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Original Research

Towards Less Agricultural Nitrogen Use in China: Perspective from a Multi-Crop and Multi-Region Partial Equilibrium Analysis

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Abstract

The increased nitrogen fertilizer use has greatly boosted the agricultural production in China, however, imposed considerable environmental issues. Reducing nitrogen use in agriculture is inevitable for China to achieve the sustainable development goals. This paper established a partial equilibrium model to evaluate the reducing effects on nitrogen use under scenarios of nitrogen optimized utilization and nitrogen use efficiency improvement among seven crops and seven regions in China. Simulations revealed that: (1) nitrogen optimized utilization helps to reduce 7.73% agricultural nitrogen use in China, soybean turns to be the only exceptional crop that nitrogen use would be doubled; (2) nitrogen use could be continuously decreasing with the nitrogen use efficiency improvement, the reducing rates are 8.28% to 27.91% under 10% to 40% improvement scenarios; (3) among the crops, soybean and peanut have far greater reducing rates than other crops, maize is simulated as the least sensitive crop; (4) East, North and Central China, contribute over 60% of nitrogen use in China, while in Northeast China, nitrogen use performs the least sensitivity to the modelling scenarios. Therefore, this paper suggests that policies and incentives on nitrogen optimized utilization and nitrogen use efficiency improvement are necessary, and heterogeneities in both crops and regions indicate that flexible adjustment strategies of cropping structures in different regions should be taken into consideration towards less agricultural nitrogen use in China.

Keywords: agricultural nitrogen use, nitrogen use efficiency, partial equilibrium model, reducing effect

Introduction

Nitrogen (N) as an essential element on the planet has played a critical role in human society and economy [1, 2]. Increased N use has greatly boosted the agricultural production, however, imposed considerable costs on environment [3, 4]. Solving the N challenge has now become the co-benefits for the world [5, 6]. Indeed, N challenge may become worse in the next decades because of the growing population and food demand, which is highly likely to be doubled by 2050 [7]. China, the largest developing economy and most

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populous country in the world, consumes 27% of global N fertilizers and becomes the biggest N use and loss country as well. According to the second national pollution census reported in 2020, 46.5% of total N loss in China comes from agricultural sources[8]. Agricultural N use in China has already exceeded its sustainable boundary, causing non-point source pollution which affects the quality of both water and land, seriously [9-11]. Therefore, reducing agricultural N use and controlling its environmental problems have become the priorities for the development of green and sustainable agriculture in China.

Due to the comprehensive processes of N absorption and utilization in agriculture, N fertilizer optimizing management and improving N use efficiency (NUE) are considered to be effective approaches to cope with the N challenges in human society [5]. Previous studies show that only 30%-50% of N inputs are regarded as effective and finally absorbed by crops, while the rest parts are treated as emissions, or N loss [12-14]. From an efficiency perspective, agricultural economists assumed that the emission part of N could be eliminated without yield decreasing, thereafter, they are able to calculate the efficiency terms including technical, allocative and scale efficiencies, by evaluating the ratio of output/inputs [9, 15-17]. According to the sustainable development goals (SDGs) proposed by United Nations, NUE has been proposed as an essential indicator in agricultural human activities[4, 9]. The global average NUE in agriculture has been moderately growing and reaching 50% since the mid of 20th century, however, some countries including China and India, NUEs are declining because of the overuse of N fertilizer [18, 19]. Based on recent estimation, NUE in China fluctuates between 21.6%-26.5% during the past decades, much lower than those in EU countries where NUEs are always over 50%, and consequently, N loss in China becomes one-third higher than the global average [20-22].

Lots of studies pay attention to the NUE improvement. Identifying effective N management practices is widely used to improve NUE [23-25]. For example, split-N fertilization can significantly help crops absorb N element from fertilizers and NUEs would be 39.1% and 37.5% for 3- or 2-splits, respectively [18]. Other practices such as integrated soil-crop system management and Slow-release fertilization, can save 18% to 25% N fertilizer input and improve NUE by 5%-10% [26, 27]. Applying these practices into agricultural production may generally reduce 15%-18% of fertilizer use and improve 4% of NUE, if considering millions of smallholders in China and India [28, 29]. At the farm scale perspective, farmers in China on average would prefer to reduce 0.3% fertilizer use for every 1% increase in farm size [30]. Zhu et al. (2022) [31] found that 1% increase in farm size brings 0.2% growth in fertilizer use efficiency, and this positive effect is mainly from the reduction in fertilizer use. Similarly using econometric regressions, some studies have investigated the impacts of specific practices on NUE, such as adopting new cultivars, new technologies and updating latest equipment [26, 32-34]. Nonetheless, most exiting researches are focusing on the individual effects from specific driving forces, rather than a systematic approach which could analyze the integrated influence, covering all human interventions in agricultural production. Many literary sources have estimated NUEs under different conditions, while very few of them have addressed the reversed effects that how much N use and N loss in agricultural production would be reduced if NUEs are improving.

