Front. Agr. Sci. Eng. 2024, 11(1): 113–121 https://doi.org/10.15302/J-FASE-2024540

REVIEW

Optimizing nitrogen management in the food system for sustainable development: a case study of Quzhou County

Fanlei MENG[1,2], Menru WANG[2,3], Yong HOU[1], Lin MA[4], Wenqi MA[5], Xuejun LIU[1], Fusuo ZHANG[1], Wen XU (✉)[1]

1 College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, State Key Laboratory of Nutrient Use and Management, National Observation and Research Station of Agriculture Green Development (Quzhou, Hebei), China Agricultural University, Beijing 100193, China.
2 Water Systems and Global Change Group, Wageningen University & Research, 6700 AA Wageningen, the Netherlands.
3 Environmental Systems Analysis Group, Wageningen University & Research, 6708 PB Wageningen, the Netherlands.
4 Key Laboratory of Agricultural Water Resources, Hebei Key Laboratory of Soil Ecology, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China.
5 College of Resources and Environment Science, Hebei Agricultural University, Baoding 071001, China.

KEYWORDS

Agriculture green development, food system, multi-objective, nitrogen management

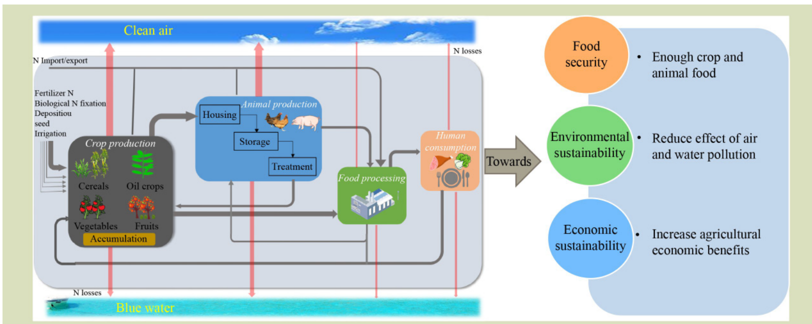
HIGHLIGHTS

- The framework of multi-objective nitrogen (N) management was developed.
- Multi-objective targets were established to support agriculture sustainable production.
- A food chain approach was developed to accurately quantify N flow in food system.
- "3R" principle was used in developing N management strategy.
- The collaboration with different stakeholders is crucial for promoting technologies.

Received September 15, 2023;
Accepted January 8, 2024.

Correspondence: wenxu@cau.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Nitrogen (N) is an essential nutrient for food production. The rapid increase in population requires high inputs of N to meet the growing food demand. If not managed well, the substantial loss of N from the food system has multiple impacts on grain yield, air and water pollution, and the economic benefits of agricultural. Multi-objective (food security, environmental sustainability and economic sustainability) synergistic consideration of N management in the food system is still lacking. This study employed strategies for optimizing N management in the food system, using Quzhou County as a typical example on the North China Plain. Firstly, a food chain approach was adopted to understand drivers and reasons behind N losses from the food system. Secondly, a top-down approach was used to define multi-objective N management, taking into consideration food security, environmental sustainability and economic sustainability. Multi-objective N management aims to reduce N losses to the environment and increase N use efficiencies, while simultaneously increasing yields and economic benefits. Thirdly, 3R (reduce-retain-recycle) N management strategies were identified for specific crops and animals through a bottom-up approach and then analyzed the potential of these strategies to achieve the multi-objectives. Finally, there is a discussion of how to engage different stakeholders to promote the technologies implementation. This study provides new insights into the synergistic achievement of multi-objective N management in the food system and the development of environmentally-friendly agriculture.

1 Introduction

Nitrogen (N) is a crucial nutrient for food production, but rapid increase in population is often accompanied by an increase in N inputs required to sustain food production[1]. Inefficient N use by food production leads to significant N losses, resulting in environmental problems such as air pollution, eutrophication and climate change[2]. To tackle these issues, the Chinese government initiated a national action plan for agriculture green development, which includes a target of enhancing N use efficiency, minimizing N losses to the environment and simultaneously increasing crop yields[3]. Therefore, it is important for muti-objective N management to ensure food security, environmental sustainability and economic sustainability.

