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Nitrogen losses from food production in the North China Plain : A case study for Quzhou

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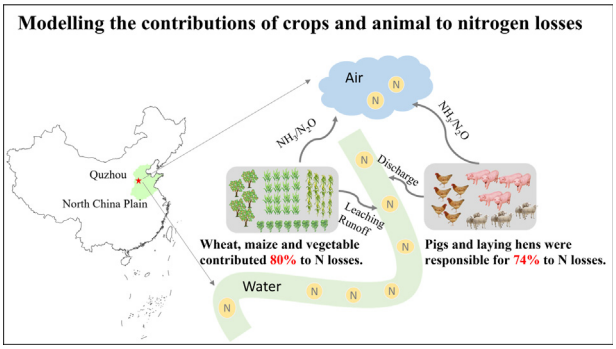
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HIGHLIGHTS

- We developed and applied the NUFER model for Quzhou in the North China Plain.
- Nitrogen (N) losses to the environment were high from food production in Quzhou.
- Wheat, maize and vegetable contributed to 80% of N losses in crop production.
- Pigs and laying hens were responsible for 74% of N losses in animal production.
- Better nutrient management in food production is needed to reduce N losses.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrogen (N) management is essential for food security. The North China Plain is an important food producing region, but also a hotspot of N losses to the environment. This results in water, soil, and air pollution. In this study, we aim to quantify the relative contribution of different crops and animals to N losses, by taking the Quzhou county as a typical example in the North China Plain. We developed and applied a new version of the NUtrient flows in Food chains, Environment, and Resource use (NUFER) model. Our model is based on updated information for N losses in Quzhou. Our results show that N losses to the environment from crop and animal production in Quzhou were approximately 9 kton in 2017. These high N losses can be explained by the low N use efficiency in food production because of poor N management. For crop production, wheat, maize, and vegetables contributed 80% to N losses. Ammonia emissions and N leaching have dominant shares in these N losses. Pigs and laying hens were responsible for 74% of N losses from animal production. Ammonia emissions to air and direct discharges of manure to water were the main contributors to these N losses. Effective reduction of N losses requires improving the nutrient management in crop (wheat, maize, vegetables) and animal (pigs, laying hens) production. Our work could support the Agricultural Green Development in the North China Plain.

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1. Introduction

China contributes largely to global food security, but experiences various environmental impacts. To grow food, nitrogen (N) is needed (Galloway et al., 2008; Robertson and Vitousek, 2009). However, only a relatively small share of the N used in crop and animal production is reaching our plates (Galloway et al., 2008; Billen et al., 2013). Large amounts of N are lost to the environment and contribute to pollution problems in water and air (Xu et al., 2018b; Zhang et al., 2020a), including acidification (Guo et al., 2010), eutrophication (Li et al., 2019), nitrate accumulation in groundwater (Gu et al., 2013), and greenhouse gas emissions (Xu et al., 2020). These impacts pose a risk to the environment and society (Liu et al., 2013; Zhang et al., 2020b).

In recent years, the Nineteenth National People's Congress in China launched a national action for Agricultural Green Development (AGD) (Shen et al., 2020). AGD aims to support agriculture towards high resource use efficiencies and low environmental impacts (Shen et al., 2020). For example, AGD requires improving N use efficiencies and reducing N losses to the environment, while increasing agricultural yields (Chen et al., 2014; Ma et al., 2019; Cui et al., 2020). To more effectively reduce N losses, region-specific N management is required (Wang et al., 2018b).

The North China Plain (NCP) is an important agricultural production region in China. NCP is responsible for 38% of farm products in China (Ju et al., 2009). NCP is also a pollution hotspot for N losses to the environment from food production. NCP covers less than 10% of the national land area, but contributes to more than half of the total N losses to the environment (Wang et al., 2018b). Several studies have demonstrated that N losses are driven by intensive crop and animal production (Wang et al., 2020b; Zhang et al., 2020b). Such intensive agricultural production results in emissions of NH_3 (ammonia) and N_2O (nitrous oxide) to the air. These emissions contribute half of the total reactive N losses to the environment in the NCP (Ma et al., 2013; Zhao et al., 2017b, 2019). The air emissions may differ between crops and animals and might be affected by nutrient management (e.g., fertilizer application and manure management). However, differences in emission factors between crop types and animal categories are not explicitly accounted for in existing studies for N losses. This may lead to over-or under-estimation of the current N losses to the environment.

Quzhou is a county with intensive agricultural production located in the NCP. Agriculture is dominated by the wheat and maize double-cropping systems. These systems are coupled with intensive pig and laying hen production, consistent with the regional structure of current crop and animal production in the NCP (Zhang et al., 2016; Zhao et al., 2017a; Wang et al., 2020b). In 2019, Quzhou was selected by the Chinese government as a demonstrate county to balance agricultural production and environment production for Agriculture Green Development (AGD) in the NCP (MOA, 2020). Quzhou also is a hotspot of N losses to the environment in China (Wang et al., 2018b). Large amounts of reactive N (e.g., NH_3) losses from agriculture to the atmosphere can enhance $PM_{2.5}$ pollution via chemical reactions with acidifying compounds (SO_2 and NO_2) from combustion sources such as coal combustion (Xu et al., 2019a). Between 2013 and 2017, the annual average $PM_{2.5}$ concentrations in Quzhou (approximately 79.5 μg m^{-3}) were close to that (approximately 88.3 μg m^{-3}) in the economically important Beijing-Tianjin-Hebei region (the major regions of NCP) (Kuerban et al., 2020; Wang et al., 2020c). Quzhou, therefore, can serve as an example for improved N management in Chinese counties where agricultural pollution is high (Liu et al., 2020).

Several models are developed to quantify N losses to the environment from food production in China (Velthof et al., 2007; Ti et al., 2011; Wang et al., 2018a). Most of these models focus on nutrient flows in food production and quantify nutrient losses to air and water at administrative scales (e.g., country and province) (Ma et al., 2012; Gu et al., 2015; Wang et al., 2018b). For instance, Ma et al. (2010) developed the first version of the NUtrient flows in Food chains, Environment, and Resource use (NUFER) model for China, followed by several different versions such as the NUFER-province (Ma et al., 2012) and NUFER-county models (Wang et al., 2018b). However, the existing models do not quantify the relative shares of different crops and animals in N losses to the air and water and their spatial variability. These models often limit their calculations to N losses from chemical fertilizers and animal manure and do not separate between crops and animals. The Model to Assess River Input of Nutrient to seAs (MARINA 2.0) that is linked with crop WOFOST (WOrld FOod STudy) models is capable of simulating N losses from different crops (Chen et al., 2020). However, the model of Chen et al. (2020) does not quantify N losses to water from different animals, nor does it calculate N losses to the air simultaneously. Besides, the model is not implemented for Quzhou and does not consider local characteristics of farmers' management. Thus, the contributions of different crops and animals to N losses for counties such as Quzhou are not known. A modeling approach to quantify how different crops and animals contribute to N losses is urgently needed for effective nutrient management.

