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Optimizing nitrogen fertilizer use for more grain and less pollution

Keyu Ren[a], Minggang Xu[a], Rong Li[b], Lei Zheng[b], Shaogui Liu[c], Stefan Reis[d,e], Huiying Wang[b], Changai Lu[a], Wenju Zhang[a], Hui Gao[c], Yinghua Duan[a, *], Baojing Gu[f, *]

[a]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[b]Arable Land Quality Monitoring and Protection Center, Ministry of Agriculture, Beijing 100125, China

[c]Yangzhou Station of Farmland Quality Protection, Yangzhou 225100, China

[d]UK Centre for Ecology & Hydrology, Penicuik, EH26 0QB, United Kingdom

[e]University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom

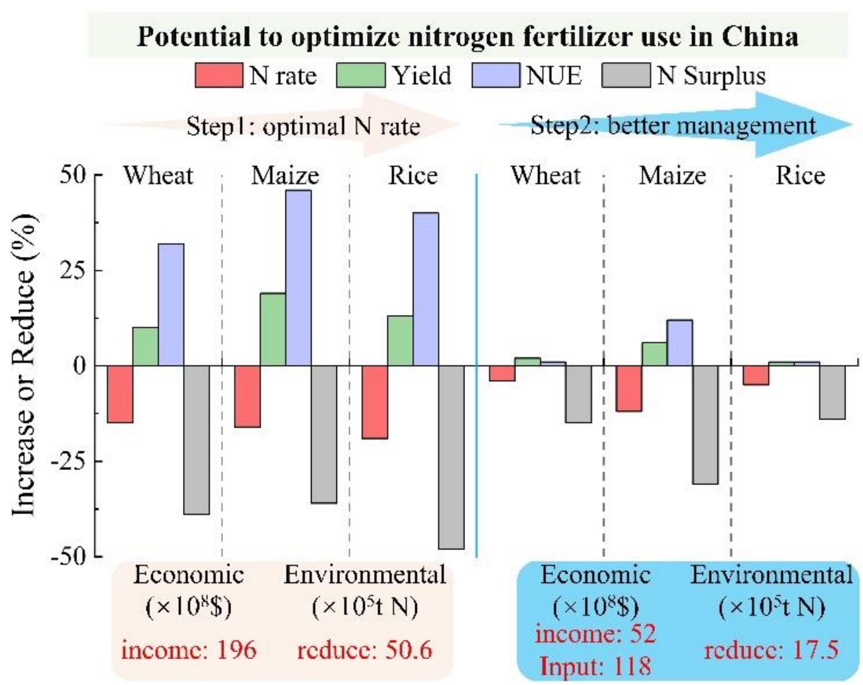
[f]College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, China

[*]Corresponding author: E-mail: duanyinghua@caas.cn (Y. Duan.); E-mail: bjgu@zju.edu.cn (B. Gu.).

Abstract: Optimal nitrogen (N) management is critical for efficient crop production and agricultural pollution control. Approximate 210–220 kg ha^{-1} N fertilizer was applied in millions of small plots through broadcasting way in China, resulting in over and loss of N fertilizers. However, it is difficult to implement advanced management practices on smallholder farms due to a lack of knowledge. Here, using 35,502 on-farm fertilization experiments, we demonstrated that smallholders in China could actually produce more grain with less N fertilizer use only through optimizing N application rate. The yields of wheat, maize and rice were shown to increase between 10% and 19% while N application rates were reduced by 15–19%. These changes resulted in an increase in N use efficiency (NUE) by 32–46% and a reduction in N surplus by 40% without actually changing farmers' operational practices. By reducing N application rates in line with official recommendations would not only save fertilizer cost while increasing crop yield, but also at the same time reduce environmental N pollution in China. Beyond of optimizing N application rate, improved management practices were required to produce more grain with less pollution, which would need about 11.8 billion US dollars for the implementation and reducing N loss reduction by 1.75 million tons to the environment.

Keywords: Crop yield, Nitrogen use efficiency, Nitrogen surplus, Environmental sustainability, Nitrogen management

Graphical abstract:



1. Introduction

Producing more food with less pollution is a grand challenge, which is crucial for global sustainable development goals (Springmann et al., 2018; Gerten et al., 2021; van Dijk et al., 2021). With growth and increasing affluence of the global population, the amount of food needed is continually increasing, and a large share of the global population is still suffering from malnutrition, especially in developing economies (Ren et al., 2019). Smallholder farming is the prevalent form of agricultural production in these developing economies, satisfying about 40% of global food demand (Lesiv et al., 2018; Duan et al., 2021). However, overuse of fertilizers often occurs on smallholder farms, leading to not only a lower crop yield, but also damages to the environment and human health (Zhang et al., 2021). Agricultural non-point-source pollution has become a dominant contributor to local environmental pressures in many regions of the world. To address these challenges, many best management practices and concepts such as soil testing and "4R" stewardship ("right fertilizer type", "right fertilization amount", "right time" and "right place") have been developed (Cui et al., 2013; Liu et al., 2016). However, they are rarely implemented on smallholder farms due to a lack of knowledge and technological facilities (Ju et al., 2016).

China is the most populous country in the world. It feeds 18% of global population with only 9% of global cropland area but is using about 30% of the global synthetic fertilizer production (FAOSTAT, 2021; Zhuang et al., 2022). Overuse of fertilizers has led to substantial damages to environmental quality and human health, including eutrophication, air pollution, soil acidification, biodiversity loss and greenhouse gas emission (Yu et al., 2019; Guo et al., 2020; Chang et al., 2021), with very high remedial costs. Chinese governments have, for instance, invested over 45 billion US dollars to control the eutrophication of Lake Tai during the past decade (Ti et al., 2018). Even used a large amount of fertilizer in many areas, yield gaps between farmers' and attainable yields are still found in China's smallholder agriculture (Zhang et al., 2016). The yield gap of wheat, maize and rice across China was found 1.2–4.2 t ha^{-1}, 1.4–10.1 t ha^{-1} and 1.6–3.1 t ha^{-1}, respectively (Li et al., 2020). Soil testing and other advanced agricultural management practices have been proposed to improve agricultural performance, such as integrated soil–crop system management practices (ISSM, which used advanced crop and nutrient management) (Chen et al., 2011, 2014). However, the small farm size (<0.5 hectare per household) and low agricultural income share (<20%) inhibit the implementation of such advanced management practices which normally require changes in agricultural operational practices (Wu et al., 2018). Therefore, it is crucial to meet the dual challenges of food security and environmental protection by optimizing fertilizer application rate without changing farmers' practices.

