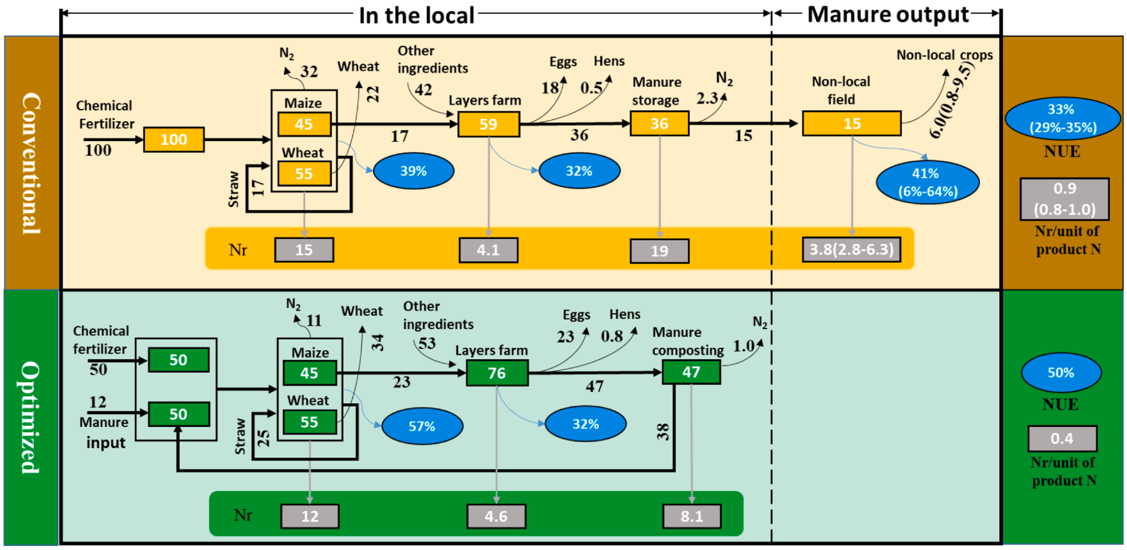

Fig. 2. Schematic of N flow in conventional (light yellow background) and optimized (light green background) cropping-poultry production systems. The values in the yellow and green boxes represent N flow in cropping-poultry production systems; the values in the blue ovals are NUE for crop cultivation, egg production and for the whole cropping-poultry production system; the values in the gray boxes represent Nr loss from each production stage per unit (kilogram) of N contained in the products.

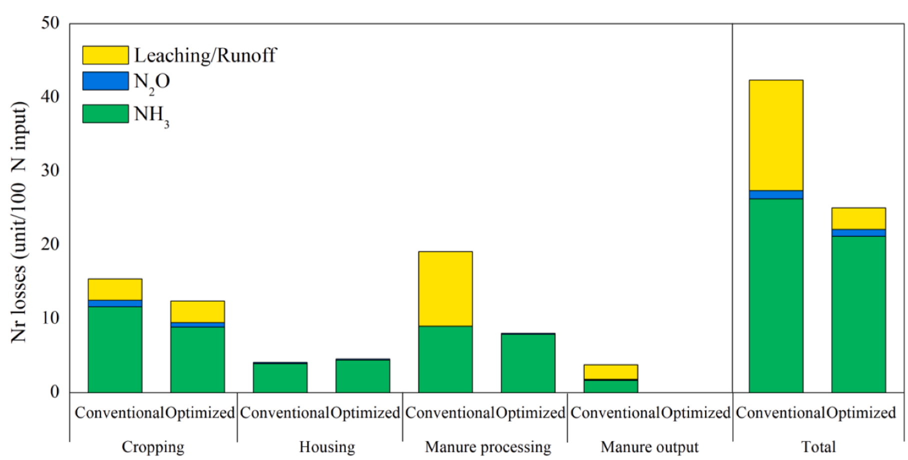

Fig. 3. Nr losses in form of ammonia (NH_3), nitrogen dioxide (N_2O) and leaching/runoff at each stage of the conventional and optimized cropping-poultry production systems (Note: Nr losses to the environment is relative to 100 units (kilograms) N input into the local cropping system).

system, the Nr losses during manure processing accounted for the largest Nr losses, because the manure was natural stored and only partially and with a delay recycled into the non-local cropping system. In the optimized system, 50% of the total Nr losses occurred in the cropping system, followed by 32% during manure processing and 18% in the housing stage. The optimized manure processing and increased manure recycling greatly reduced Nr losses and made the N flow more circular in the optimized system. The total Nr loss of the conventional system was 0.9 kg Nr (kg product N)$^{-1}$, while it was only 0.4 kg Nr (kg product N)$^{-1}$ in the optimized system. Thus Nr losses were much smaller in the optimized system than in the conventional system per kg of product N.