In this study, we aim to quantify the relative contribution of different crops and animals to N losses by taking the Quzhou county as a typical example in the NCP. To this end, we develop and apply a new version of the NUFER model for Quzhou (see Section 2 for the model description and Section 3 for the model results).

2. Methodology

2.1. Study area

Quzhou is a county with intensive agricultural production located in the center of the NCP (Fig. 1). It has a total population of 433,000, living in 342 villages of 10 townships with a total area of 667 km^2 (Zhang et al., 2016). Wheat, maize, cotton, soybean, and vegetables are the dominant crops, while animal production is dominated by pigs, laying hens, sheep, and beef cattle (NBSC, 2017). The distribution of crop and animal production varies among the ten towns (NBSC, 2017; Tables S1 and S2). For example, vegetables are mainly planted in the Quzhou town, while pigs and laying hens are mainly distributed in the Nanliyue and Baizhai towns.

2.2. NUFER model description and development

The NUFER model was developed by Ma et al. (2010) to quantify N flows in the food chain based on a mass balance approach. The food chain consists of crop production, animal production, food processing, and human consumption (Ma et al., 2010, 2012). This model quantifies N flows for China, its provinces, and counties for several years between 1980 and 2013 (Ma et al., 2012, 2013; Wang et al., 2018b). The NUFER model has been widely used to assess N losses to the environment and N use efficiencies in food production, including crop and animal production (Ma et al., 2012; Wang et al., 2017, 2018a, 2018b).

In this study, we developed a new version of NUFER based on the NUFER-county model (Wang et al., 2018b) to quantify the relative contribution of different crops and animals to N losses from food production in 2017. The year 2017 was chosen to represent the current status of food production. N losses in our model include losses to water and air. N loses to water are from leaching, surface runoff, and erosion in crop production, and the direct discharge of animal manure in animal production. N losses to the air include emissions of NH_3 and N_2O from crop and animal production systems.

The NUFER model in this study differed from the original NUFER model in the four aspects (Fig. 2). First, it is a new application of the model to Quzhou. Second, we developed a modeling approach for NUFER to analyze the contribution of individual crops and animal species to air and water pollution. For example, our fertilizer application is for individual crops, which was not done in the original version. Third, we updated the fractions of animal manure recycling to cropland

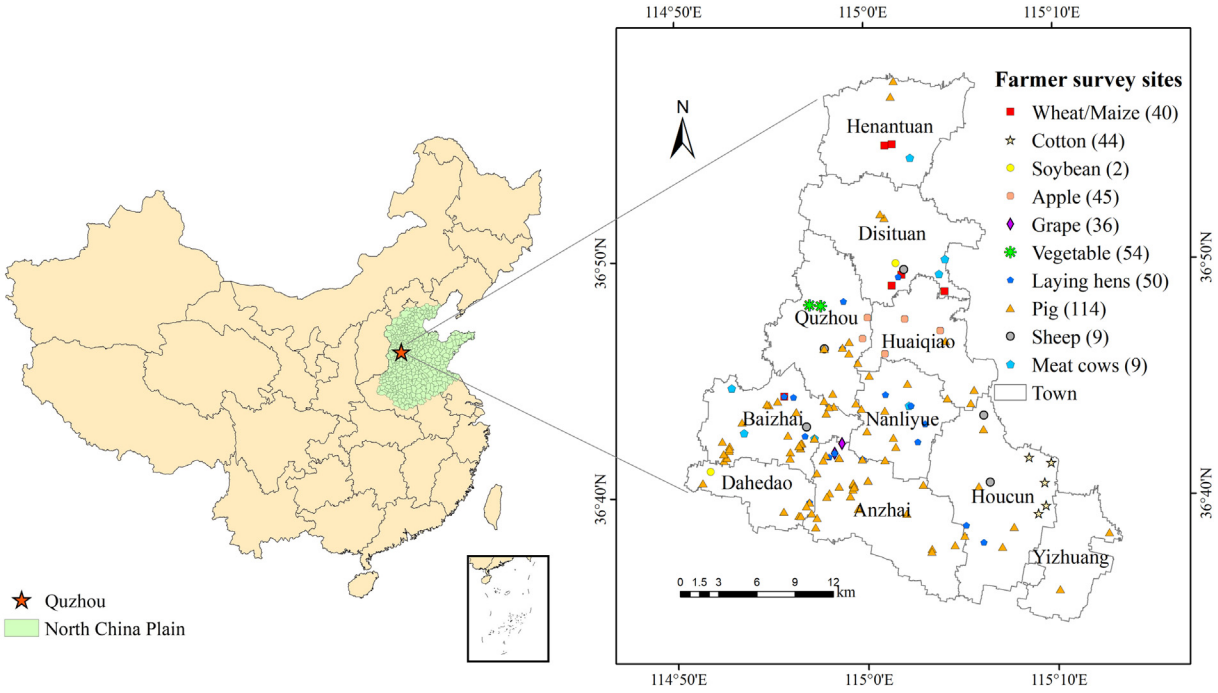


Fig. 1. The study area and locations of farmer survey sites in Quzhou. The Quzhou county includes ten towns: Henantuan, Disituan, Quzhou, Huaiqiao, Baizhai, Nanliyue, Dahedao, Anzhai, Houcun, and Yizhuang. 443 farmers were surveyed during the period of 2018–2020. The data collected based on these surveys is provided in Table S3.

based on results of a recent survey (Table S3). The Chinese government implemented many policies to improve animal manure management (e.g., restrictions of manure discharge to rivers without treatment) during 2015–2017 (CSC, 2015; Bai et al., 2018). These policies have reduced the direct discharge of animal manure to water in Quzhou and thus changed the fractions of animal manure recycling to cropland in the original NUFER model (Zhao et al., 2017a; Wang et al., 2020b). Fourth, we updated the emission factors for NH_3 and N_2O for chemical fertilizer and animal manure using local field measurements for wheat-maize cropping system and the recent literature for other crops (Ying, 2019; Zhang et al., 2020c; Ma et al., 2021; Tables S4 and S5). This is a crucial improvement as emission factors have a direct influence on the magnitude of N losses to the environment.

To quantify the relative contribution of different crops and animals to N losses, we updated model inputs based on statistical yearbooks (NBSC, 2018), monitoring datasets (Tables S4 and 5), and farm surveys (locations are in Fig. 1; Table S3). The updated model inputs are summarized as follows.

First, we updated the model inputs for human activities in food production and consumption in Quzhou. Data on food production, such as sown areas and animal numbers, are mainly from the Quzhou Statistical Yearbook in 2017 (NBSC, 2017; Tables S1 and 2). Data on N management in food production such as fertilizer application and manure management (see Table S3) was collected through the survey of 443 farmers in Quzhou (Fig. 1). The survey provides data for seven crops types (wheat, maize, cotton, soybean, apple, grape, and vegetable) and four animal types (laying hens, pigs, sheep, and beef cattle). The dry and wet N deposition was based on the Quzhou long-term monitoring station (Xu et al., 2018a, 2019b; Table S6). Data on urban and rural food consumption was obtained from the Hebei Statistical Yearbook 2018 (NBSC, 2018; Table S7).