Previous studies have shown that appropriate reduction of nitrogen (N) fertilizer rate can increase crop yield and reduce greenhouse gas emissions (Wu et al., 2014, 2015; Zhang et al., 2018). However, N quota do not directly reflect the quality of N management in cropland, because higher N inputs may be used effectively by crops in high-yielding areas with low N losses (Li et al., 2020). To improve N management in crop production, the EU Nitrogen Expert Panel (2015) proposed NUE as an easy-to-use indicator based on the N balance approach, but emphasized that NUE need to be interpreted together with the quantity of N removed in harvested product (as a proxy for crop yield) and N surplus (Zhang et al., 2015; Zhang et al., 2019). Nitrogen surplus is an indicator that reflects the N input-output balance of a field, farm or for a specific region, and is an effective indicator to evaluate environmental risk of N losses (McLellan et al., 2018). Therefore, it is of great significance to evaluate the rationality of optimizing N application rate and to improve targeted fertilization practices for the efficient crop production and agricultural pollution control.

Optimizing the N application rate does not completely satisfy the optimum nitrogen management (N output $\geq$ 80 kg ha^{-1}, 50% $\leq$ NUE $\leq$ 90%, N surplus $\leq$ 80 kg ha^{-1}) (EU Nitrogen Expert Panel, 2015) in all regions. Traditional field management practices such as "sparse planting with high fertilizer technology", one-time surface broadcasting and insufficient application of manure are still existing for smallholders in many regions of China. For urea fertilizer, surface broadcasting is prone to runoff and leaching loss in humid regions, and NH_3 volatilization loss in high-temperature and arid regions (Gu et al., 2020). Better management strategies are needed. For example, application of slow-release N fertilizer significantly reduced reactive N losses (Xia et al., 2017a; Li et al., 2018a), and manure application enhanced the storage of fertilizer N in soil for subsequent use (Duan et al., 2021). In addition, compared with the traditional planting system, the yield could be significantly increased by 4.7–9.5% with the planting density was increased by 25–40% (Fu et al., 2020; Guo et al., 2021; Zheng et al., 2021). Therefore, the optimization of farmers' practices should be further carried out according to the specific problems in each region (Ding et al., 2020; Zhang et al., 2019).

In this paper we quantify the relationship between N application rate and crop yield across China, based on data from 35,502 on-farm fertilization experiments conducted over a period from 2005 to 2015. This assessment has a focus on farmers' practices at national scale and the following key objectives: 1) to quantify the optimal N application rate and related crop yield, N use efficiency (NUE) and N surplus in different regions of China; 2) to estimate the reduction potential of N fertilizer use and how this contributes to crop yield and N loss reduction, without changing farmers' practices; 3) to estimate the economic input and benefits of further optimizing farm management practices.

2. Materials and Methods

2.1. Experimental location, soil property, and treatment

A total of 35,502 field trials were conducted over the period 2005 to 2015 for main food crops (n = 10,583 for wheat, 15,042 for maize and 9,877 for rice), with sites covered 1,865 counties, 31 provinces in China (Fig. 1). Based on climatic condition and cropping system, study area was subdivided into six principal regions (Zhang et al., 2019), i.e., Northeast region (NE), North China Plain region (NCP), Middle and lower Yangtze River region (MLYR), Southeast region (SE), Southwest region (SW), Northwest region (NW) of China (Supplementary Fig. S1 shows the detailed subregion and crop distribution). The soil fertility of field trials was similar with local field in each region. The soil properties before experiments were 15–30 g kg^{-1} for SOM, 0.9–1.9 g kg^{-1} for TN, 82–167 mg kg^{-1} for AN, 14–27 mg kg^{-1} for AP, 75–170 mg kg^{-1} for AK, 5.4–8.0 for pH value. The detailed data could be found in Supplementary Fig. S3. There was no data available in other region and not included in the present study.

This experiment was designed by the Ministry of Agriculture and Rural Affairs of China to determine the optimal rate of fertilization. There were 4 treatments with gradient N fertilizer application rates at each site without replication: (1) no N fertilizer treatment (N_0); (2) low N fertilizer treatment (N_L); (3) Medium N fertilizer treatment (N_M); (4) high

N fertilizer treatment (N_H). The rate of N_M treatment was determined according to the target yield (1.1 times the average yield of the past 5 years in the local region) by local agricultural extension employees (Staff of the Local Agriculture Bureau and Agricultural Technology Centre that have been trained). The N fertilizer application rates of N_M treatment were 60–300 kg ha^{-1} for wheat, 61.5–300 kg ha^{-1} for maize and 60–300 kg ha^{-1} for rice, respectively, because of the variation of soil and climate in the countrywide. The application rates of N fertilizer for N_L and N_H treatments were 50% and 150% of that for N_M treatment, respectively. Approximately one-third of granular urea was applied at sowing, while the remainder was applied as a topdressing. The application rates of P and K fertilizer were 36–180 kg P_2O_5 ha^{-1} and 30–180 kg K_2O ha^{-1}, respectively, both averagely 90 kg ha^{-1} in each treatment, and were applied by broadcasting before sowing. None of these experiments had inputs of animal manure or other organic N sources.

The area of each plot in field trials was approximately 40 m^2. In order to scientifically compare farmers' practice and experimental practice design, the managements of all experiments, including variety, planting, harvesting, weed and pest control, was undertaken by local farmers according to their experience. Upon harvest, a 2.5m × 8m section was harvested from each experimental plot to measure yield. Grain yield of wheat, maize and rice was adjusted to a moisture content of 14%, 15.5% and 14%, respectively, and was displayed for all regions in Supplementary Fig. S2.