3.2. GHG emissions

A comparison was made between the two systems in terms of GHG emissions, including changes in SOC, CH_4, N_2O and indirect N_2O emissions (Fig. 4 and Fig. S4). Emissions of N_2O accounted for 61% and 66% of the total GHG emissions from the conventional and the optimized systems, respectively. Emissions of CH_4 accounted for 16% and 18%, respectively. Indirect N_2O emissions, introduced by Nr losses in the form of NH_3 emissions and leaching, accounted for 23% and 17%, respectively. Emissions of N_2O were mainly attributed to crop production, while CH_4 emissions were mainly attributed to the housing stage (except for the case where manure was applied to a rice system, which accounted for 75% of system CH_4 emission; Fig. S4). In the conventional system, the manure processing stage contributed most to indirect N_2O emissions, because more than half of the N was lost into the environment via NH_3 emissions and leaching. The GHG emissions were reduced by 25%–43% in the optimized system compared with those in the conventional system. Crop production was the largest contributor. Overall, 18 and 12 kg CO_2-eq were emitted (by N_2O and CH_4 with a GWP of 298 and 25 compared to CO_2) produced in the conventional and optimized systems, respectively, implying that the GHG emissions were reduced by 35% on average in the optimized system.

The soil can be both a source and a sink for GHGs. We estimated that there was an increase of 1.2 and 0.7 (0.5–1.2) Mg C ha^{-1} yr^{-1} in the top soil layer (0–20 cm) of the optimized and conventional system, respectively, induced by the manure application. Thus, the net GHGs exchange in the conventional system was 581 units of CO_2-eq on average (range 490 – 737 units CO_2-eq due to to different cropping system), while the

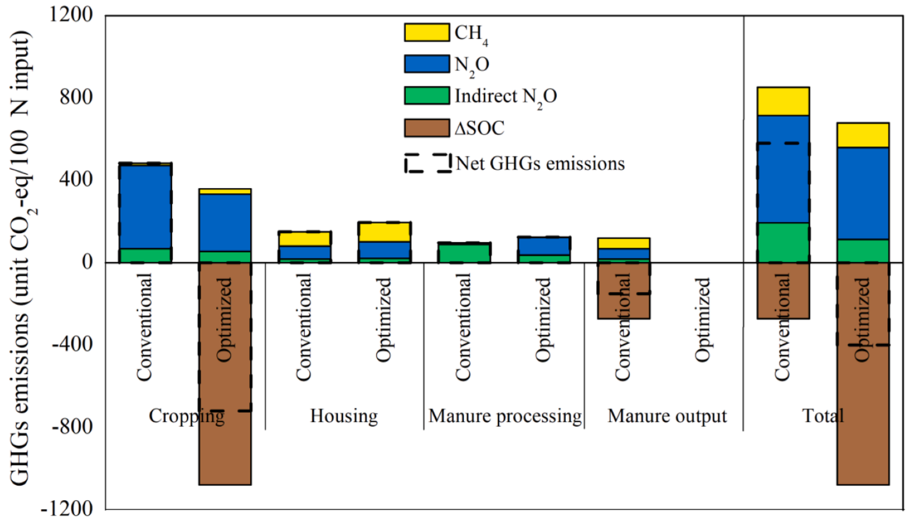

Fig. 4. Net GHG emissions, including direct and indirect N_2O emissions, CH_4 emissions and soil organic carbon (SOC) changes at each stage (cropping, housing and manure processing) in the conventional and optimized cropping-poultry production systems. (Note: GHG emissions to the environment are relative to 100 units (kilograms) kg N input into the local cropping system).

net GHGs exchange in the optimized system was -399 units CO_2-eq. Thus all N_2O and CH_4 emissions were offset by the increased SOC sequestration in the optimized system.