Second, we updated the model inputs for transformation and partitioning coefficients for Quzhou. Examples of these coefficients are the fractions of straws return to cropland and animal manure applied to cropland. The coefficient for manure applications was derived based on the farmer survey and sown-areas of different crops (Table S3).

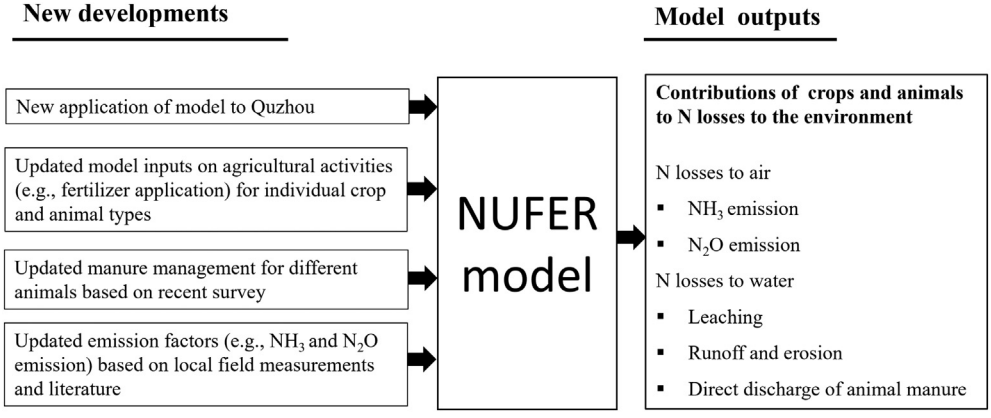


Fig. 2. New model developments of NUFER (Nutrient flows in the Food chains, Environment, and Resource use) for Quzhou (Ma et al., 2010). "New developments" illustrate the aspects that are new in NUFER for Quzhou compared to the version of Ma et al. (2010). The model quantifies nitrogen (N) losses to air and water from different crops and animals. NH_3 is ammonia; N_2O is nitrous oxide.

The manure applied to vegetables and fruits are directly from the farmer survey. The rest of the manure, after applying to vegetables and fruits, is applied to other crops based on the proportion of their sown areas to the total sown areas (Chen et al., 2020). The net N import via feed cops, food crops and animal products were calculated following the approach of Ma et al. (2010, 2012), and Wang et al. (2018b).

Third, we updated the emission factors for N losses from different crops. The emission factors are derived from the monitoring stations in Quzhou, summary of literature, and existing models. In our study, the emission factors for wheat and maize for Quzhou are based on local monitoring data, and depend on fertilizer types (Unpublished data; Table S4). However, for other crops there were no local monitoring available data for Quzhou to be used as a basis for emission factors. Therefore, we updated the emission factors for other crops based on relevant literature (Ying, 2019; Zhang et al., 2020c; Ma et al., 2021; Tables S4 and S5). We selected literature that considers the fertilizer types that are typically applied to crops in Quzhou. The emission factors in animal production were the same as in the original NUFER-county model (Ma et al., 2012; Wang et al., 2018b; Table S8).

2.3. Calculating nitrogen losses and use efficiencies

2.3.1. Nitrogen losses from food production

We calculated N losses to the environment from food production using the NUFER model for 2017 for Quzhou. The equations to quantify the N losses to the environment for different crops and animals are shown in Box 1. The NH_3 and N_2O emissions to air from crop production were calculated by source including losses from chemical fertilizers and animal manure. N losses from surface runoff and erosion were quantified based on soil-specific and climate-specific fractions (such as soil type, precipitation), respectively. N losses due to leaching, accumulation, and denitrification were calculated from the proportion of N surplus in crop production (Box 1). The proportions for N leaching and accumulation in Quzhou or NCP from summary of published studies (Ju et al., 2009; Lv, 2019, Liu et al., 2021; Table S9). For animal production, losses of NH_3 emissions, N_2O emissions, and the direct discharges of animal manure were calculated as fractions to the total N in animal manure. The fractions were provided in Table S8.

2.3.2. Nitrogen use efficiencies

N use efficiencies in crop production (NUEc, %) is defined as the portion of N retained in the main crop products to the total N input to crop production. NUEc is calculated according to Eqs. (1) and (2) following the approach of Ma et al. (2012):

$$NUE_C = \left(Oc_{\text{main products}}/I_c\right) \times 100\% \quad (1)$$

$$Ic = Ic_{\text{chemical fertilizer}} + Ic_{\text{manure}} + Ic_{\text{irrigation}} + Ic_{\text{residues}} + Ic_{\text{seeds}} + Ic_{\text{fixation}} + Ic_{\text{deposition}} \quad (2)$$

where Ic refers to the total N input to crop production. $Oc_{\text{main products}}$ is the N that is harvested in the main products (e.g., product of wheat) from crops. $Ic_{\text{chemical fertilizer}}$ is N input to cropland from chemical N fertilizers. Ic_{manure} is N input to cropland from animal manure. $Ic_{\text{irrigation}}$ is N input to cropland from irrigation. Ic_{residues} is N input to cropland from residues. Ic_{seeds} is N input to cropland from seeds. Ic_{fixation} is N input to cropland from biological N_2 fixation. $Ic_{\text{deposition}}$ is N input to cropland from atmospheric N deposition. The units for all Ic and Oc are kton N $year^{-1}$.

Nitrogen use efficiencies in animal production (NUEa) is defined as the ratio of N output in main products, and total N input in animal production. NUEa was calculated according to Eqs. (3), (4), and (5) following the approach of Ma et al. (2012):

$$NUE_a = \left(Oa_{\text{main products}}/I_a\right) \times 100\% \quad (3)$$

$$Oa_{\text{main products}} = Oa_{\text{meat}} + Oa_{\text{egg}} + Oa_{\text{milk}} \quad (4)$$

$$Ia = Ia_{\text{main crop products}} + Ia_{\text{by-products}} + Ia_{\text{crop residues}} + Ia_{\text{animal by products}} + Ia_{\text{kitchen residues}} + Ia_{\text{feed}} \quad (5)$$

where $Oa_{\text{main products}}$ is the main product (e.g., meat) of animal production. Ia is the input for animal production. The input includes main crop products, by-products, crop residues, animal by-products, kitchen residues, and feed from import. The unit for all Ia and Oa are kton N $year^{-1}$.