2.2 Soil and plant sampling and analysis

For each treatment plot, soil properties were examined prior to starting the experiments, and values were determined based on soil samples from a combined sample of 10–20 cores from depths of 0–20 cm. Five stover and grain samples were collected and analyzed separately after harvest. Soil samples were dried and sieved for determining soil organic C content by vitriol acid-potassium dichromate oxidation (Walkley and Black, 1934); representative subsamples were taken to determine pH (1:1 w/v soil/water); total N was determined by the method described by Black (1965); available N (alkaline hydrolyzable) was measured following the procedures described by Lu (2000); available P was determined by the Olsen P method described by Olsen et al. (1954) and available K by the method of Shi (1976). To determine the N content, the stover and grain samples were digested with H_2SO_4-H_2O_2 separately, and the concentrations of total N in the digesting solution were measured using the micro-Kjeldahl method (Page, 1982). Three subsamples were analyzed for each sample and average values were reported. The climatic data for each experimental site were derived from local weather stations. The data of soil nutrient and climate for each region are shown in Supplementary Fig. S3 and Supplementary Fig. S4, respectively.

2.3. Estimation of optimal N application rate

In this study, the optimal N application rate was calculated to obtain maximum economic benefits. First, a quadratic regression model was used to assess the grain yield response to N application rate for the 35,502 on-farm N fertilizer experiments, showing that yield significantly responded to the N rate ($P < 0.05$) (Wallach and Loisel, 1994). Total economic income was calculated from yield increase (yield increase times grain price) with every 1 kg N ha^{-1} fertilizer application. Then, another quadratic regression model was established, where Y is the net economic return on N application (gross return minus fertilizer cost); X is the N fertilizer application rate. The N application rate corresponded to the highest net economic return was determined as optimal N application rate in the quadratic regression curve (Stehfest and Bouwman, 2006). The N fertilizer price and market prices of cereal were determined according to the reported by the Ministry of Agriculture and Rural Affairs of the People's Republic of China in 2018–2020: the average price of N fertilizer was \$0.67 kg^{-1} N, and the mean price of wheat, maize and rice grain were \$0.18, 0.15 and 0.21 kg^{-1}, respectively (Ministry of Agriculture and Rural Affairs of China, 2020a).

2.4. Nitrogen use efficiency (NUE) and nitrogen surplus (N_{sur})

In this study, the NUE concept focused on the efficiency of all N inputs transferring to harvested crop N. N_{sur} was used to evaluate the balance of N input and output. The main external N input included the following sources: chemical fertilizer, atmospheric deposition, biological N fixation. Minor N inputs (e.g., from irrigation and seed) were not accounted for. The N output includes the N harvested in cereal grain without considering straw, because of the governmental ban on straw burning and economic incentives to return straw since 2000 (Han et al., 2018; Zhao et al.,2018). Nitrogen use efficiency and N_{sur} are calculated as

$$NUE = N_{har} / (N_{fer} + N_{dep} + N_{fix}) \times 100\% \quad (1)$$

$$N_{sur} = N_{fer} + N_{dep} + N_{fix} - N_{har} \quad (2)$$

where N_{har} is the N output by harvested in cereal grain, N_{fer}, N_{dep} and N_{fix} are the N input by chemical fertilizer, atmospheric deposition, biological N fixation, respectively.

The N input from atmospheric deposition is obtained from the seasonal average N deposition summarized by Xu et al. (2015) comprising data from 27 rural sites covered by the National Nitrogen Deposition Monitoring Network (NNDMN). There are 2–8 monitoring sites in each region of this study according to the data in NNDMN. Regional N deposition rates were determined as the average of measurements at all sites in each region, and N deposition rates on specific crops per growth season were estimated according to the planting and harvest period of the crops. Nitrogen input from biological N fixation was 25 kg N ha^{-1} for rice, and 5 kg N ha^{-1} for both wheat and maize (Zhang et al., 2019). The average N input for each region is shown in Supplementary Table S1.

We calculated the grain N harvest by grain yield and grain N concentration (if experiments did not determine grain N concentration, the value of N content is derived from Ti et al. (2012), at 2.3%, 1.4% and 1.9% of grain N content for wheat, maize and rice, respectively):

$$N_{har} = \text{dry matter grain yield} \times \text{grain N concentration} \quad (3)$$

2.5. Evaluation system

The EU Nitrogen Expert Panel (2015) proposed an evaluation system for evaluating farmland N management by comprehensively considering N input and output, the NUE, and an N surplus index in a cropping system. Experts believe that the best N management can be achieved with values of N output ≥ 80 kg ha^{-1}, 50% ≤ NUE ≤ 90%, N surplus ≤ 80 kg ha^{-1}. When NUE > 90%, there is a risk of soil N mining, and if NUE < 50%, there is a risk of substantial N losses to the environment. The minimum N output (80 kg ha^{-1}) is set to meet the minimum production level, the maximum N surplus is limited (80 kg ha^{-1}) to avoid substantial N losses. We referred to this evaluation system to evaluate whether the optimal N application rate can meet the best N management.

2.6. Economic and environmental benefits

In this study, the economic benefits of optimizing N application rate include two main elements: (1) benefit of cost saving from reduced N fertilizer application; (2) benefit of increasing yield. The benefits of optimizing N application rate were estimated by comparing with farmers' conventional N application rate in China. Data on farmers' conventional fertilizer application rates/practices were derived from published literature (Wu et al., 2016) (Supplementary Table S2). Economic benefits were derived by multiplying N reduction (yield increase) per unit area by the price of fertilizer N (grain) and by the planting area of the crop, in which the planting area of wheat, maize and rice were 2.4, 4.1 and 3.0×10^6 ha^{-1}, respectively (see Supplementary Table S3 for more details) (National Bureau of Statistics of the People's Republic of China, 2020). The environmental benefits were expressed by the reduction of N surplus.