The North China Plain (NCP) is a region of significant N loss in China, accounting for 50% of the total national N loss despite occupying only 10% of the land[4]. Quzhou, located on the NCP, is a representative agricultural county where double cropping of wheat and maize dominates crop production. Additionally, intensive pigs and laying hens production reflect the current regional structure of food production on the NCP[5]. Although Quzhou is a demonstration site for agriculture green development[5], it still faces significant challenges related to N losses from agricultural practices, leading to air and water pollution[5]. Agricultural production in Quzhou emits large ammonia (NH_3) emission, resulting in annual average concentrations of NH_3 in the air of about 40 $\mu g \cdot m^{-3}$[6,7]. Agricultural NH_3 emissions can chemically react with acidifying compounds (sulfur dioxide and nitrogen dioxide) and contribute to $PM_{2.5}$ pollution[8]. The annual average $PM_{2.5}$ concentration in Quzhou was about 56 $\mu g \cdot m^{-3}$ during 2019–2021, which is close to that in the Beijing-Tianjin-Hebei region (50 $\mu g \cdot m^{-3}$)[9–12]. Moreover, the nitrate leaching from wheat and maize production was 209 $kg \cdot ha^{-1}$ N in Quzhou, exacerbating the risk of groundwater pollution[13]. Quzhou also made great effort to optimal N management in Quzhou. Various N management technologies have been developed, such as the 4R nutrient management (right fertilizer type, right amount, right placement and right time) and improvements in animal production (such as low protein feeding and manure composting)[14,15]. Therefore, Quzhou can serve as an ideal case study to explore optimizing N management on the NCP.

2 Challenges and opportunities in multi-objective N management in the food system

Excessive N in the food system, leading to significant environmental losses, is a prevalent global issue, particularly in developing countries[16]. Agriculture on the NCP faces challenges of high N inputs and environmental loss[17]. Implementing multi-objective N management presents a challenge for improving food production by effectively reducing N losses, enhancing N use efficiency, and increasing agricultural yields and economic benefits[18]. This challenge is not limited to China but is also experienced in other regions worldwide. For our study, we selected Quzhou County as a case study, as it would be strongly indicative for the NCP as a whole. Quzhou County is representative at the county level and serves as an appropriate spatial unit for making N management recommendations in China. However, achieving the synergistic realization of these multi-objectives poses significant challenges to agricultural N management, as it requires cooperation between government, researchers, businesses and smallholders[19].

2.1 One of the major challenges is to accurately quantify N flows in the food chain

To accurately quantify N flows in the food chain is key step for optimizing N management. The N losses occur throughout the entire food production process, from crop production to human consumption[1,4]. However, reducing N losses is challenging due to the various forms of N [e.g., NH_3, nitrogen oxides (NO_2), nitrate nitrogen (NO_3^--N) leaching][2,5]. Researches on food system should consider the interactions and nutrient flows between subsystems, as well as the trade-offs and synergies of innovative technologies in minimizing N losses. Some models have been developed to quantify N flows in food production[1,4], such as MITERRA-EUROPE[20], the Coupled Human and Natural Systems Nitrogen Cycling Model[21], NUFER (NUtrient flows in Food chains, Environment and Resource use) model[22]. For example, Ma et al.[22] developed the first version of NUFER model to assess N losses and N use efficiencies in the food system in China, followed by several different versions such as NUFER-province[23] and NUFER-county[4]. These models often overlook the losses of N from specific crop and animal species. They typically focus on N losses from chemical fertilizers and animal manure without distinguishing between crops and animals[5]. This limitation is primarily due to the lack of specific activity data (e.g., fertilizer application) and emission factors (such as NH_3 and N_2O emission factors). Developing new models to accurately quantify N flows in the food chain at the county scale, while considering the contributions of different crops and animals, poses a significant challenge.

2.2 Second challenge is to develop multi-objective N management targets

The establishment of multi-objective goals for N management will provide benchmarks for effectively proposing optimized N management. N losses from food system have different impact, such as air and groundwater pollution[24]. For example, there are considerable losses of N in the form of NH_3 emissions to air and NO_3^--N leaching to groundwater[24]. These losses contribute to $PM_{2.5}$ pollution and the accumulation of nitrates in groundwater, posing significant risks to human health[2,5]. In addition, excessive N inputs can lead to significant N losses, such as those resulting from over-fertilization. These high inputs do not lead to increased yields and result in wasted economic investments for farmers. Most studies tends to be an assessment of the abatement potential and cost-benefit of N management technologies[2,25]. Lack of establishment of N management targets to constrain agricultural production to achieve a win-win situation for both food production and environmental protection. Schulte-Uebbing et al.[26] developed the N emissions target of crop production, which links impact of surface water, deposition, and groundwater, but this study did not consider whole food production. How to establish N management target that integrate food safety, environmental sustainability and economic sustainability is an important challenge for optimizing N management.