3. Results

3.1. Nitrogen losses from food production in Quzhou

Nitrogen losses to the environment from food production were approximately 9 kton in 2017. This includes N losses to the air and water. The share of crops and animals in these losses was 54% and 46%, respectively (Fig. 3). NH_3 emissions (4.1 kton) to the air took the dominant share in the total N losses to the environment. N_2O emissions to the air took the smallest share (0.2 kton). N losses to water from leaching, direct discharges of manure, and runoff and erosion were 2.1, 1.9, and 0.8 kton, respectively.

Nitrogen losses can be explained by the N use efficiencies. The N use efficiencies in crop production and animal production were 28% and 18% in 2017, respectively. Such low N use efficiencies were mainly due to the high N inputs to food production. This implies that considerable amounts of N were lost and did not reach the food products. Particularly in crop production, the total N input per administrative area reached 442 kg ha^{-1}. This total N input is 17% higher than the fertilization rate that is suggested for crop production in Quzhou (Zhang et al., 2020b; Table S3). Approximately 1.9 kton manure was directly discharged to water from animal production causing losses of N.

Nitrogen losses differ among the ten towns in Quzhou (Fig. 4). The total N losses to over administrative area were 82–197 kg N ha^{-1}. The highest N losses occurred in the Baizhai town (197 kg N ha^{-1}), followed by the Nanliyue town (193 kg N ha^{-1}). The town with the lowest losses (82 kg N ha^{-1}) was Disituan. The high N losses in towns can be explained by the structure of the planting area and animal species. For example, the livestock units (LU) per cultivated land in the Nanliyue and Baizhai were 10.8 and 9.1 LU ha^{-1}, respectively (Fig. S2, the calculation of LU was provided in Appendix B).

Nitrogen losses differ among sources in the ten towns (Fig. 4). The share of N losses to air and water was 48% and 52%, respectively. The main N losses to the air did not differ largely among the towns. NH_3 and N_2O emissions to the air from food production accounted for 45% and 3%, respectively. However, the N losses to water varied greatly among towns. The largest direct discharge of manure appeared in Baizhai (accounted for 27% of total N losses to water and air), which can be explained by the high livestock units (LU) per cultivated area. The largest leaching was in Henantuan (accounted for 32% of total N losses to water and air), which is mainly affected by the sown area of vegetable.

3.2. Nitrogen losses from different crops in Quzhou

Nitrogen losses differed among crops (Fig. 5a). The total N losses to the environment from eight crops were 5.0 kton in Quzhou in 2017. The model calculated the contributions of different crops to the total N losses to the environment. These contributions were 33%, 28%, 19%, 10%, and 9% for wheat, maize, vegetables, cotton, and fruits, respectively (Fig. S3). Wheat, maize, and vegetable production was responsible for 80% of the N losses from crop production. Wheat and maize production contributed 3.0 kton of N in the environment. Vegetable production contributed 0.9 kton of N to the environment. The N losses can be explained by sown area and the total N input to the cropland. For example, wheat and maize required the largest sown areas, accounting for more than 80% of the total sown area. N losses from vegetable production

Box 1
Equations to quantify nitrogen (N) losses to the environment from crop and animal production following the NUFER model.

Crop production

(1) $O_{NH_3} = I_{chemical\ fertilzier} \times EF_{NH_3 fertilizr} + Ic_{manure} \times EF_{NH_3 manure}$

(2) $O_{N_2O} = I_{chemical\ fertilzier} \times EF_{N_2O\ fertilizr} + Ic_{manure} \times EF_{N_2O\ manure}$

(3) $O_{\text{runoff}} = N_{application} \times SRF_{max} \times flu \times minimum\ of\ (fp, frc, fs)$

(4) $O_{\text{erosion}} = N_{application} \times EF_{erosion,max} \times fp \times minimum\ of\ (flu, frc, fs)$

$N_{application} = I_{fertilizer} + I_{manure} + I_{deposition} + I_{seed} + I_{irrigation} + I_{fixation}$

$N_{surplus} = N_{application} - O_{crop\ products} - O_{NH_3} - O_{N_2O} - O_{\text{runoff}} - O_{\text{erosion}}$

(5) $O_{accumulation} = N_{surplus} \times Proportion_{accumulation}$

(6) $O_{leaching} = N_{surplus} \times Proportion_{leaching}$

(7) $O_{Denitrification} = N_{surplus} \times Proportion_{Denitification}$

Notation

O_{NH_3} :N losses to air via NH_3 emission from applied synthetic fertilizers and animal manures, unit: kton.
O_{N_2O} :N losses to air via N_2O emission from applied synthetic fertilizers and animal manures, unit:kton.
O_{runoff} :N losses to water via surface runoff, unit: kton.
O_{erosion} :N losses to water via erosion, unit: kton.
$O_{leahing}$:N losses to water via leaching, unit: kton.
$O_{denitrification}$:N losses to air via denitrification, unit: kton.
$O_{accumulation}$:the net storage of N in the top soil(0-1m), unit:kton.
$I_{chemical\ fertilzier}$:N Input via chemical fertilizers, unit: kton.
I_{manure} : N input via animal manure, unit: kton.
$I_{irrigation}$: N input from biological N fixation, unit: kton.
$I_{deposition}$: N input from N deposition, unit: kton.
$I_{\text{irrigation}}$: N input from N irrigation, unit: kton.
$I_{fixation}$: N input from Biological N fixation, unit: kton.
$I_{fixation}$: N input from Biological N fixation, unit: kton.
$N_{application}$: N input from all N resource, unit: kton.
$N_{surplus}$: N surplus in crop production, unit: kton.

Animal production

(1) $Oa_{NH_3} = Oa_{\text{manure}} \times EF_{NH_3,\text{manure}}$

(2) $Oa_{N_2O} = Oa_{\text{manure}} \times EF_{N_2O,\text{manure}}$

(3) $Oa_{denitrification} = Oa_{\text{manure}} \times EF_{denitrification,\text{manure}}$

(4) $Oa_{discharge} = Surplus_{\text{manure}} \times EF_{discharge,\text{manure}}$

$Surplus_{manure} = Oa_{manure} - Oa_{NH_3} - Oa_{N_2O} - Oa_{denitrification} - Oa_{discharge}$

Notation

Oa_{NH_3} :N loss via NH_3 emission from animal manure in housing, storage and treatment sector, respectively
Oa_{N_2O} :N loss via N_2O emission from animal manure in housing, storage and treatment sector, respectively
$Oa_{denitrification}$:N loss via denitrification from animal manure in housing, storage and treatment sector, respectively
$Oa_{discharge}$:N loss via discharge from animal manure in housing, storage and treatment sector, respectively
$Surplus_{manure}$:Manures N surplus of in housing, storage and treatment sector, respectively.
Oa_{manure} :Amount of manures N in housing, storage and treatment
$EF_{NH_3,\text{manure}}$: NH_3 emission factors for manure in housing, storage and treatment sector ,respectively
$EF_{N_2O,\text{manure}}$: N_2O emission factors for manure in housing, storage and treatment sector respectively
$EF_{denitrification,\text{manure}}$: Denitrification factors for manure in housing, storage and treatment sector, respectively

occurred mainly from chemical N fertilizer applications. The amount of chemical N fertilizers applied to vegetables was more than twice the amount applied to cotton production (Table S3). As a result, vegetable production provided higher N losses (0.9 kton) than cotton production (0.5 kton).