Different optimization strategies were applied to regions which cannot meet all requirements for best N management practices in the EU Nitrogen Expert Panel under optimization of N application (Supplementary Fig. S5) (Fu et al., 2020; Shen et al., 2018). The management strategies included: (1) combined application of organic fertilizer with chemical fertilizer for regions where NUE > 90%. The target application rate and price of organic fertilizer were obtained from Li et al. (2020). (2) applying slow-release N fertilizer for regions where NUE $\geqslant$ 50% while $N_{sur} > 80$kg ha^{-1}. The target application rate and price of slow-release N fertilizer were obtained from Li et al. (2018a, 2018b). The reduced environmental N from this strategy was the difference in N input for urea application and slow-release N fertilizer application. (3) increasing planting density and applying slow-release N fertilizer for regions where NUE < 50%. The economic input from seed and income from increased grain yield were calculated according to Ministry of Agriculture and Rural Affairs of China (2020a) and Zhang et al. (2015). The reduced environmental N from this strategy was the difference in N input for urea application and slow-release N fertilizer application. (4) implement high-standard farmland construction for regions where $N_{output} < 80$ kg ha^{-1}, which were supposed with extremely low fertility. The economic input for high-standard farmland construction was 2.39×10^3 \$ ha^{-1} (Ministry of Agriculture and Rural Affairs of China, 2020b). The price of wheat, maize and rice grain were \$0.18, 0.15 and 0.21 kg^{-1}, respectively, in the calculation of economic income by increasing yield (Ministry of Agriculture and Rural Affairs of China, 2020a). The economic input for those management strategies was estimated by multiplying the area by the cost input of per unit area in each region. Supplementary Table S4 showed the detailed economic input of specific management strategies and related cost.

3. Results and discussion

3.1. Optimal N rate

Crop yield typically increases with N fertilizer application until a maximum yield level is reached. Beyond this point, a further increase of N application rate will reduce crop yield (Zhang et al., 2018; Zhang et al., 2019). The economic optimum yields of wheat, maize and rice are estimated at 6.3, 9.0 and 8.1 Mg ha^{-1} with an optimal N application rate of 178, 184 and 170 kg N ha^{-1}, respectively (Fig. 1). Under an optimal N rate, the NUE can be as high as 72%, 60% and 73%, and the N surplus 67, 96 and 65 kg N ha^{-1} for wheat, maize and rice, respectively (Fig. 2 and Supplementary Fig. S6). With the exception of maize, the N surplus is much smaller than the threshold of N residual in soil derived from the Nitrates Directive (80 kg ha^{-1}) (van Grinsven et al., 2012). Optimizing N application rate alone can achieve a good performance of crop production using farmers' practices.

Substantial variations of the optimal N application rate and crop yield are found across China (Cui et al.,2018; Li et al., 2020). Generally, higher optimal N application rates are found in regions with better natural conditions such as high soil fertility and convenient climate, including the North China Plain (NCP) and the Middle-Lower Yangtze Plain (MLYP). Higher application rates of N fertilizer in such area tend to result in a high crop yield in these regions, as well as high NUE and low N surplus. Relatively lower optimal N application rate and related yields are found in other regions e.g. across Western China, primarily due to low soil organic matter and nutrient contents, and less favorable precipitation and temperature (Chen et al., 2011; Liu et al., 2019).

Although a higher yield is found for maize compared to wheat and rice, it has the lowest NUE, and the largest N surplus, with N surplus > 80 kg N ha^{-1} commonly found for maize production in many regions in China (Fig. 2). The lower N content in grain of maize (1.4%) than in wheat (2.3%) and rice (1.9%) attributed to the lower N output of maize crop.

Furthermore, it was reported that higher nitrate leaching and ammonia volatilization was found in maize season (summer) than in wheat and rice seasons, which might lead to a high N surplus (Chen et al., 2014). Some hotspot areas of high N application rates, yield, NUE and N surplus are found scattered across many regions, illustrating the existence of substantial variations of agricultural management at local scale. Meanwhile, NUE above 90% and N surplus below 0 kg N ha^{-1} are also found in some regions, suggesting that soil N mining occurs in these regions, despite a prevalence of excess N fertilizer use (Fig. 3).

3.2. Mitigation potential

Compared to farmers' conventional N application rate, strategies aiming to optimize N application can not only lead to a reduction in the application rate of N fertilizers, but also improve crop yield and NUE without changing farmers' practices. The yields of wheat, maize and rice can be increased by 10%, 19% and 13% with an optimal N application rate reduced by 15%, 16% and 19%, respectively. Under such an optimal N rate, NUE can increase by 32%, 46% and 40%, and N surplus decline by 39%, 36% and 48%, respectively (Fig. 4 and Supplementary Table S2).

By optimizing the N application rate, fertilizer cost savings for wheat, maize and rice production of 0.5, 1.0 and 0.8 billion US dollars, and increase grain income by 2.4, 9.1 and 5.8 billion US dollars, respectively could be achieved. From an environmental protection point of view, the overall N surplus of croplands would be reduced by 5.1 Tg N (Fig. 5 and Supplementary Table S3). Such a reduction in the N application rate based on official recommendations would not only achieve fertilizer cost savings and increase crop yield, but also have substantial environmental benefits in China.

3.3. Better management

The relationships between N input and N output (harvested N) of the three main crops of China under the optimal N rate are compared with the minimum productivity level (N output = 80 kg ha^{-1}) and ranges for NUE (50%–90%) that suggested by the EU Nitrogen Expert Panel (2015) (Fig. 3). Nitrogen use efficiency can reach 50%–90% in 67% of wheat producing regions, 54% of maize producing regions and 74% of rice producing regions respectively, of which 40%, 30% and 46% can achieve N surplus less than 80 kg ha^{-1} (Fig.

3). However, 54%–70% of the regions producing these three crops have the risks of soil N mining, N pollution and food insecurity with the reasons of insufficient nutrient supply, ammonia volatilization from urea, and improper management. Therefore, further adjustments to the management are also required to avoid the risks since solely achieving an optimal N application rate is only a partial solution to the overall problem.