In this regard, we conduct a partial equilibrium framework, instead of econometric method, to analyze the integrated impacts on agricultural N use in China from different NUE levels. In order to reveal the heterogeneities on both regions and crops, this study select seven regions (east, north, south, north-east, north-west, south-west and central) as our study areas, and seven main crops (rice, wheat, maize, soybean, peanut, rapeseed and potato), which contribute over 70% of total agricultural production, are taken into analysis. N loss across regions and crops are also included. The rest parts of this paper are as following: section 2 introduces the methods used in this study, including the details of partial equilibrium model structure, data sources and designed scenarios; simulation results under different scenarios, as well as discussions, are presented in section 3; the last section gives the conclusions and policy implications.

Methodology

Model Construction

With the purpose of evaluating the reducing effects on agricultural N use under NUE improvements, this study developed a price endogenous partial equilibrium model (PEPEM), with multi-region and multi-product inside. As a partial equilibrium analysis through nonlinear programming, the PEPEM has been wildly used by economists to access the influences of policies or other external shocks on agricultural production and related environmental performance [35, 36]. In detail, the PEPEM hypothesizes that market equilibrium prices and quantities are determined endogenously, enabling the model to gain more flexible structure, and higher accuracy level of simulations, compared with the general equilibrium analysis [37, 38]. Particularly, we take seven main crops into analysis as multi-product, and seven regions covering all 31 provinces in the mainland, China (Hongkong. Macao and Taiwan are not included because of data accessibility and quality), are treated as multi regions in the PEPEM. Noted that the PEPEM has three fundamental assumptions: 1) agricultural products in domestic market can be traded freely among different regions; 2) international trade quantity remains stable and does not affect domestic market, where products supply is always sufficient;

3) famers are rational and have the ability to reallocate resources, pursuing maximization of social welfare. The PEPEM is constructed as follows:

(1) Objective function.

The maximum of total social welfare (*SW*) in Chinese agricultural sector:

$$Max\ SW = \sum_{c}\int P_{c}^{d}(X_c^d,\omega_c)dX_c^d - \sum_{c,i} NfC_{ci} - \sum_{c,i} nNfFC_{ci}$$
$$-\sum_{c,i} WC_{ci} - \sum_{c,i} pc_{ci} * X_{ci}^s - \sum_c \int P_c^{im}(Q_c^{im})dQ_c^{im}$$
$$+\sum_c \int P_c^{ex}(Q_c^{ex})dQ_c^{ex} \tag{1}$$

where $p_c^d(X_c^d, \omega_c)$ refers to the inverse demand function for crop c. x_c^d is the annual agricultural product demand of crop c. NfC_{ci} is the cost of N fertilizer for crop c in the region i, while $nNfC_{ci}$ denotes the cost of non-N fertilizers in production. IC_{ci} is the irrigation cost. pc_{ci} represents the other cost except those of fertilizer and irrigation, at the per unit output level. X_{ci}^s is the annual supply. Q_c^{im} and Q_c^{ex} are annual import and export quantities between domestic and external market, respectively. P_c^{im} and P_c^{ex} are trading prices.