Nitrogen losses differ slightly among sources and crops (Fig. 5a). Crop production emitted 1.8 kton of NH_3 and 0.2 kton of N_2O to the air. N was lost to water from crop production through leaching (2.1 kton), and runoff and erosion (0.8 kton). NH_3 emissions to the air and N leaching to water were the main N losses from crop production. The contribution of wheat and maize to NH_3 emissions was approximately 63%. Vegetable production contributed 14% to NH_3 emissions. Wheat, maize, and vegetables contributed 27%, 33%, and 21% to N leaching, respectively. The high potential to reduce N losses

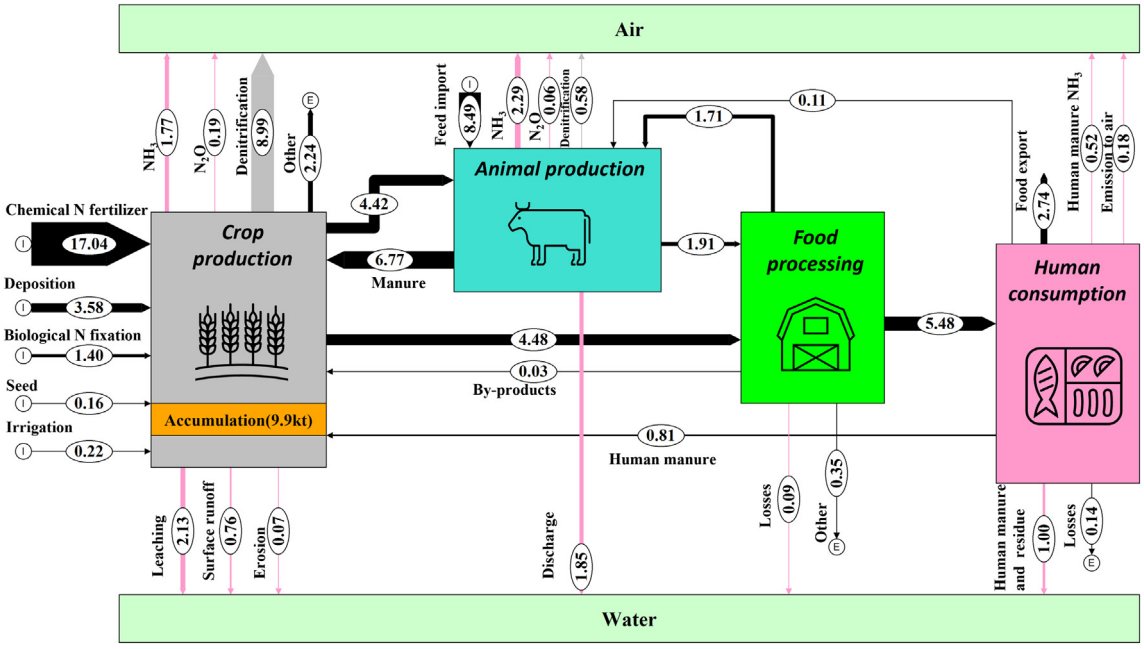


Fig. 3. Nitrogen flows in food production in Quzhou in 2017 (kton, the value of circles in the figure), including ammonia (NH_3) and nitrous oxide (N_2O). Red arrows indicate the losses of reactive nitrogen. Black arrows indicate the N input and products of N output. Grey arrows indicate the N output by denitrification, which is not pollutants. The green box refers to the air and water. Source: the NUFER model (see Section 2 for the model description).

are in mitigating NH_3 emissions and leaching especially from wheat, maize, and vegetables.

Nitrogen losses from crop production differed among the ten towns (Fig. 6). Approximately 60% of N losses from crop production came from wheat and maize among the towns. In addition, the production of wheat and maize was a dominant source of N losses to the environment, including towns Disituan (86%), Baizhai (78%), Quzhou (62%). Among the ten towns, other crops were also important. For example, vegetables contributed approximately 30% to the total N losses to the environment in Henantuan and Quzhou. The spatial variability among towns can partly be explained by the regional differences for sown areas and total N input of different crops (Fig. S1 and Table. S1).

3.3. Nitrogen losses from different animals in Quzhou

Nitrogen losses differed among animal species (Fig. 5b). The total N loss to the environment from seven animal species was 4.2 kton in Quzhou in 2017. The contributions of animals in these losses were

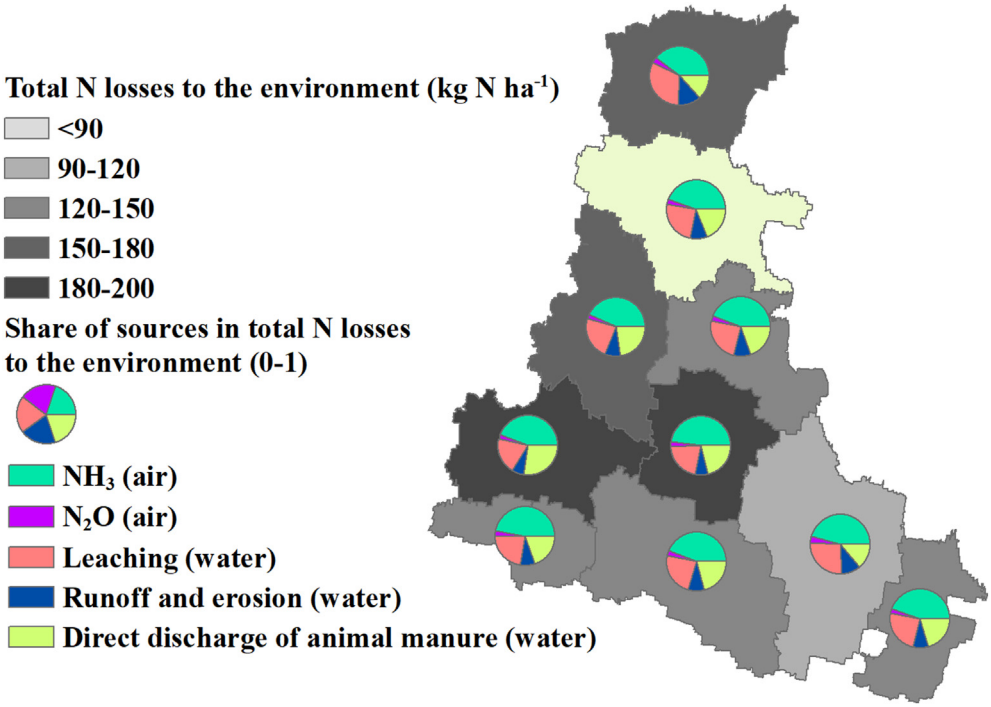


Fig. 4. Total nitrogen (N) losses to the environment from food production by towns in Quzhou (kg N ha^{-1}) and their sources (shares). The N losses including ammonia (NH_3), nitrous oxide (N_2O), leaching, runoff and erosion, and direct discharge of animal manure. The names of the towns are shown in Fig. 1. Source: the NUFER model (see Section 2 for the model description).