2.3 Third challenge is to develop effective N management solution

N management options has received widely attention[2,27]. Various N management technologies have been developed in crop and animal production[25]. For example, optimal N application rate can achieve 21% yield increase, 15% reduction of N fertilizer application and 35% reduction of N losses[17,28]. Enhanced fertilizer (such as urease inhibitor products and coasted controlled release fertilizer) can reduce N losses by 22% to 64%, of which the urease inhibitor products can reduce NH_3 emissions from crop production by 63%[29]. In animal production, reducing crude protein feeding levels by 1% to 2% does not impact animal production and can significantly reduce total N excretion by 10% compared to traditional feeding levels[30]. Manure mulching technology can reduce the contact area of manure and urine with the air, realizing a 50% to 98% reduction in NH_3 emissions[31]. However, current research focuses on analyzing the potential for technical emission reductions in crop production or animal production, and lacks a management strategy for N management based on N management targets. In addition, the full implementation of these N management technologies (such as enhanced fertilizer and low protein feeding) is hindered by various constraints, such as limited technology knowledge, high implementation costs for farmers and the introduction of new technologies or products[19,32]. How to explore effective options to meet N emissions target is an important challenge for optimizing N management.

3 Framework for optimizing N management in the food system

We present a framework for optimizing N management in the food system (Fig. 1). In this study, we used a top-down and bottom-up approaches to explore optimizing N management, taking Quzhou as a case study. The top-down approach involves defining multi-objective N management that integrates food security, environmental sustainability, and economic sustainability. The bottom-up approach involves identifying 3Rs (reduce-reuse-recycle) management strategies for specific crops and animals through local fieldwork in Quzhou. Ultimately, the optimization of N management options is formulated to achieve multi-objectives synergistically in the food system. The framework serves the following purposes: (1) quantifying the N flows in the food system using the NUFER model; (2) identifying multi-objective N targets that consider food security, and environmental and economic sustainability; and (3) exploring effective N management options to achieve these multi-objectives through scenario analysis. The application of the framework in Quzhou is described below.

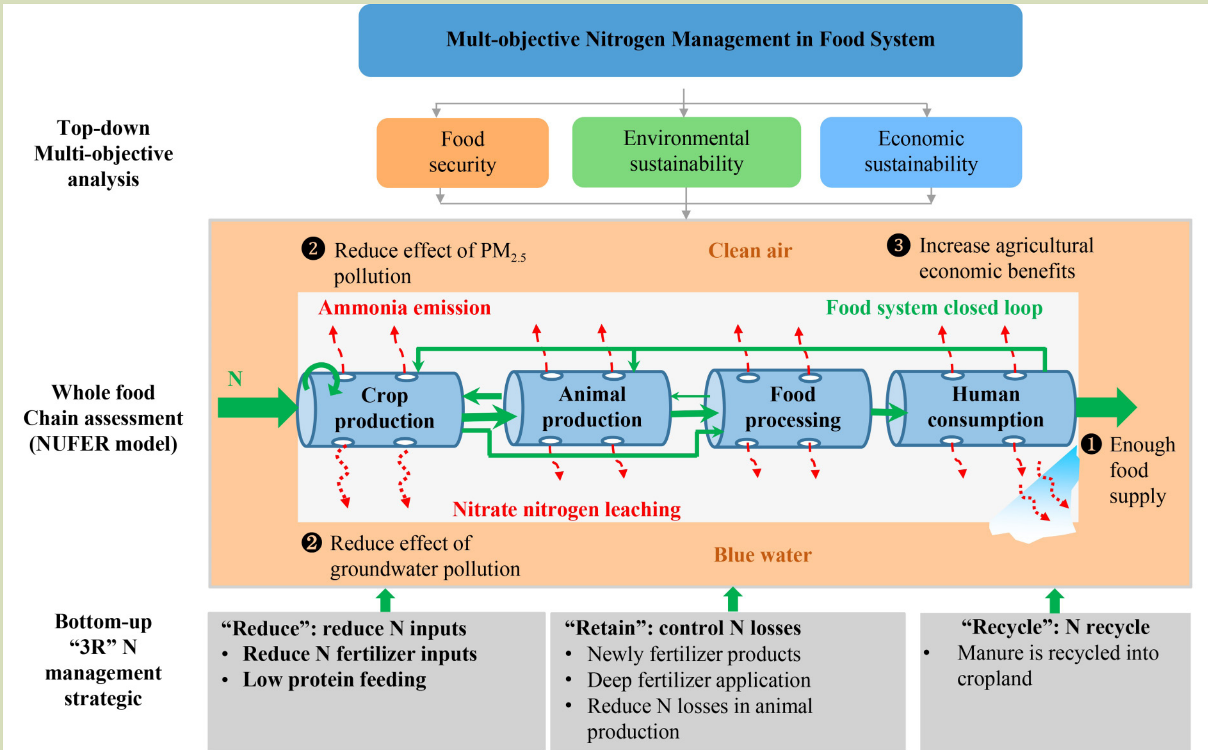


Fig. 1 Integrated assessment framework for evaluating N losses and improvement of N management in the food system in Quzhou, North China Plain. The whole food chain assessment by NUFER (NUtrient flows in Food chains, Environment and Resource use) model[5].