(2) Constraints.

a. market equilibrium (supply-demand balance).

$$X_c^d + EX_C \leq \sum_i X_{ci}^s + IM_C \tag{2}$$

Eq. (2) expresses the supply-demand balance constraint of crops. X_c^d represents the demand of crop c in China, X_{ci}^s refers to its supply from region i. EX_c and IM_c are the export and import quantities. Noted that total demand shall be less than or equal to total supply.

$$\sum y_{ci} * L_{ci} \geq X_{ci}^s \tag{3}$$

Eq. (3) indicates that one crop's total production shall be equal or higher than total supply. y_{ci} is the yield (per ha) and L_{ci} is the planting acreage of crop c in region i.

b. land use.

$$L_i = \sum \tau_i * hL_{ci} + \sum \gamma_i * s_{ci} \tag{4}$$

$$\sum \tau_i + \sum \gamma_i \leq 1 \tag{5}$$

L_i is the planting acreage of all seven main crops in region i, and hL_{ci} refers to the historical observation of crop c's planting acreage. s_{ci} is the feasible planting acreage, representing the upper limit of land use in one region. τ and γ are the weights, which are determined endogenously. The sum of them shall be less than or equal to 1. Eq. (4) and (5) implicitly reflect the technology, management and policy constraints of planting acreages within the limits of historical acreage observations [39].

c. Water use (irrigation).

$$\sum_c L_{ci}W_{cit} \leq W_{it} \tag{6}$$

W_{cit} is the irrigation water used (per ha) for crop c in region i at period t. W_{it} is the accessible quantity of water supply for agricultural production. Eq. (6) expresses the limitation of water resources.

(3) N loss estimation.

Referring to existing researches [40, 41], agricultural N loss in this study could be estimated by N fertilizer use and several coefficients, specific calculating formula of N loss is:

$$NL = \sum[(ro_{ci} + le_{ci})/aNUE_{ci}] * Nf_{ci} * L_{ci} \tag{7}$$

where *NL* is short for N loss, ro_{ci} and le_{ci} refer to the N loss coefficients for crop c in region i, which are runoff- and leaching-induced N loss rates, $aNUE_{ci}$ is the NUE calculated in advance.

Data Source

Crop production datasets, including the information of planting acreages, outputs and yields, are captured from "statistical yearbooks (2019)" of 31 provinces and National Bureau of Statistics of China. As shown in figure 1, we divided 31 provinces into seven regions, according to "China Physical Geographics (2015)", which are: East (Anhui, Fujian, Jiangsu, Jiangxi, Shandong, Shanghai and Zhejiang), North (Beijing, Hebei, Inner Mongolia, Shanxi and Tianjin), Southwest (Chongqing, Guizhou, Sichuan, Xizang and Yunnan), North-west (Gansu, Ningxia, Qinghai, Shaanxi and Xinjiang), South (Guangdong, Guangxi and Hainan), Central (Henan, Hubei and Hunan) and Northeast (Heilongjiang, Jilin and Liaoning).

"Compilation of Cost and Benefit of National Agricultural Products (2019)" provides agricultural inputs datasets of both quantities and values (prices), such as labor force, fertilizer (including N, non-N and compound fertilizer), pesticide, agricultural film and irrigation water use, etc. Noted that N fertilizer use in this paper is defined as the sum of N fertilizer and compound fertilizer multiplied by its N weight. As for the demands of main agricultural products, we firstly derive necessary datasets from the BRIC Agricultural Database, and then estimate the quantities of feeding, industrial use, seed use and loss, according to the approaches proposed by Xue and Zhang (2017). The elasticities of crops' demand are provided by Wang et al. (2019). N loss coefficients including runoff- and leaching-induced rates, are referring to Ti et al. (2012) and Yu et al. (2022) [38, 40-42].

Model Calibration

Calibration was carried out before simulation to guarantee the validity of the PEPEM. Statistical datasets