For regions where a risk of soil N depletion is indicated (NUE > 90%), maintaining soil fertility through manure application is required (Duan et al., 2021; Xia et al., 2017b) with an associated estimated annual cost of 0.9, 0.7 and 0.9 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table S4). In contrast, in regions where NUE can reach 50%–90% while N surplus exceeds 80 kg ha^{-1}, this indicates that N input exceeds N demand of crops and hence substantial N loss occurs. Here, N inputs and losses need to be reduced by best N management such as deep placement of N fertilizers and slow-release N fertilizer (Li et al., 2018a; Xia et al., 2017a) which incur additional costs of 0.3, 0.4 and 0.3 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table S5).

Even when achieving an optimal N rate, there are still many regions where N surplus > 80 kg N ha^{-1} and NUE < 50%, especially for maize (31%) (Fig. 3b). In this study, the straw was assumed to be all returned to the field in this study (straw N output was offset by straw N input), which might lead to high N surplus and low NUE (especially for maize due to high straw biomass). It is still common to remove straw from the field in large area, although the straw burning was banned and economic incentives for returning straw were introduced by the Chinese government since 2000 (Zhang et al., 2019). In these areas crop yield per unit area can only be increased and the application of N fertilizer reduced by reasonably increasing planting density and at the same time applying slow-release N fertilizers (Li et al., 2018a; Wei et al., 2017), at an additional cost of 0.2, 0.7 and 0.1 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table S4). Regions with an average N output below 80 kg ha^{-1} food security concerns are most prominent, which mostly occurs in the Western China (Fig. 1). Such areas with the problems of inadequate farmland infrastructure (e.g. barren land, sloping land, saline-alkali land and no irrigation facilities) (Norse and Ju, 2015). Based on the results of high standard farmland construction project in China (Ministry of Agriculture and Rural Affairs of China, 2020b), we need to additional cost 7.3 billion US dollars (wheat: 2.3, maize: 4.7, rice: 0.3 billion US dollars) to improve the farmland infrastructure in the areas where the N output below 80 kg ha^{-1} (Fig. 5 and Supplementary Table S4).

The optimization of fertilization practices (best N management) can increase the yield of wheat, maize and rice by 2%, 6% and 1% while simultaneously reducing the N application rate by 4%, 12% and 5%, respectively, considering an optimal N application rate with farmers' practices (Fig. 4 and Supplementary Table S2). The optimization of the fertilization practices has a significant effect in maize producing areas, with an increase of NUE by 12%, and a reduction of the N surplus by 31% (Supplementary Fig. S7 illustrates the spatial distribution of N application rates, yield, NUE and N surplus after optimizing fertilization practices). Economic benefits arising from fertilizer cost savings and yield increases can increase revenues by up to 5.2 billion US dollars as a consequence of optimizing fertilization practices. At the same time, these managements reduce the N surplus by 1.7 Tg N (see Fig. 5 and Supplementary Table S3). This means that optimizing N fertilizer use could produce more yield with less pollution.

3.4. Future work in the related aspect

Although optimal N application rate and best management practices showed potential for improving the economic and environmental performance of N fertilizer in the present study, there are some inevitable uncertainties resulting from the methodology. For example, the experimental plot (40 m^2) is not as big as that in the farmer's field, which might lead to more meticulous management from local farmer in planting, irrigation, harvesting, weed and pest control, although the management requirement of all experiments was consistent with farmers' practices except for the fertilization treatment in this study. Some of the N concentration in grain was referenced from Ti et al. (2012) due to the lacking in some sites, which might attribute to the discrepancy of the N uptake among various varieties and management (Zhang et al., 2021). The exact nutrient (N, P, K) content in crop cannot be missing in future studies, especially in national trials.

Though a few other studies (Cui et al., 2018; Khoshnevisan et al., 2020) also proposed the perspective to reduce N fertilizer application rate, Ju et al (2021) raised that excessive and long-term reduction of N fertilizer may aggravate the soil N mining and reduce soil fertility. Hence, it's important to evaluate the effect of long-term N fertilizer reduction on grain production for sustainable agriculture in the future work.

4. Conclusion

This study clarified the optimal N application rate and related crop yield, N use efficiency and N surplus in different regions and counties of China. The yields of wheat, maize and rice can increase 10–19% while N application rates were reduced by 15–19%. These changes resulted in an increase in N use efficiency by 32–46% and a reduction in N surplus by 40% without actually changing farmers' operational practices. In other words, the smallholders can produce more grain with less N fertilizer use only through optimizing N application rates, without requiring a wholesale change in farmers' practices. However, while better management is a fundamental requirement to improve agricultural sustainability in many regions, achieving an optimal N application rate can only solve part of the problem, and at a cost of an estimated 11.8 billion US dollars. We demonstrate in our study, that the economic and environmental benefits of optimizing nitrogen fertilizer use will result in a net economic benefit over the implementation cost, hence facilitating sustainable development of agriculture in China, without resulting in economic losses. This study can slow down the food security and nitrogen pollution problems due to global population growth by reducing the nitrogen application rate and improving farmers' practices. And the results could provide a reference for the global rational use of nitrogen fertilizers.

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CRediT authorship contribution statement

Keyu Ren: Formal analysis, Data curation, Writing - original draft, Visualization. **Minggang Xu:** Conceptualization, Supervision. **Rong Li:** Resources. **Lei Zheng:** Resources. **Shaogui Liu:** Investigation. **Stefan Reis:** Writing - Review & Editing. **Huiying Wang:** Resources. **Changai Lu:** Writing - Review & Editing. **Wenju Zhang:** Writing - Review & Editing. **Hui Gao:** Investigation. **Yinghua Duan:** Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Baojing Gu:** Conceptualization, Writing - original draft, 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 and materials availability

All data are available in the main text or the supplementary materials. Additional data related to this paper may be requested from the authors.

Supplementary Materials

Supplementary Materials are available for this paper.