3.1 The N flow in the food system in Quzhou in 2020

To gain a better understanding of understand drivers and reasons behind N losses from the food system. Meng et al.[5] improved the NUFER-county model and successfully quantified N losses from different crops and animals in the food system of Quzhou. In this study, we use the NUFER-county model to quantify the N flows in the food system and identify the contribution of different crops and animals in Quzhou in 2020. We further updated data on local farmer diets using a farmer survey, and agricultural actives data (such as animal number and crop yield) in Quzhou in 2020[33,34]. The uncertain and evaluation of NUFER model in Quzhou see the Meng et al.[5]. We found the N losses to the environment from the food chain in Quzhou in 2020 amounted to 9.4 kt, with about 88% of these losses stemming from crop and animal production (Fig. 2). These can be explained by the low N use efficiency (19%) of food production. Among crop production, wheat, maize, and vegetables accounted for 77% of N losses, while pigs and laying hens were responsible for 71% of the N losses from animal production. NH_3 and N_2O emissions to air were calculated to be 4.6 and 0.4 kt, respectively. N losses to water from direct discharges of manure, leaching, runoff and erosions were 4.4 kt in total. NH_3 emissions to air and nitrate leaching to water contribute to 69% of total N losses to the environment in Quzhou. Hence, it is crucial to prioritize N management in both crop and animal production throughout the entire food system.

3.2 Multi-objective of N management target for food system in Quzhou

The multi-objective N management target was developed, which integrates food security, and environmental and economic sustainability. To better understand the multi-objective N management targets, some indicators have been selected taking into main N losses pathway in the food system, local environmental pollution problem and data availability (Table 1). For environmental sustainability, this study focused more on reducing effect of air and water pollution and improving N resource efficiency. The NH_3 emissions target was set to meet Chinese $PM_{2.5}$ standard (35 $\mu g \cdot m^{-3}$), while the target for NO_3^--N leaching was set to meet the safe drinking groundwater nitrate concentration standard (11.3 $mg \cdot L^{-1}$ NO_3^--N) set by World Health Origination. And our study also considers N use efficiency in food production and cereal

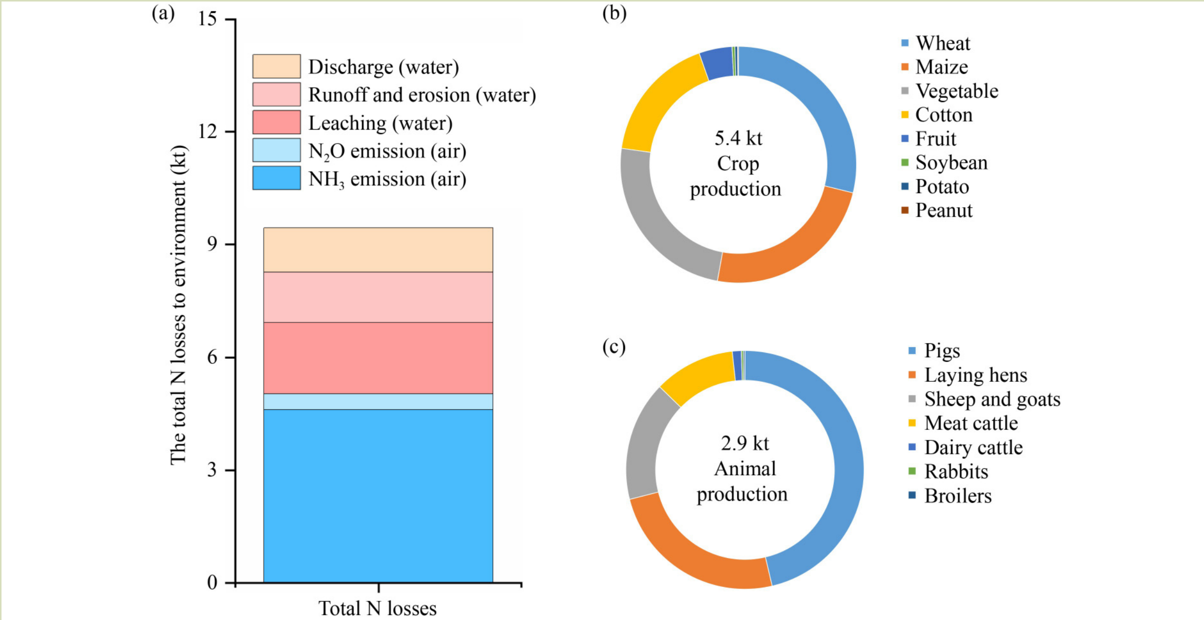


Fig. 2 N losses (kt) to environment (a), from crop production (b), and animal production (c) in Quzhou in 2020. The total N losses included ammonia, nitrous oxide, leaching, runoff and erosion, and direct discharge of manure (discharge).