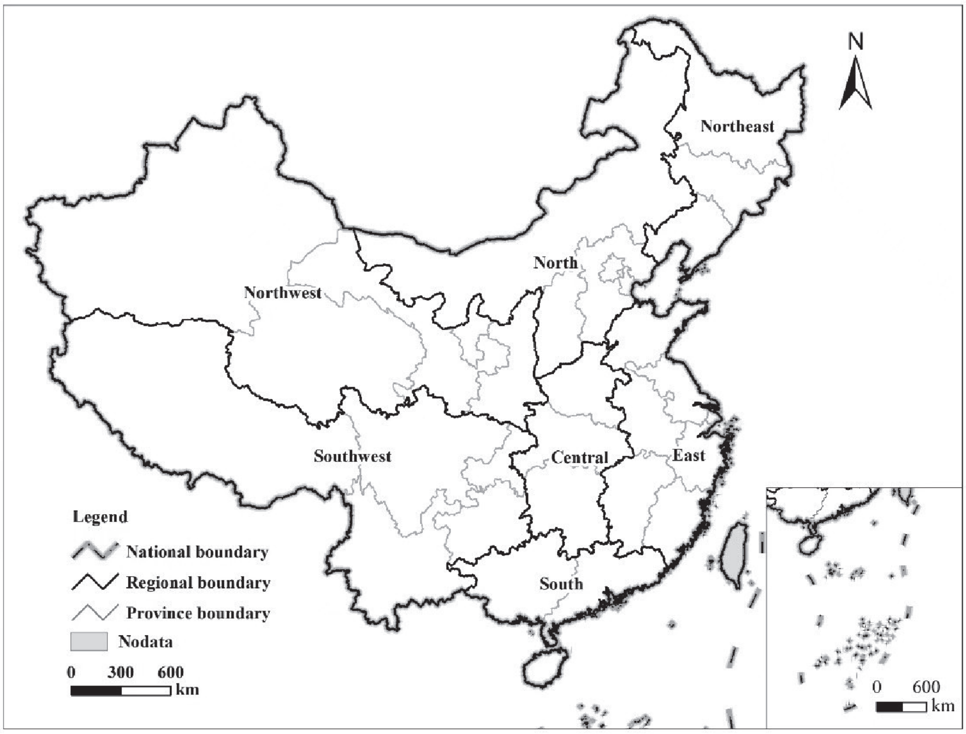

Fig. 1. Seven regions in China.

of the seven main crops in China, covering planting acreages, outputs and prices, are calibrated in the model. As shown in Table 1, most of the variations between observations and calibrations in acreage, output and price, fall within 1% and only one of them exceeds 4% (Potato's acreage, 4.64%). In terms of these results, we regard the PEPEM as a proper model that can simulate Chinese agricultural production systems accurately with high validity. The PEPEM, thereby, can be applied in further simulations.

Scenario Design

Based on the PEPEM, we designed and incorporated the following scenarios into simulation analysis:

(1) Business as usual (BAU).

Instead of directly using observations from statistical yearbooks of 2019, we select calibrated values of seven main crops as the benchmark of the PEPEM analysis, which is treated as the business as usual (BAU) scenario in this study.

(2) Nitrogen optimized use (NOU).

The crop yield in general will increase if farmer use N fertilizers, however if overused, the crop would be harmed and turn to less output. There exists a quadratic relationship between crop yield and its N use, if given other conditions such as fertilization scheme, farming system, etc. Nitrogen optimized use here refers to a combination of nitrogen use measures. Therefore, it is available to estimate the maximum of crop yield and total social welfare of agricultural sector by locating the optimized N use quantity, which can be revealed through historical data (2009-2018) and quadratic regression. In the PEPEM, we regard the N use as an endogenous decision variable in simulation.

(3) Nitrogen use efficiency improvement (NUE+).

Improving NUE levels, induced by technological progresses, may influence N use in agricultural production [7, 28]. Here we design four scenarios of NUE+, denoted as NUE+10%, NUE+20%, NUE+30% and NUE+40%, to access the reductions of N use when NUE are improving by four levels, compared to NOU scenario. The NUE+ scenarios are supposed to integrate the multiple effects from different technology adoptions or management applications, in terms of simplifying the comprehensive impacts of technological progresses in Chinese agriculture. Noted that if 30% improvement could be achieved, China's NUE in agriculture would reach to the level of most EU countries.

Results and Discussion

Nitrogen Optimized Use

(1) Crops' simulation.

The simulation results of crops are presented in Table 2. Compared with BAU results, NOU can improve 3.62% total output of main crops, save 8.21% of agricultural land use and consequently, reduce 7.73% and 7.98% of N use and N loss in Chinese agricultural sector. Maize production, particularly, contributes the largest land use saving (7.45 million ha, 17.71%) and N use reduction (1.05 million t, 14.65%). Wheat and

Table 1. Calibrations of main crops in the PEPEM.