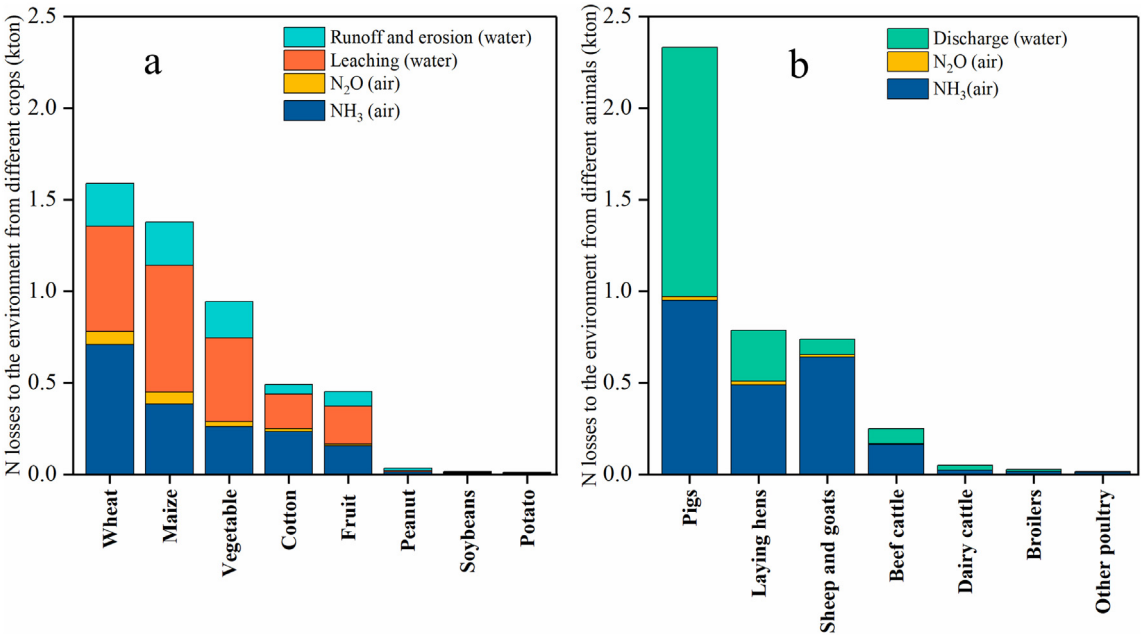


Fig. 5. (a) Nitrogen (N) losses from crop production in Quzhou (kton); (b) N losses from animal production in Quzhou (kton). The N losses include ammonia (NH_3), nitrous oxide (N_2O), leaching, runoff and erosion, and direct discharge of manure (discharge). Source: the NUFER model (see Section 2 for the model description).

55%, 19%, 18%, 6%, and 1% for pigs, laying hens, sheep and goats, beef cattle, and dairy cattle, respectively (Fig. S4). Pigs and laying hen production contributed 74% to the N losses to the environment. Pig production contributed 2.3 kton of N losses to the environment. This was 0.8 kton for laying hen production. The N losses can be explained by the animal density and the animal manure to the field (Tables S2 and S3). The largest number of animals were pigs and laying hens in Quzhou. The direct discharge of manure happened often because of the lack of effective manure management.

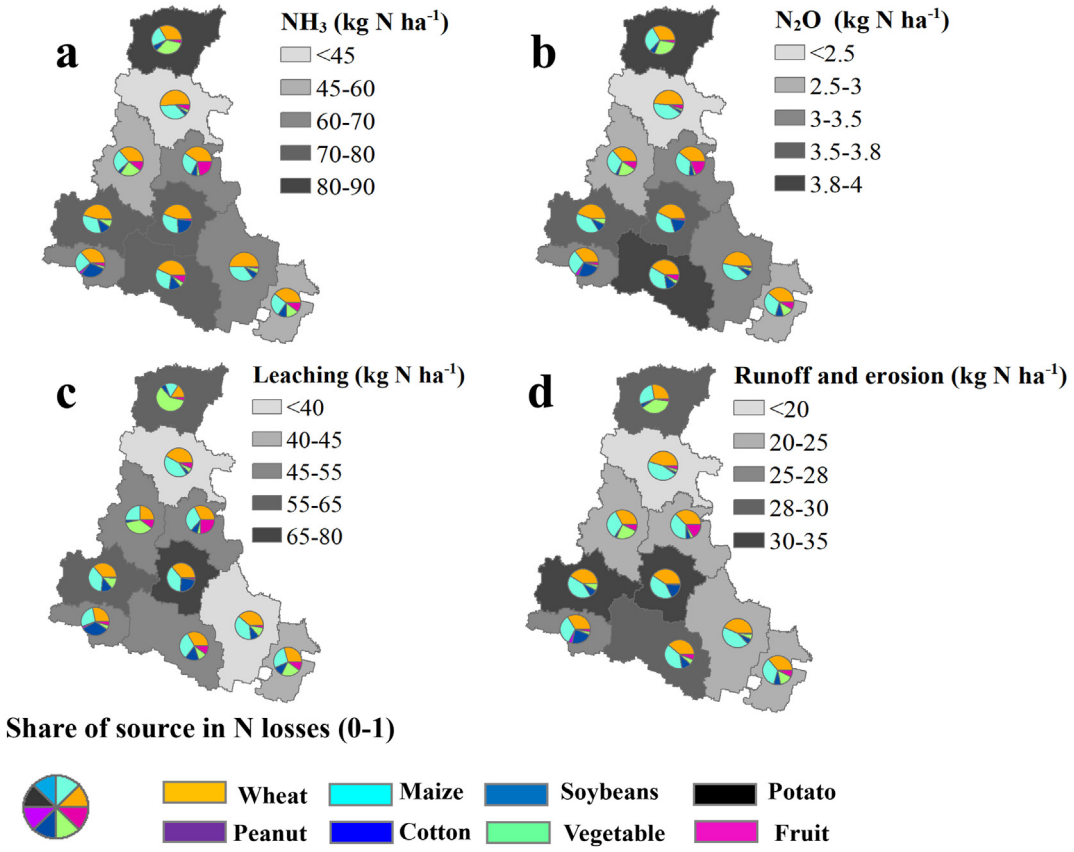


Fig. 6. Nitrogen (N) losses from crop production to the air and waters in the towns of Quzhou (kg N ha^{-1}) and share of crops in N losses (shares). Losses include (a) ammonia (NH_3) emission, (b) nitrous oxide (N_2O) emission, (c) leaching, (d) runoff and erosion. Source: the NUFER model (see Section 2 for the model description).