Table 1 The effective options for multi-objective N management in the food system in Quzhou

Three pillars	Indicator	Units	Current (2020)	Optimal major crops and animals	Target
Food security	Cereal (wheat and maize) production	kt	398	**459**	398
	Protein production of crop and animal production	kt	36	**39**	15
	Food self-sufficiency rate	%	256	**279**	95
Environmental sustainability	Ammonia emission from food production (air)	kt	4.6	**3.59**	2.1
	Nitrate nitrogen leaching from food production (water)	kt	1.9	**1.67**	1.7
	N use efficiency in food production	%	19	**25**	19
Economic sustainability	Agriculture value	CNY	3.5×10^9	$\mathbf{3.8 \times 10^9}$	3.5×10^9

Note: Comprehensive measures for major crops and animals: concurrent improvement of N management for maize, wheat, laying hens and pigs; improvement of wheat and maize production by reducing N fertilizer application rates, deep fertilizer placement and urease inhibitor technology; and improvement of pigs and laying hens production by a combination of low crude protein, additives during composting and increasing manure return croplands. The values given in green meet targets but those in red did not.

production at least no lower current situation. In terms of food security, the primary focus is on ensuring an adequate supply of crops and animal food for the local population, aiming for local food self-sufficiency (ratio of food consumption to food production, with a food self-sufficiency rate of not less than 95%[35], supply enough protein for human health, daily per capita intake of 78 g of protein as a health standard in China[36]. The protein production of crop and animal production is calculated by sum of protein of crop and animal products in Quzhou in 2020. Furthermore, economic indicators are considered to promote agricultural benefits, with agriculture value serving as indicator to better understand the status of agricultural practices. The agriculture value was calculated by sum of different crops and animal products from Quzhou statistics in 2020. In our study, we assume the target of agriculture value at least no lower current situation.

3.3 Effective options for achievement multi-objective N management in the food system

Our study considered the 3R principles to summary N management option in the entire food system in Quzhou based on local fieldwork and literature summary: reduce N input in food production, such as optimal N application rate and low protein feeding; retain N within the system food system by minimizing losses, such as deep application fertilizer, enhanced fertilizer; and recycle manure to croplands. China has a strict policy prohibiting direct discharge of manure and the utilization rate of manure resources has reached about 90%[37]. Various N management technologies in crop and animal production have been developed in Quzhou, which can be used to support the identification of effective options. In terms of crop production, the integrated of optimal N rates, deep fertilizer placement and the application of urease inhibitors resulted in a reduction of NH_3 emissions by 49% and 39%, an increase in N use efficiency by 28% and 40%, and a 25% and 19% increase in benefits to farmers for wheat and maize in Quzhou, respectively[19]. For animal production in Quzhou, comprehensive measures such as reducing crude protein levels, using additives during composting and utilizing chemical fertilizers with recycled manure were found to decrease reactive N and NH_3 emissions by 52% and 34%, respectively, while increasing N use efficiency by 52% in the laying hens-crops system[14]. The increase of agricultural value comes from the increase in the production of wheat and maize, and from the scale effect of egg production in Quzhou. In addition, government, enterprises and local farmers have jointly established a laying-hens cooperative, which has realized a 23% increase in the value of egg production by implementing laying-hens whole chain emission reduction technology and creating a green production brand for laying hens while classifying eggs for sale[38].

We used NUFER model to explore effective N management solutions to achieve multi-objectives N management through scenario analysis, which is show in a combine of summary of options for Quzhou (Table 1). A combination of reduced N fertilizer, deep fertilizer placement, urease inhibitor technology, low crude protein, additives during composting and increase manure return croplands can reduce nitrate leaching by 12%, while increasing grain yield by 15% and N use efficiency of food production by 31%, achieving the emission reduction goal of multi-objective in the food system, compared the reference year-2020. However, the NH_3 emissions reduction achieved was only 22%, which did not meet NH_3 emissions target. In the future, we need to explore more effective N management measures and simultaneously optimize N management for other crops and animals.

3.4 Collaborating with different stakeholders to promote technology implementation

To promote the implementation of N management options, it is important to foster collaboration between all stakeholders[19,32]. While scientists and enterprises develop new technologies and products, their adoption by farmers may be limited without the support of the government. It is crucial for farmers to trust scientists, enterprises and government, or at the very least, be curious and willing to implement these options[32]. Therefore, establishing effective linkages between stakeholders is necessary to accelerate technology innovation, transfer and application.