3.3. Cost-revenue analysis of the system

The costs and revenues of the two systems are shown in Figs. 5 and

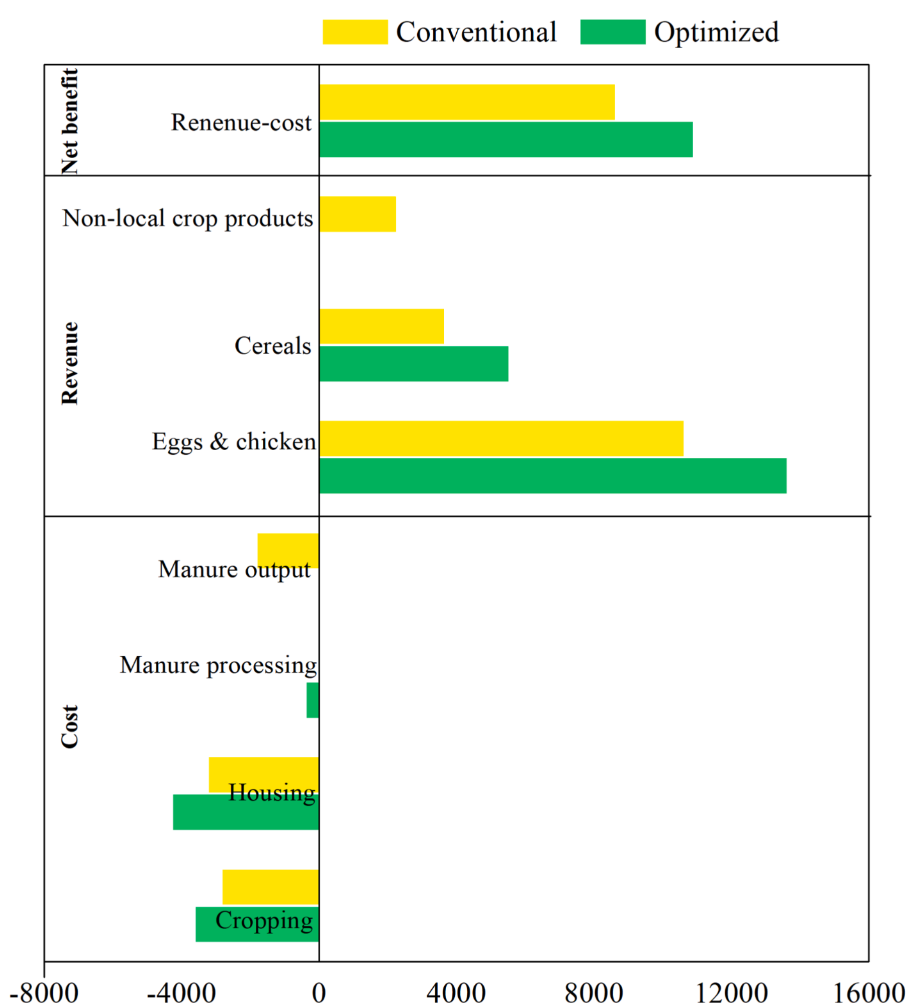

Fig. 5. Costs, revenues and net benefits in the conventional and optimized cropping-poultry production systems. (data is shown in Table S8) (Note: cost-revenue is in relative to 100 units (kilograms) N input into the local cropping system).

Fig. S5. Given a 100-unit N input into the cropping system, there was a cost of 8,616 (7,865–10,296) and 10,883 RMB Yuan in the conventional and the optimized systems, respectively. Crop production and poultry production accounted for 44% and 52% of the total costs in the optimized system, while 36% and 41% of the total costs in the conventional system, respectively. Manure processing accounted for only approximately 0.4%–4.5% of the total costs in the two systems, the remainder of the cost of 23% (17%–33%) was attributed to other regions in the conventional system. Fertilizer and machinery costs were similar, at 33% and 30% of the cropping cost in the conventional system. Machinery incurred largest cost (32%) in crop production in the optimized system, followed by fertilizer (16%), seeds (13%), labor (12%) and purchased manure (12%). The animal production sector accounted for the largest part, in which feed accounted around 70% of the cost in both systems. In the optimized system, the manure processing cost was 4.5% of the total costs for the composting materials, while it only accounted for less than 1% in the conventional system.

The revenue in the optimized systems was 19,125 RMB Yuan, which was 14% more than in the conventional system. Crop production and animal production contributed 36% (30%–42%) and 64% (58%–70%) in the conventional system, respectively, compared to 29% and 71% of that in the optimized system. The net benefits were 8616 and 10,883 RMB Yuan in the conventional and the optimized systems, respectively, implying that 21% (5%–28%) more net benefit was obtained in the optimized system, with same N input. The cost to benefit ratio was 43% in the optimized system versus 48% (43%–51%) in the conventional system, implying better return on investment in the optimized system.