	Acreage (million ha)		Output (million t)		Price (CNY/kg)	
	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
Rice	30.189	30.085	212.129	212.129	2.59	2.59
		(-0.34%)		(0.00%)		(0.00%)
Wheat	24.266	24.108	131.444	131.444	2.22	2.22
		(-0.65%)		(0.00%)		(0.00%)
Maize	42.130	42.133	257.178	257.178	1.75	1.75
		(0.01%)		(0.00%)		(0.00%)
Soybean	8.413	8.151	15.967	15.967	3.84	3.84
		(-3.12%)		(0.00%)		(0.00%)
Peanut	4.625	4.676	17.332	17.987	5.70	5.92
		(1.10%)		(3.78%)		(3.86%)
Rapeseed	6.549	6.349	13.281	13.454	5.23	5.28
		(-3.05%)		(1.30%)		(0.96%)
Potato	4.941	4.712	18.708	18.708	1.56	1.56
		(-4.64%)		(0.00%)		(0.00%)
Total	121.114	120.214	666.039	666.867	-	-
		(-0.74%)		(0.12%)		-

Notes: % in parentheses refer to the variations between observations and calibrations.

Table 2. Crops' simulation under BAU and NOU scenarios.

	Acreage (million ha)		Output (million t)		N use (million t)		N loss (million t)	
	BAU	NOU	BAU	NOU	BAU	NOU	BAU	NOU
Rice	30.09	28.53	212.13	215.69	5.09	4.79	0.43	0.40
		(-5.18%)		(1.68%)		(-5.92%)		(-5.91%)
Wheat	24.11	22.46	131.44	138.80	4.76	4.43	0.77	0.71
		(-6.83%)		(5.60%)		(-7.05%)		(-7.06%)
Maize	42.13	34.67	257.18	263.36	7.15	6.10	1.15	0.98
		(-17.71%)		(2.40%)		(-14.65%)		(-14.66%)
Soybean	8.15	9.47	15.97	22.46	0.32	0.66	0.05	0.11
		(16.22%)		(40.65%)		(105.21%)		(105.43%)
Peanut	4.68	4.63	17.99	18.17	0.52	0.52	0.08	0.08
		(-0.94%)		(0.99%)		(0.29%)		(0.36%)
Rapeseed	6.35	6.03	13.45	13.80	0.77	0.61	0.13	0.10
		(-5.06%)		(2.56%)		(-20.77%)		(-20.79%)
Potato	4.71	4.56	18.71	18.71	1.05	1.04	0.17	0.16
		(-3.33%)		(-0.01%)		(-1.26%)		(-1.30%)
Total in China	120.214	110.35	666.87	691.00	19.67	18.15	2.77	2.55
		(-8.21%)		(3.62%)		(-7.73%)		(-7.98%)

Notes: % in parentheses refer to the variations between observations and calibrations.

rice, another two staple crops in China, account for the second (6.83%, 7.05%) and third (5.18%, 5.92) largest. Peanut production changes the least that all variations fall within 1%. Apparently, most of the seven main crops share the consistent variation trend with overall results after applying NOU.

However, there is one exception, soybean. Results in soybean production have shown totally opposite changes that optimized use of N would increase its acreage by 16.22% and simultaneously, double its N use and N loss as a consequence. These results may indicate that reducing N use is beneficial to improve yield levels because N might be overused in these crops nowadays in China. While on the contrary, N use in soybean production has not reached its optimized quantity yet and inputting more N fertilizers might be helpful to derive higher output. Indeed, soybean belongs to leguminous crops which need more N element from fertilizer and environment than other crops like cereals or grains. As for the N loss, the reducing rates are very close to and consistent with those of N use.

(2) Regions' simulation.

Table 3 gives a regional perspective of NOU simulation results. Similar to the conclusions from Table 2, most of the seven regions share the consistent variation trend with overall results in China after applying NOU. Southwest and northwest China would save almost 20% agricultural land use under NOU conditions, meanwhile, 12.28% and 24.97% N use would be reduced, respectively. Over 3 million ha of land use would be saved in central, and as well as in northeast China, where the reducing rates of N use are 5.13% and 6.42%. South China is the smallest agricultural region among the seven, and the least sensitive area to NOU that there is only 4.85% decrease in agricultural land use and 1.19% reduction in N use, far less than other regions and the average level in China.