In the case of Quzhou, the demonstration-square model was developed to balance food security and improve air quality. This model involves collaboration between government, researchers, enterprises and local farmers to co-develop feasible N management options[32]. For example, researchers, such as Science Technology Backyard students, conduct field trials and provide guidance on management to leading farmers, allowing them to explore the effects of potential practices for reducing NH_3 emissions in maize and wheat production. The local government contributes by implementing policies that encourage and support farmers in adopting new technologies, as well as providing financial subsidies to reduce costs and support the purchase of new types of fertilizers. Enterprises contribute by producing stable and effective fertilizer products that include urease inhibitors. Additionally, smallholder farmers learn new technologies from the leader farmer and spread these ideas among other farmers in Quzhou[19,32]. Collaborating with different stakeholders to create and implement new technological approaches can be effective in facilitating technology transfer and application[19,32]

4 Concluding remarks and outlook

We have developed a framework to explore strategies for optimizing N management in the food system. This approach was applied to Quzhou County on the North China Plain as a representative case study, with the aim of defining multi-objective N management and identifying options for achieving multi-objectives N management. Our research has three key contributions.

First, we further improve NUFER-county model to quantify N flows in the food system and contribution of different crops and animals in Quzhou in 2020. This model helped us understand the drivers and reasons behind N losses from the food system. This main approach by NUFER model combines farmer surveys, monitoring data (e.g., NH_3 and N_2O emission factor) and statistical data. Our approach can help to prioritize options to reduce N losses from crop and animal production. In the future study, to accurately quantify N flows in the food chain, we should strengthen the integration of modeling methods and monitoring data, especially by updating key parameters of the model based on monitoring data.

Second, we explored the development of multi-objective N emissions target in the food system in Quzhou. In our study, we built the relationships between the main N loss pathway and local environmental problems. The targets for NH_3 emissions and NO_3^--N leaching were developed, which combine of Chinese $PM_{2.5}$ standard (35 $\mu g \cdot m^{-3}$) and a drinking water standard of 11.3 $mg \cdot L^{-1}$ NO_3^--N. Meanwhile, we also selected food self-sufficiency rate, protein production of crop and animal production, and agriculture value as indictors to ensure food security and economic sustainability. In the future, the multi-objective N emissions target need more explore. In China, different counties will likely have differing environmental problems. In northern China, $PM_{2.5}$ is a serious problem. However, eutrophication of water bodies may also be a problem in southern China. We should developed N management targets to match the main agricultural development problems specific to a local area. In addition, food security does not only consider enough food supply, we also need consider nutritional quality, and affordability and accessibility of food items. In the future study, we will be important to consider different N management targets for food security.

Third, we followed the 3R principle to explore optimizing N management to meet the multi-objective goals in Quzhou. A combination of reduced N fertilizer, deep fertilizer placement, urease inhibitor technology, low crude protein, additives during composting and more manure return to croplands in crop and animal production provide possible ways to meet these N managing targets. With the development of N management technologies, such as crop rotations, planting densities, timing of crop husbandry practices, improved genetic crop varieties, improved animal breeds, changes in animal categories and housing systems, which will give more options to meet N management targets. Technology costs and farmer acceptance will also need to be assessed in the future. In addition, we will also need to explore structurer strategies to meet future food demanding and N management targets. In future study, the technical, structural and consumption-based measures on N management need to be a key focus for the food system. To achieve a synthesis of multi-objective N management, it is crucial for scientists and stakeholders from different sectors, such as government, enterprises and farmers, to collaborate and integrate their expertise and approaches.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (42175137)，the Major Science and Technology Project of Yunnan Province (202202AE090034), the China Scholarship Council (201913043) and Hainan University, the High-level Team Project of China Agricultural University. We acknowledge Jiahui Kang, Zhilong He, Xiaoying Zhang, Zhibiao Wei, Luncheng You, Shilei Cui, Siqi Wang, and Zhichao An from China Agricultural University for their constructive comments and data summary.

Compliance with ethics guidelines

Fanlei Meng, Mengru Wang, Yong Hou, Lin Ma, Wenqi Ma, Xuejun Liu, Fusuo Zhang, and Wen Xu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Ma L, Bai Z, Ma W, Guo M, Jiang R, Liu J, Oenema O, Velthof G L, Whitmore A P, Crawford J, Dobermann A, Schwoob M, Zhang F. Exploring future food provision scenarios for China. *Environmental Science & Technology*, 2019, **53**(3): 1385–1393
2. Gu B, Zhang X, Lam S K, Yu Y, van Grinsven H J M, Zhang S, Wang X, Bodirsky B L, Wang S, Duan J, Ren C, Bouwman L, de Vries W, Xu J, Sutton M A, Chen D. Cost-effective mitigation of nitrogen pollution from global croplands. *Nature*, 2023, **613**(7942): 77–84
3. Shen J, Zhu Q, Jiao X, Ying H, Wang H, Wen X, Xu W, Li T, Cong W, Liu X, Hou Y, Cui Z, Oenema O, Davies W J, Zhang F. Agriculture Green Development: a model for China and the world. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 5–13
4. Wang M, Ma L, Strokal M, Ma W, Liu X, Kroeze C. Hotspots for nitrogen and phosphorus losses from food production in