4. Discussion

4.1. Reduction in Nr losses and increase in NUE

Emissions of NH_3 were the dominant Nr losses pathway in both the conventional and the optimized systems (Fig. 3 and Fig. S3). Our results were consistent with the Nr loss estimations for the national upland agro-ecosystem (Liu et al., 2020b). The largest reduction of Nr losses in the optimized system came from the decrease in leaching and runoff losses because prolonged manure storage in open-ground natural systems was replaced by direct manure composting and recycling into the local cropping system. Although the Nr losses were reduced by 48%–57% in the optimized system, further reductions could be achieved by using additional techniques. For example, only 29%–39% of NH_3 emission mitigation was achieved. Another study found that an additional 93% and 47% reductions in NH_3 volatilization could be realized, when urease inhibitors were applied with urea fertilizer during the topdressing process for summer maize and winter wheat, respectively (Sha et al., 2020). If this approach also would have been applied in the optimized system, another 17% of NH_3 emissions and 14% of total Nr losses would have been mitigated. Of course, this will increase the cost. Furthermore, some studies found that acid air scrubbers in animal barns can decrease 55%–70% of NH_3 emission from the housing system (Melse and Ogink, 2005; Lin et al., 2014). Assuming that a 62.5% reduction in the NH_3 emissions would be achieved, this means that a further reduction of 11% of the Nr losses could be made per unit of product N. If all potential approaches were combined together, the Nr losses could be reduced to 0.33 kg Nr (kg of product N)$^{-1}$, equivalent to only 36% of that in the conventional system.

In addition, increasing crop yields is another potential approach for mitigating Nr losses, especially when N inputs do not increase (Chen et al., 2014).Thus, crop yield and N uptake were significantly increased in the optimized system, resulting in a higher NUE of the cropping system (from 39% to 57%). In the optimized system, the reduction in total N inputs decreased Nr losses, also because of the substitution of synthetic fertilizer by manure, which increased the soil fertility and thereby increased crop yield and NUE. Moreover, the recycling of manure into crop fields avoided manure being discharged and thus increased the system NUE significantly.

4.2. Reduction in GHG emissions

The reduction in GHG emissions at the cropping stage in the optimized system was attributed to the lower synthetic fertilizer N input and the use of composted manure. Further, there is still a potential to increase crop yields by 30%–40% in our optimized system when compared with other integrated soil-crop system management experiments in China as well as with maize production in the US (Chen et al., 2014). This could further reduce the GHG emission intensity per unit of product (Grassini and Cassman, 2012). At the housing stage, the GHGs emission were slightly higher in the optimized system than in the conventional system, this was attributed to increased N input embedded in feed and to an additional product output rather than to an increase in emission intensity. At the manure processing stage, composting with additives increased N_2O emissions but avoided indirect N_2O emissions, because NH_3 volatilization and manure discharge were reduced in the optimized system. It should be noted that not only the increased SOC sequestration compensated for the N_2O and CH_4 emissions from the optimized system, but also the 50% reduction in the use of chemical fertilizer reduced the GHG emissions associated with fertilizer production and transportation. (Zhang et al., 2013).

4.3. Economic and societal benefits of the optimized poultry production system

Next to the large net economic benefit of the optimized system, there is also a substantial societal benefit related to ecosystem, human health and climate change. Assuming associated costs of 37.5, 2.1 and 9.3 RMB Yuan per kg Nr losses through NH_3, N_2O emissions to air and Nr leaching into water (Xia et al., 2016), respectively, a reduction of 41% (39%–44%) of the Nr losses in the optimized system indicated an indirect benefit of 304 (270–401) RMB Yuan for the society. Moreover, the reduction of 889 to 1136 kg CO_2-eq saved 49–193 RMB Yuan at the current carbon exchange market value (50–197 RMB Yuan/t CO_2-eq) in China (Table S9). It should be noted that the CO_2 price depends on personal and market willingness to pay, which is higher in Europe than in China. Yet, the optimized production system still offers substantial environmental and societal benefits.