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Figure legend

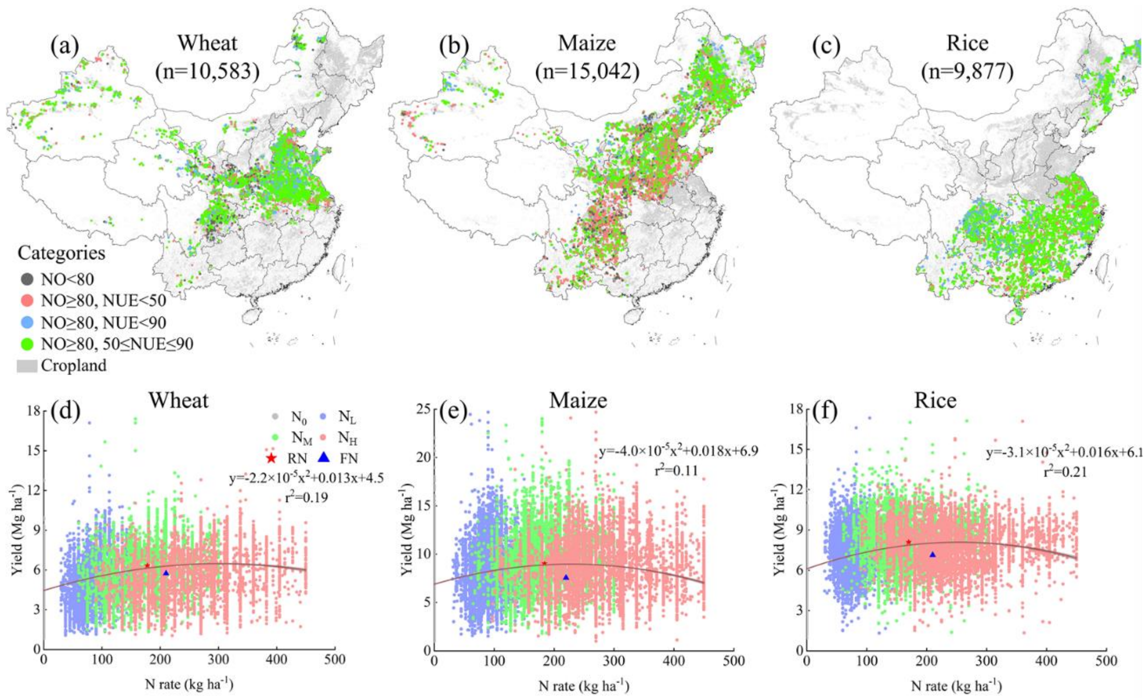
Fig. 1. Distribution of fertilization experiments and yield response curves. (a)–(c) regional experimental site distribution of wheat, maize, and rice, respectively; n indicates experimental sites number; NO: nitrogen (N) output of optimal N rates (unit: kg ha^{-1}), indicates the N harvested in cereal grain under optimal N rates; NUE: nitrogen use efficiency of optimal N rates (unit: %). (d)–(f) yield response to N application rate for wheat, maize, and rice, respectively. N_0: no N fertilizer treatment; N_L: low N fertilizer treatment; N_M: medium N fertilizer treatment; N_H: high N fertilizer treatment; Red star in (d)–(f) represent optimal N rates (RN); Blue triangles in (d)–(f) represent farmers' conventional fertilizer application rates (FN).

Fig. 2. Optimal N application rate (N rate) and corresponding yield, nitrogen use efficiency (NUE) and nitrogen surplus (N_{sur}) of three grain crops for wheat (a)–(d), maize (e)–(h), and rice (i)–(l).

Fig. 3. Response of N output to N input under optimal N application rate. The model of N input and output from EU Nitrogen Expert Panel (2015). NO: nitrogen output (unit: kg ha^{-1}), indicates the N harvested in cereal grain without considering straw; NUE: nitrogen use efficiency (unit: %); N_{sur}: nitrogen surplus (unit: kg ha^{-1}). Color of the dots represent the density of dots. Numbers on the top of the bars (**b**) refer to the percentage of sites in each quadrant (**a**) to all sites in each crop (wheat: 10,583, maize: 15,042, rice: 9,877).

Fig. 4. Potential for reduction of nitrogen (N) fertilizer and improvement of nitrogen use efficiency (NUE) under optimal N rate (RN) and best N management (BN), compared with that under farmers' conventional N application rate (FN). (**a**) Fertilizer N application rate of three crops under different N management. (**b**) Yield of three crops under different N management. (**c**) NUE of three crops under different N management. (**d**) N surplus of three crops under different N management.

Fig. 5. Economic and environmental benefits under optimal N rate and best management. NO: nitrogen output (unit: kg ha^{-1}), indicates the N harvested in cereal grain without considering straw; NUE: nitrogen use efficiency (unit: %); N_{sur}: nitrogen surplus (unit: kg ha^{-1}).