The only exception is east China, where NOU does not help to save land use in agriculture while instead, the total acreage of the main crops in east China improves 6.22% from 28.69 million ha to 30.47 million ha. Noted that N use in this region does not increase along with the growing acreage of crops. In fact, 0.3 1 million t of N use would be reduced by applying NOU, and the reducing rate is close to those of north and northeast China. The reasons why east China is special and would expand 1.78 million ha of agricultural land use if N use is optimized might be that east China has great hydrothermal conditions and climate for agricultural production, as well as sufficient labor forces, developed market, supply chain, and technological supports. Another possible explanation could be that some areas in east China, such as Anhui, Jiangsu and Shandong, belong to Huang-Huai-Hai plain, which is one of the most important major soybean-producing areas in China. In this regard, expanding agricultural acreage, especially for soybean production, becomes reasonable.

Table 3. Regions' simulation under BAU and NOU scenarios.

	Acreage (million ha)		Output (million t)		N use (million t)		N loss (million t)	
	BAU	NOU	BAU	NOU	BAU	NOU	BAU	NOU
East	28.69	30.47	168.27	197.92	4.98	4.67	0.65	0.60
		(6.22%)		(17.62%)		(-6.29%)		(-7.36%)
North	15.66	13.74	85.98	91.18	3.84	3.61	0.61	0.58
		(-12.23%)		(6.04%)		(-5.81%)		(-5.30%)
Southwest	15.65	12.64	73.52	70.41	2.48	2.17	0.35	0.30
		(-19.22%)		(-4.23%)		(-12.28%)		(-13.20%)
Northwest	8.78	7.07	43.50	45.19	1.35	1.01	0.21	0.16
		(-19.49%)		(3.89%)		(-24.97%)		(-25.22%)
South	5.33	5.07	27.55	28.41	0.88	0.87	0.09	0.09
		(-4.85%)		(3.09%)		(-1.19%)		(-1.20%)
Central	23.79	20.39	134.51	123.62	3.24	3.07	0.42	0.41
		(-14.28%)		(-8.10%)		(-5.13%)		(-3.17%)
Northeast	23.22	20.96	132.70	134.28	2.90	2.71	0.44	0.41
		(-9.74%)		(1.19%)		(-6.42%)		(-6.22%)
China	121.21	110.35	666.87	691.00	19.67	18.15	2.77	2.55
		(-8.21%)		(3.62%)		(-7.73%)		(-7.98%)

Notes: % in parentheses refer to the variations between observations and calibrations.

Nitrogen Use Efficiency Improvement

Based on the results of NOU simulations, we then evaluate the impacts of improving NUE levels among different crops and regions.

(1) Crops' simulation.

As expected, N use in Chinese agricultural sector would be continuously decreasing with the improvement of NUE. Compared to the results of NOU, N use drops from 18.145 million t to 13.082 million t (NUE+40%), and the reducing rates are 8.28%, 15.06%, 21.24% and 27.91% under NUE+10%, NUE+20%, NUE+30% and NUE+40% scenarios, respectively. While if considering changes of acreage, N use drops from 0.164 t/ha under NOU to 0.125 t/ha under NUE+40%, and the reducing effects would become less significant that the rates decrease to 2.90%, 10.13%, 16.71% and 23.79%. To further investigate heterogeneities among different crops, we calculate the reducing rates of N use (t/ha) in each of the seven main crops under four NUE+ scenarios, as shown in Fig. 2.

Referring to the average level, the reducing rates of soybean and peanut, are far greater than other crops. N use (t/ha) in soybean production drops rapidly by 19.15% from 0.069 t/ha under NOU to 0.056 t/ha under NUE+10%, while the reducing rates in other crops are less than 2%. Maize, in particular, seems to be the least sensitive crop in N use to the improvements of NUE. N use (t/ha) in maize production decreases moderately from 0.176 t/ha under NOU to 0.174 t/ha and 0.167 t/ha under NUE+10% and NUE+20% scenarios, where the reducing rates are 0.65% and 4.81%, respectively. These results indicate that though improving NUE would help to reduce N use in all crops, these activities might be more effective in oil crops such as soybean and peanut, than in cereals like maize, rice and wheat.

(2) Regions' simulation.