4.4. Uncertainties and limitations of the study

In the current study, we designed the conventional and the optimized cropping-poultry production systems and conducted in-situ measurements of Nr losses and GHG emissions. However, not all the parameters were directly measured from the designed systems. For example, GHG emissions at the housing stage and leaching at the cropping stage were estimated from previous studies, which could introduce uncertainties. Moreover, the evaluation referring the Nr losses and net GHG exchange, induced by manure output in the conventional system, was conducted by using the parameters of published researches. The destination of manure was assumed to be different crop systems (vegetable, maize, wheat, rice and fruit), but there is uncertainty related to the relative proportions of the various systems. In addition, the low protein feeding (LCP approach) was aimed at mitigating the Nr losses by reducing the N content of the excreta without affecting the productivity of the poultry system. We recommend that Nr losses mitigation approaches should be combined with approaches that improve animal productivity. Meanwhile, the current study only focused on cereal crop and poultry production systems and did not consider other cash crops and livestock production. We therefore recommend that multiple production systems should be included in the future evaluation.

4.5. Recommendations

In response to the global climate change agreements, China aims to reach peak GHG emissions by 2030 and achieve carbon neutrality by 2060 (Xinhua net, 2020). Increasing NUE and recoupling cropping and animal production have been highlighted in the agricultural section of China's 14th Five Year Plan (2021–2025). Both goals support China's development strategy for more sustainable and high-quality growth. However, to reach this ambitious target, a thorough regional and nationwide reform of production systems must be implemented, and appropriate strategies for collaboration among different stakeholders should be developed.

First, we recommend manure recycling in locally connected cropping-poultry production systems. The number of households producing both crops and livestock (i.e., mixed farming systems) declined from 71% in the 1980s to 12% in the 2010s (Jin et al., 2020). Livestock production has become more and more intensive and specialized, causing spatial separation with cropland. This spatial mismatch in production and the need for manure transportation is one of the main reason for the low use of manure by crop farmers (Zhang et al., 2020). For farmers with animal production, the amount of manure produced exceeds the environmental capacity of their own land owing to their limited area of arable farmland, while for crop farmers, manure is often unavailable, even if they want to use it. Our study results indicate that manure recycling in locally connected cropping-poultry production systems has triple advantages in Nr losses mitigation, GHGs emission reduction and net economic benefit acquisition. The prolonged manure storage and the limited recycling of manure in cropland, causes that a large proportion of manure N is lost in the conventional system. The local manure recycling in the optimized system provides an opportunity to shorten the manure storage time and reduce the risk of manure N loss. Spatial reallocation of livestock production systems and rescaling of industrialized livestock farming systems into medium-sized industrial production systems are possible ways to reduce the high transportation costs and increase manure recycling (Zhang et al., 2019).

Second, we recommend that technology groups work together with the policy-development community to develop more integrated approaches that provide farmers with access to modern technologies. Survey results show that only 21% of dairy farms and less than 2% of poultry farms have adopted manure treatment technologies (Tan et al., 2021), while mechanized application of slurry and manure is still rare in China. Investments in technology and machinery throughout the agricultural production chain are needed to encourage farmers to engage in improved manure management and recycling.

Last but not least, we recommend that more access is given to the technologies and strategies available to farmers for developing circular production systems. it is extremely important to increase farmers' awareness of circular production systems, not only from economic and environmental perspectives but also from rural vitalization perspectives.. Meanwhile, government subsidies should be set up for the upgrade of facilities and machinery to encourage farmers to apply environmentally friendly management techniques.

5. Conclusions

The Nr losses and net GHGs exchange of conventional and optimized cropping-poultry systems were fully assessed. The Nr losses resulting from 100 units (kilogram) N input into local cropping system were 42 and 25 units in the conventional and optimized systems, respectively. Maize-wheat cultivation and manure processing stages are the two main contributors to Nr losses. The greater efforts in decreasing Nr losses should be at first in the optimization of crops production and manure processing. The transition from the conventional to optimized system for cropping-poultry production has the huge potential for system NUE increasing (increased from 33% to 50%) and N losses reduction (decreased from 0.9 to 0.4 units N losses per unit N product) as well as net GHGs exchange reduction, in relation to 100 units (kilogram) N input into local cropping system. Moreover, it would raise net economic benefit by 21% in the optimized system.

CRediT authorship contribution statement

Zhilong He: Investigation, Data curation, Writing – original draft. **Ying Zhang:** Conceptualization, Data curation, Supervision, Writing – review & editing. **Xuejun Liu:** Supervision, Writing – review & editing. **Wim de Vries:** Supervision, Writing – review & editing. **Gerard H. Ros:** Supervision, Writing – review & editing. **Oene Oenema:** Supervision, Writing – review & editing. **Wen Xu:** Methodology. **Yong Hou:** Methodology. **Hongliang Wang:** Methodology. **Fusuo Zhang:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Supplementary materials

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