China: a county-scale analysis. *Environmental Science & Technology*, 2018, **52**(10): 5782–5791

5. Meng F, Wang M, Strokal M, Kroeze C, Ma L, Li Y, Zhang Q, Wei Z, Hou Y, Liu X, Xu W, Zhang F. Nitrogen losses from food production in the North China Plain: a case study for Quzhou. *Science of the Total Environment*, 2022, **816**: 151557
6. Feng S, Xu W, Cheng M, Ma Y, Wu L, Kang J, Wang K, Tang A, Collett J L Jr, Fang Y, Goulding K, Liu X, Zhang F. Overlooked nonagricultural and wintertime agricultural NH_3 emissions in Quzhou County, North China Plain: evidence from 15N-stable isotopes. *Environmental Science & Technology Letters*, 2022, **9**(2): 127–133
7. Meng F, Zhang Y, Kang J, Heal M R, Reis S, Wang M, Liu L, Wang K, Yu S, Li P, Wei J, Hou Y, Zhang Y, Liu X, Cui Z, Xu W, Zhang F. Trends in secondary inorganic aerosol pollution in China and its responses to emission controls of precursors in wintertime. *Atmospheric Chemistry and Physics*, 2022, **22**(9): 6291–6308
8. Xu W, Zhao Y, Wen Z, Chang Y, Pan Y, Sun Y, Ma X, Sha Z, Li Z, Kang J, Liu L, Tang A, Wang K, Zhang Y, Guo Y, Zhang L, Sheng L, Zhang X, Gu B, Song Y, Van Damme M, Clarisse L, Coheur P F, Collett J L Jr, Goulding K, Zhang F, He K, Liu X. Increasing importance of ammonia emission abatement in $PM_{2.5}$ pollution control. *Science Bulletin*, 2022, **67**(17): 1745–1749
9. Ministry of Ecology and Environment of the People's Republic of China (MEE). Bulletin on the State of China’s Ecological Environment in 2019. Beijing: *MEE*, 2019 (in Chinese)
10. Ministry of Ecology and Environment of the People's Republic of China (MEE). Bulletin on the State of China’s Ecological Environment in 2020. Beijing: *MEE,* 2020 (in Chinese)
11. Ministry of Ecology and Environment of the People's Republic of China (MEE). Bulletin on the State of China’s Ecological Environment in 2021. Beijing: *MEE*, 2021 (in Chinese)
12. Wang K Y. Network Monitoring and Assessment of Air and Water Environmental Quality in Quzhou County. Thesis for the Master’s Degree. Beijing: *China Agricultural University,* 2023 (in Chinese)
13. Niu X, Zhang C, Ju X. Mechanism of nitrogen leaching in fluvo-aquic soil and deep vadose zone in the North China Plain. *Chinese Journal of Eco-Agriculture*, 2021, **29**(1): 53–65 (in Chinese)
14. He Z, Zhang Y, Liu X, Xu W, Hou Y, Wang H, Zhang F. Ammonia mitigation potential in an optimized crop-layer production system. *Science of the Total Environment*, 2022, **841**: 156701
15. Wang J, Sha Z, Zhang J, Qin W, Xu W, Goulding K, Liu X. Improving nitrogen fertilizer use efficiency and minimizing losses and global warming potential by optimizing applications and using nitrogen synergists in a maize-wheat rotation. *Agriculture, Ecosystems & Environment*, 2023, **353**: 108538
16. Liu X, Cui Z, Hao T, Yuan L, Zhang Y, Gu B, Xu W, Ying H, Zhang W, Li T, Yan X, Goulding K, Kanter D, Howarth R, Stevens C, Ladha J, Li Q, Liu L, de Vries W, Zhang F. A new approach to holistic nitrogen management in China. *Frontiers of Agricultural Science and Engineering*, 2022, **9**(3): 490–510
17. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang Z, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Ying H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, **555**(7696): 363–366
18. Guo Y, Chen Y, Searchinger T D, Zhou M, Pan D, Yang J, Wu L, Cui Z, Zhang W, Zhang F, Ma L, Sun Y, Zondlo M A, Zhang L, Mauzerall D L. Air quality, nitrogen use efficiency and food security in China are improved by cost-effective agricultural nitrogen management. *Nature Food*, 2020, **1**(10): 648–658
19. Kang J, Wang J, Heal M R, Goulding K, De Vries W, Zhao Y, Feng S, Zhang X, Gu B, Niu X, Zhang H, Liu X, Cui Z, Zhang F, Xu W. Ammonia mitigation campaign with smallholder farmers improves air quality while ensuring high cereal production. *Nature Food*, 2023, **4**(9): 751–761
20. Velthof G L, Oudendag D, Witzke H P, Asman W A H, Klimont Z, Oenema O. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *Journal of Environmental Quality*, 2009, **38**(2): 402–417
21. Gu B, Ju X, Chang J, Ge Y, Vitousek P M. Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National Academy of Sciences of the United States of America*, 2015, **112**(28): 8792–8797
22. Ma L, Ma W Q, Velthof G L, Wang F H, Qin W, Zhang F S, Oenema O. Modeling nutrient flows in the food chain of China. *Journal of Environmental Quality*, 2010, **39**(4): 1279–1289
23. Ma L, Velthof G L, Wang F H, Qin W, Zhang W F, Liu Z, Zhang Y, Wei J, Lesschen J P, Ma W Q, Oenema O, Zhang F S. Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. *Science of the Total Environment*, 2012, **434**: 51–61
24. Meng F, Ronda R, Strokal M, Kroeze C, Ma L, Krolc M, de Graaf I, Zhao Y, Wang Y, Du X, Liu X, Xu W, Zhang F, Wang M. Setting goals for agricultural nitrogen emission reduction to ensure safe air and groundwater quality: a case study of Quzhou, the North China Plain. *Journal of Environmental Management*, 2024, **351**: 119737
25. Zhang X, Gu B, Van Grinsven H, Lam S K, Liang X, Bai M, Chen D. Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. *Nature Communications*, 2020, **11**(1): 4357
26. Schulte-Uebbing L F, Beusen A H W, Bouwman A F, de Vries W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature*, 2022, **610**(7932): 507–512
27. Zhang X, Yao G, Vishwakarma S, Dalin C, Komarek A M, Kanter D R, Davis K F, Pfeifer K, Zhao J, Zou T, D’odorico P, Folberth C, Rodriguez F G, Fanzo J, Rosa L, Dennison W, Musumba M, Heyman A, Davidson E A. Quantitative

assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth*, 2021, **4**(9): 1262–1277

28. Chen X, Cui Z, Vitousek P, Cassman K, Matson P, Bai J, Meng Q, Hou P, Yue S, Romheld V, Zhang F. Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(16): 6399–6404
29. Li T Y. Evaluation of integrated effectiveness of enhanced efficiency fertilizers and influencing Factors. Dissertation for the Doctoral Degree. Beijing: *China Agricultural University*, 2018 (in Chinese)
30. Wang H, Long W, Chadwick D, Velthof G L, Oenema O, Ma W, Wang J, Qin W, Hou Y, Zhang F. Can dietary manipulations improve the productivity of pigs with lower environmental and economic cost? A global meta-analysis *Agriculture, Ecosystems & Environment*, 2020, **289**: 106748
31. Ma Y F. Environmental and Economic Performance and Optimization Approach of Typical Crop-livestock Systems. Dissertation for the Doctoral Degree. Beijing: *China Agricultural University*, 2018 (in Chinese)
32. Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z. Closing yield gaps in China by empowering smallholder farmers. *Nature*, 2016, **537**(7622): 671–674
33. Wei Z, Zhuang M, Hellegers P, Cui Z, Hoffland E. Towards circular nitrogen use in the agri-food system at village and county level in China. *Agricultural Systems*, 2023, **209**: 103683
34. National Bureau of Statistics of the People's Republic of China (NBSC). Quzhou Statistical Yearbook. Beijing: *China Statistics Press*, 2020 (in Chinese)
35. The Comprehensive Group for Research on Agricultural Development Strategy in China by 2050. Strategies for China's Agricultural Development Toward 2050. *Strategic Study of CAE*, 2022, **24**(1): 1–10
36. The Central People's Government of the People's Republic of China. China's Food and Nutrition Development Program (2014–2020). Beijing: *The Central People's Government of the People's Republic of China*, 2014. Available at The Central People's Government of the People's Republic of China website on December 6, 2023
37. Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA). Notice on the Resource Utilization of Livestock and Poultry Manure in 2020. Beijing: *MARA*, 2020. Available at MARA website on December 6, 2023
38. Wang S Q. The Way to Regulate Environmental and Economic Benefits of Supply Chain of Quzhou Laying Hens. Thesis for the Marster's Degree. Beijing: *China Agricultural University*, 2023 (in Chinese)