Similar to the crops' simulation, N use in regions would be gradually going down with the improvement of NUE as well. Most of the regions, as shown in Fig. 3, share the same decreasing trend that the reducing rates are around 9%, 16%, 22% and 28% under NUE+10%, NUE+20%, NUE+30% and NUE+40% scenarios. The reducing curves of the regions are very close to the average level in China, except for two areas, North and Northeast China. The reducing rates in North China are approximately 1.5% to 2% higher than the average in each NUE+ scenario, while on the contrary, N use in t Northeast China performs less sensitive to NUE improvement, the reducing rates of which are 5.94%, 10.15%, 15.12% and 22.19%, respectively. These results might be explained by incorporating information from Fig. 2 that maize is the least sensitive crop in N use with respect to the improvements of NUE, and Northeast China actually, happens to be the largest major maize-producing area in the country. Overall, improving NUE would be helpful to reduce N use in all regions, but the effectiveness differs. Activities on NUE improvement might be more effective in North China than in other in other regions.

In order to further investigate regional information, we hereby give a Chinese map of N use in provinces

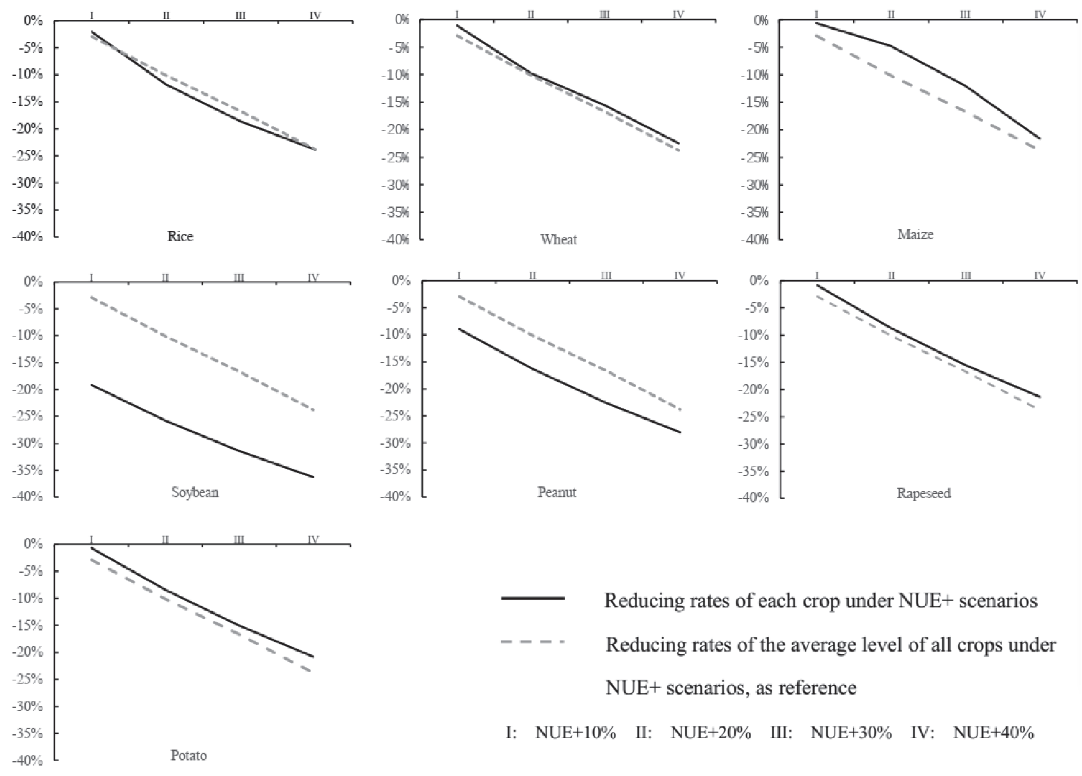

Fig. 2. Reducing rates of crops' N use (t/ha) under NUE+ scenarios.