Nitrogen losses differed slightly among sources and animals (Fig. 5b). Animal production emitted 2.3 kton of NH_3 and 0.1 kton of N_2O to the air. The N loss to water from animal production was through direct discharge of manure (1.9 kton). NH_3 emissions to air and manure discharge to water were the major N losses from crop production. The contribution of pigs to NH_3 emissions was approximately 41%. The contribution of laying hens was 21% for NH_3 emissions. Pigs and laying hens contributed 74% and 15% to direct discharge of manure, respectively. The potential to reduce N losses are in mitigating NH_3 emission and manure discharge especially from pigs and laying hens.

Nitrogen losses from animal production differed among the ten towns (Fig. 7). Approximately 80% of N losses from animal production were from pigs and laying hens among the ten towns. In addition, the production of pigs and laying hens was dominant source of N losses to the environment, including towns Baizhai (73%), Anzhai (72%), and Disituan (55%). Among the ten towns, other animals were also important for N losses. For example, sheep and goats contributed by approximately 30% of total N losses to the water and air in Henantuan and Houcun. The spatial variability of N losses was affected by animal number and manure management (Fig. S2 and Table S3).

4. Discussion

4.1. Model uncertainties

We provide a new version of the NUFER model that integrates agricultural management information of different crops and animals through a farmer survey (see Fig. 2). This makes it possible to quantify the contribution of crops and animals to N losses, which was not possible in an earlier version of the NUFER model (Ma et al., 2012; Wang et al., 2018b). Our insights can contribute to identifying sustainable N management pathways to reduce N losses to the environment.

However, our model has uncertainties. For example, our emission factors for N_2O, runoff, and erosion from the production of fruits and vegetables are simplified (Tables S4 and S5). The emissions factors are based on published paper in China, which are not special for Quzhou. However, we believe that our simplified emission factors do not largely affect our main conclusions. This is because N_2O, runoff, and erosion are considered minor contributors to the total N losses to the environment from food production.

We address uncertainties using four options according to a "building trust" approach (Strokal et al., 2021). The first option is to compare model outputs with existing studies. For example, our emissions of NH_3 in 2017 are lower than in the other studies (Ju et al., 2009; Ma et al., 2010). This is associated with the type and application of chemical fertilizers. We account for a shift from ammonium bicarbonate to urea fertilizers, the use of compound fertilizers, and the technology-fertilizer deep application based on farmer survey (Guo et al., 2020; Wu et al., 2020). In our study, the direct discharge of manure is the main reason for N losses from animal production. This is in line with the results of the MARINA model for the Chinese rivers (Strokal et al., 2016; Wang et al., 2020b). However, other studies did not provide the share of animals in direct discharges of animal manure. We do this for eight animals and ten towns (Figs. 4 and 5). NH_3 emissions and direct discharges of animal manure to water are dominant N losses to the environment from crop and animal production. We show are for the year 2017. This is consistent with the findings by Zhao et al. (2017a), showing that more than half of N losses from animal production in NCP were from NH_3 emissions and direct discharges of animal manure to air and water for the years 2012–2015. Our results indicated that pigs and laying hens were the major sources from NH_3 emissions in animal production, which is in line with Wang et al. (2021). Bai et al. (2016) and Wei et al. (2018) indicate the importance of improving manure management in pigs and laying hens production to reduce N losses to air and water in the NCP. In addition, our estimates of the N use efficiencies (Table S10) in agriculture are comparable with other studies (Ma et al., 2010, 2013; Wang et al., 2017, 2018b). For example, in our study, the N use efficiencies in crop and animal production were 28% and 18%, respectively. These are close to 26% in crop production and 17% in animal production from Wang et al. (2018b) for Quzhou in 2012.

The second option is to compare the spatial pattern of N losses with existing models. Some counties in the NCP are known to be hotspots of N losses to air and water (Wang et al., 2018b; Jin et al., 2020b). In these hotspots, $PM_{2.5}$ pollution and contamination of groundwater may be high (Zhao et al., 2017b, 2019). Our study confirms that Quzhou is a pollution hotspot: N losses in Quzhou are 134 kg N ha^{-1} (N losses exceeding 96 kg N ha^{-1} are considered hotspots following Wang et al. (2018b)). Our study identifies N losses by crop type and animal species. This new information helps to better understand sources of air pollution in pollution hotspot. The spatial distribution of N losses to the environment from food production was also studied for Quzhou (Wang et al., 2020a). Wang et al. (2020a) provided N losses and showed differences between the towns of Quzhou and Baizhai. We do this for ten towns (Figs. 4–5). Our spatial distribution of high N losses from food production in 2017 is comparable to that of Wang et al. (2020a).

The third option is to perform a sensitivity analysis. We selected two model inputs that influence simultaneously air and water pollution. These are (1) fertilizer application rate and (2) the fraction of manure that is directly discharged to water. We run the model by increasing or decreasing these inputs by 10% and 30%. We show results in Figs. S5–S7. The sensitivity analysis confirms our conclusion that improvements in fertilizer application and manure recycling are effective

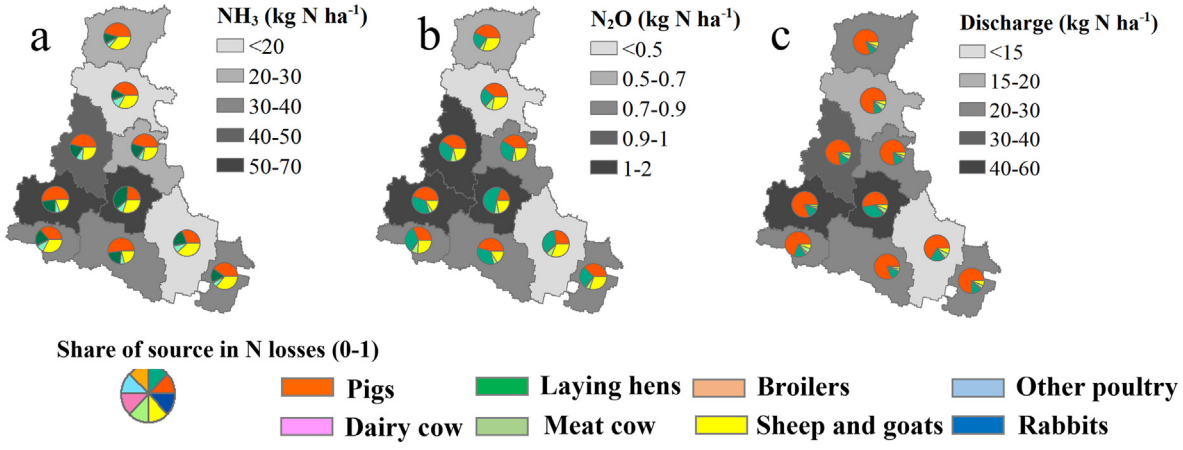


Fig. 7. Nitrogen (N) losses from animal production to the air and water in the towns of Quzhou (kg N ha^{-1}) and share of animals in N losses (shares). Losses include: (a) ammonia (NH_3) emission, (b) nitrous oxide (N_2O) emission, (c) direct discharge of animal manure (discharge). Source: the NUFER model (see Section 2 for the model description).