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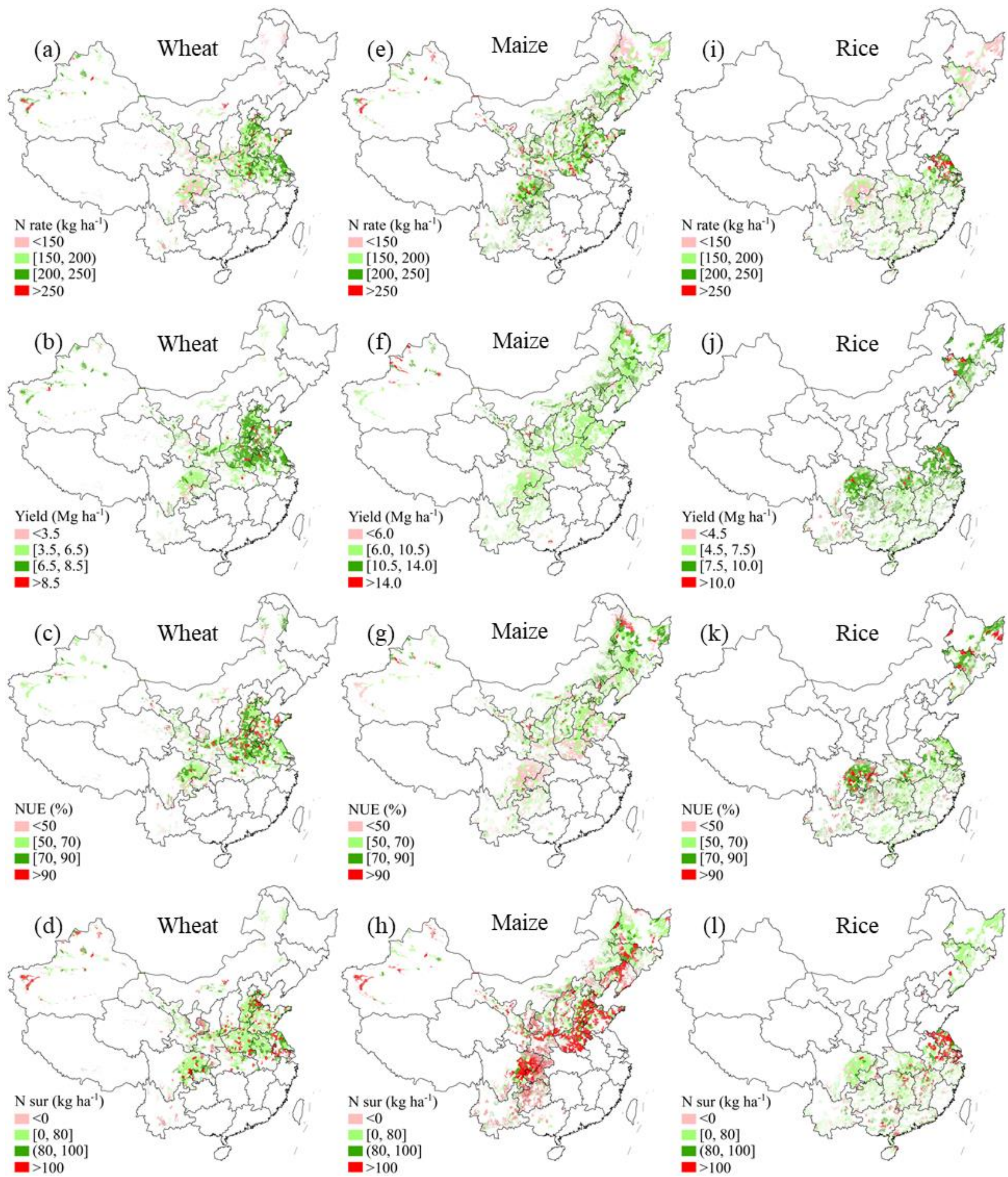

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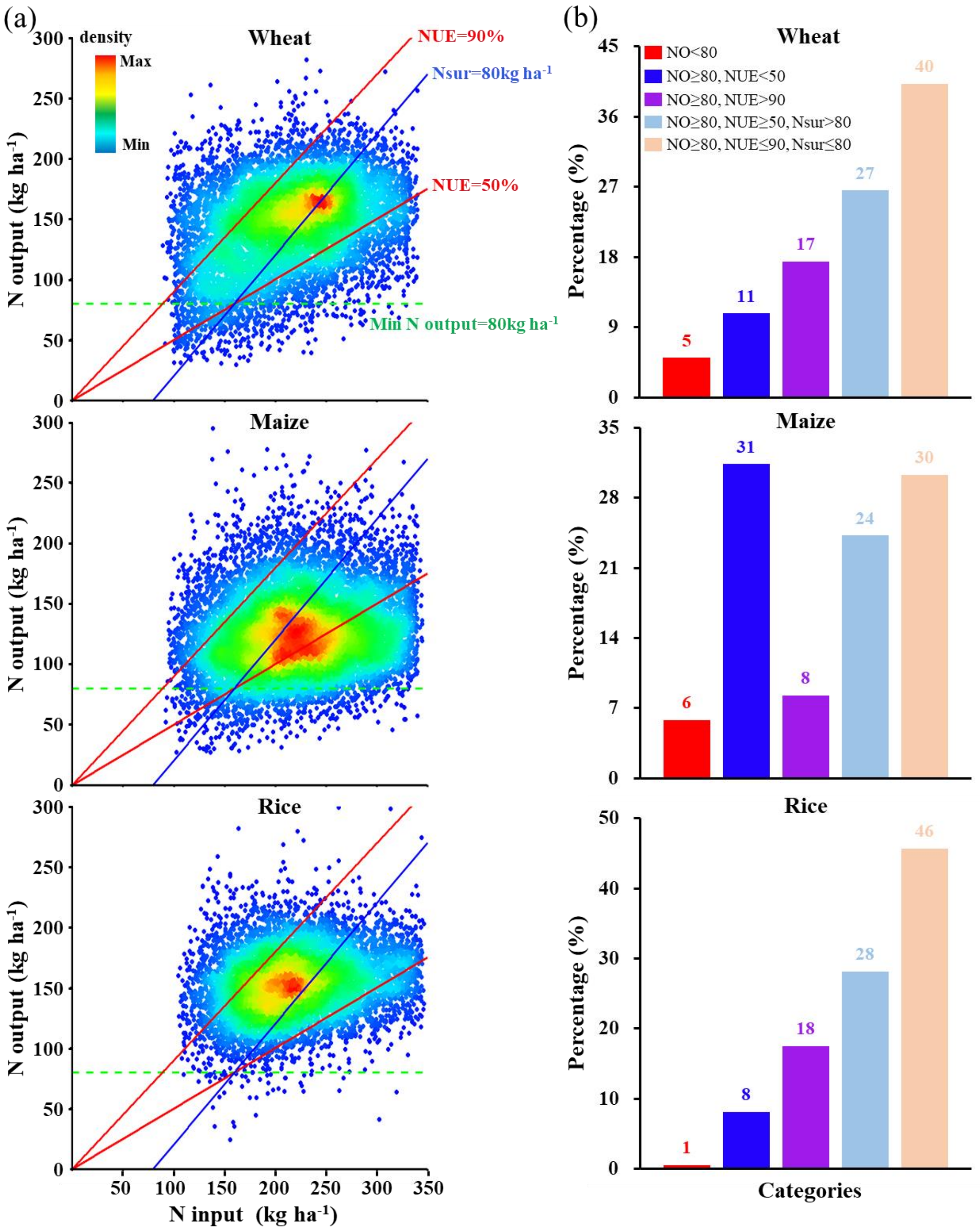