in reducing N losses from both crop and animal production in Quzhou. This is because the N losses to air and water are sensitive to changes in fertilization and fractions of manure discharge (Fig. S5). N losses from crop production are more sensitive to changes in fertilization (e.g., a 22% decrease in N losses to air and water as results of a 30% decrease in fertilizer inputs). N losses to air and water from animal production are more sensitive to changes in the fractions of manure discharge to water. For example, we calculated a 13% decrease in N losses to the air and water as result of 30% decrease in the fraction of direct manure discharges. This is the net effect of less manure discharge to rivers and more manure applications to cropland. Our sensitivity analysis also confirms our conclusion that managing fertilization in wheat, maize, and vegetable production is a promising strategy to reduce N losses from crop production. This is because the model outputs are sensitive to changes in the fertilization of these crop types, which are the dominant contributors of crop-related N losses to the environment (Fig. S6). For example, a 30% increase in the use of chemical N fertilizers for wheat, maize, and vegetables results in 19–26% changes in N losses to the air and water by these crops. The sensitivity analysis confirms that managing manure in pigs and laying hens is a promising strategy to reduce N losses from animal production. This is because the N losses to air and water are sensitive to changes in the factions of manure discharge to water (Fig. S7).

The fourth option is to reflect on uncertainties in the modeling approach. Our model builds on existing modeling approaches of NUFER (Ma et al., 2010; Ma et al., 2012; Wang et al., 2018a). Those approaches have been evaluated and widely accepted in the literature. We improved them by adding local information. We believe this improved the model for local analysis (Quzhou) and gives trust in using our NUFER model to quantify the contribution of different crops and animals to N losses.

4.2. Regional nitrogen management and outlook

In this study, we considered Quzhou as an example to quantify the contribution of N losses to the environment from different crops and animals. This information can support AGD in developing optimal N management. AGD has been recently promoted in China. This movement aims to achieve sustainable agricultural production with low environmental impacts (Shen et al., 2020). The information of our study provides a new perspective to support AGD in three main ways.

First, our information can help to prioritize options to reduce N losses from crop and animal production. For instance, our results indicate that wheat, maize, and vegetables are responsible for N losses to the environment during crop production. This was mainly due to the overuse of chemical N fertilizer. This implies that improved nutrient management in cereals and vegetables will likely reduce N losses to the environment in Quzhou. Therefore, reducing the overuse of chemical N fertilizer in wheat, maize, and vegetable productions could be a priority in pollution reduction policies for Quzhou. In animal production, pigs and laying hens contribute the most N losses in animal production by NH_3 emissions and direct discharges of animal manure. Options to reduce NH_3 emissions and recycling of manure back to cropland are promising in animal production. In addition, agricultural NH_3 can react with acidifying sulfuric acid and nitric acid in the atmosphere to produce secondary inorganic aerosols. This may lead to acidifying deposition and the development of haze pollution (An et al., 2019; Liu et al., 2020). A recent study concluded that the contribution of agricultural NH_3 emission to $PM_{2.5}$ concentration in the Beijing–Tianjin–Hebei region increased from 21% in 2015 to 25% in 2018 (Chen et al., 2021). Improving nutrient use efficiency (e.g., by improved fertilization and recycling of manure) may contribute to reduction of $PM_{2.5}$ formation and environmental degradation (Ortiz-Montalvo et al., 2014; Zhan et al., 2021).

Second, models can be used to identify region-specific management options in reducing N losses from food production. Our information can help improve N management among towns in a county. For instance, the Nanliyue and Baizhai tows have many animals, producing more manure than needed of crop production. In contrast, the Quzhou town is dominated by vegetable production. Here manure supply is less than needed. Our insights can help develop management options to balance the manure supply and demand among the towns. This can reduce N losses (Zhang et al., 2019; Jin et al., 2020a). In addition, several policies have been introduced for spatial planning in China. Examples are the reallocation of pigs from the southern region to the northern region for breeding in China (Bai et al., 2019). These policies aim to reduce N losses to water in the southern region (Bai et al., 2019). This model can be used to understand the impacts of livestock reallocation on N losses and N use efficiency (Wei et al., 2018) and support the optimal structure of crops and animals in regional N management.

Third, our model can explore the options to reduce N losses in the whole food production chain. The NUFER model was developed for whole crop and animal production. Future studies could apply the model to assess effects of synergistic combination of options to reduce N losses for AGD. The combination of options including avoid over-fertilization (Chen et al., 2011), enhanced-efficiency fertilizer (e.g., urease inhibitors) (Ju and Zhang, 2017), low-protein feed in animal breeding (Hou et al., 2016), covering solid and slurry manure (Sajeev et al., 2018), recycling of manure to croplands (Zhang et al., 2019), and healthy diets (Willett et al., 2020). This can help us identify the maximum potential for reduce N losses and provide the N management strategies for other countries to support AGD.

5. Conclusions

We quantified the relative shares of crops and animals in N losses from food production, and took Quzhou county as a typical example for the North China Plain. To this end, we developed a new version of the NUFER model. We calculate that, in 2017, approximately 9 kton of N was lost to air and water from food production in Quzhou. This is associated with the low N use efficiency in crop (28%) and animal (18%) production. Wheat, maize, and vegetable production were responsible for 80% of N losses to the environment from crop production. Pigs and laying hen production contributed by 74% to N losses to the environment from animal production. NH_3 emissions, N leaching, and direct discharges of manure were the main contributors of total N losses to environment from crop and animal production. Improving nutrient management of crops (wheat, maize, vegetables) and animals (pigs, laying hens) is urgently needed to reduce N losses.

Our study can support the formulation of effective nutrient management in food production to reduce N losses and to support Agricultural Green Development. Our quantitative information can help to identify crops and animals contributing most to air and water pollution. In future research, our model could be used to identify synergetic solutions for simultaneous reduction of air and water pollution from food production. This will improve N use efficiency in the Quzhou county, and serve as an example for other counties in China.

CRediT authorship contribution statement

Fanlei Meng: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Mengru Wang:** Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Maryna Strokal:** Conceptualization, Writing – original draft, Writing – review & editing. **Carolien Kroeze:** Conceptualization, Writing – review & editing. **Lin Ma:** Conceptualization, Writing – review & editing. **Yanan Li:** Data curation, Writing – review & editing. **Qi Zhang:** Data curation, Writing – review & editing. **Zhibiao Wei:** Data curation, Writing – review & editing. **Yong Hou:** Writing – review & editing. **Xuejun Liu:** Writing – review & editing. **Wen Xu:** Conceptualization, Formal analysis,

Visualization, Writing – original draft, Writing – review & editing. **Fusuo Zhang:** Conceptualization, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151557.

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