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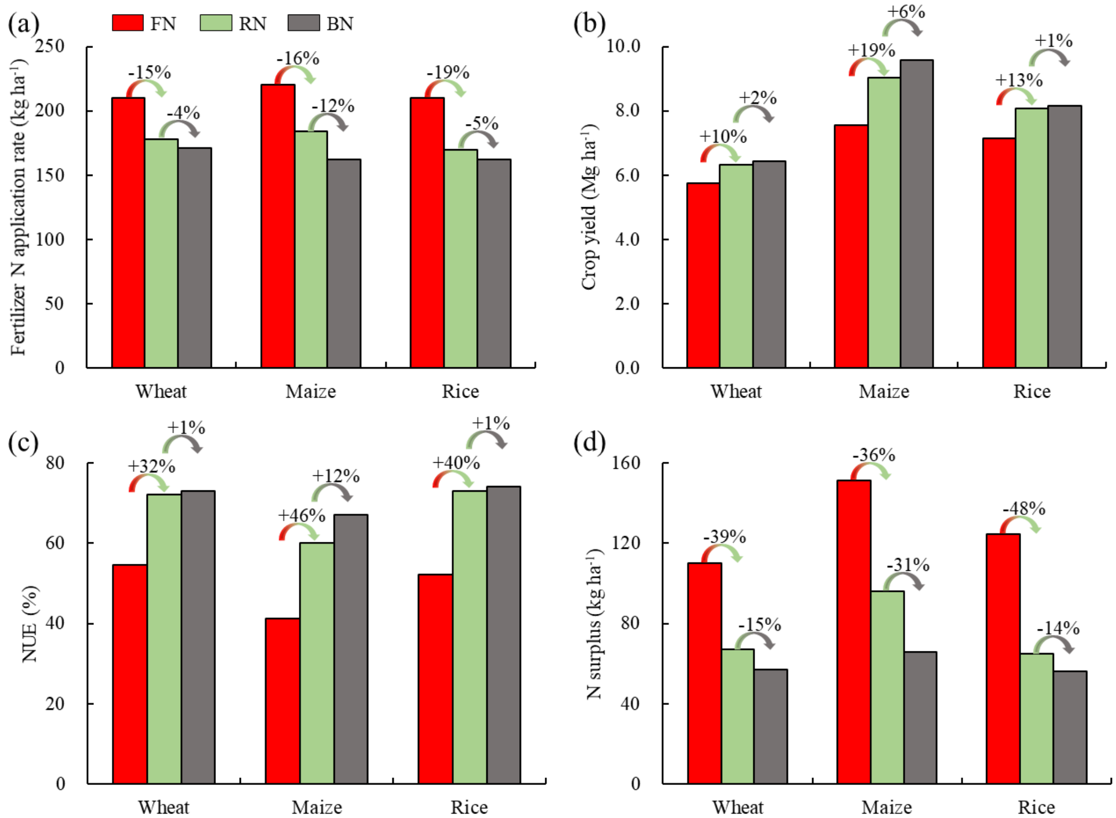

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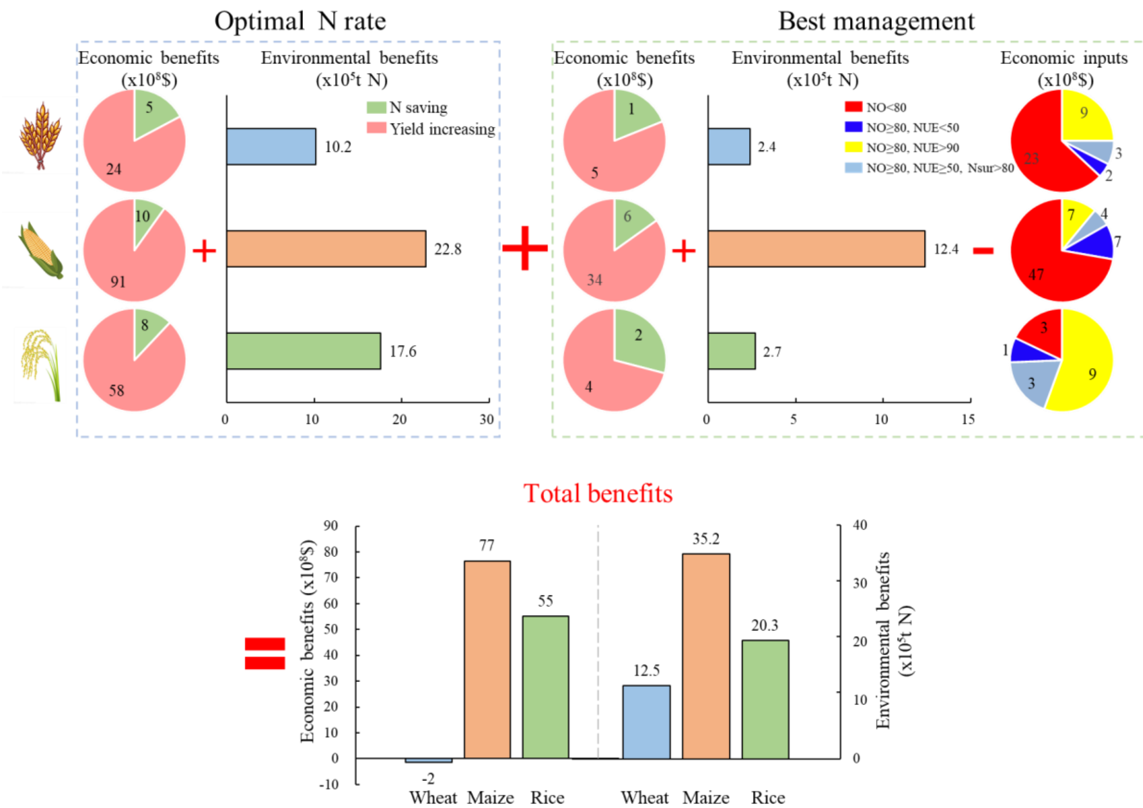

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