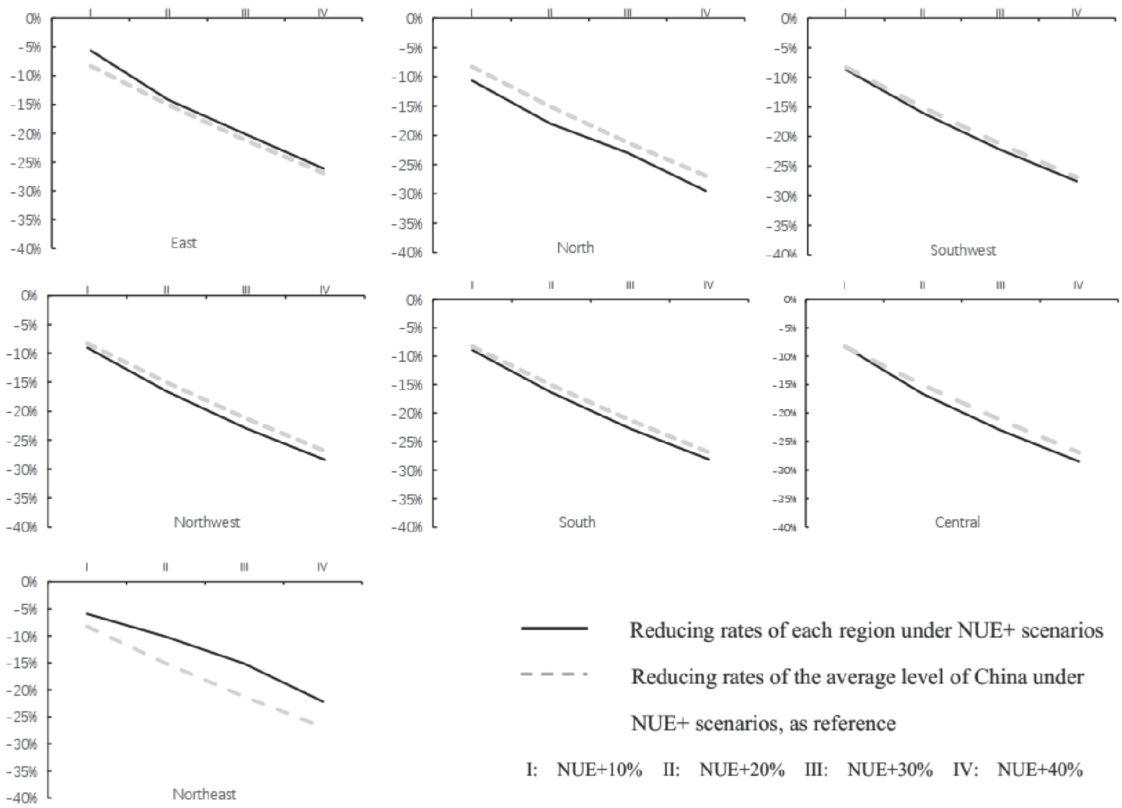

Fig. 3. Reducing rates of regions' N use (t/ha) under NUE+ scenarios.

(seen in Fig. 4). According to this map, Anhui and Jiangsu from East, Henan from Central, Shanxi and Inner-Mongolia from North China, are the largest N use provinces in China. In this context, this result might explain the conclusions from Table 2 that East, North and Central China contribute over 60% of N use in the whole country, under all scenarios designed in this study, including BAU, NOU and NUE+. The gradient dark columns are referring to the reducing rates of NUE+ scenarios. Without exceptions, results in all provinces are consistent with the regions' simulation that improving NUE performs effectively on N use reduction, especially in Hebei from North China, where the reducing rates reach to 16.34%, 23.17%, 28.96% and 33.95% under four NUE+ scenarios. Shanghai from East China, however, is significantly different from other provinces. Even under NUE+40% scenario, N use in Shanghai would be merely reduced by 9.96%, which could be explained by the limitation of agricultural production in this area and moreover, NUE+ sensitive crops such as soybean and peanut, are not major planting choices in Shanghai.

Discussion

Unlike most existing literatures that applied econometric approaches and regression models to access the impacts of specific activities and other driving forces on agricultural N fertilizer use [9, 13, 26], this study employed partial equilibrium analysis instead, which enabled us to reveal the integrated effects, rather than individual effects, on N use in Chinese agricultural sector. We conducted nitrogen optimized use (NOU) scenario to represent the benchmark, and designed nitrogen use efficiency improvement (NUE+) scenarios. In previous studies, NUE was often estimated by statistical data which could be derived from site-year observations and field plot surveys [4, 28, 43]. While in this work, the improvements of NUE were simplified by hypothesizing 10% to 40% growth in terms of representing technological or managerial development in agriculture, as a replacement of time series calculation of NUE. Hence, this study might be one of the earliest studies that analyzed the reversed impacts from NUE improvement to N use in agriculture, instead of assessing the driving forces on NUE changes in previous studies.

Multiple crops including rice, wheat, maize, soybean, peanut, rapeseed and potato, were covered within analysis in this work. While relevant studies paid attention to one crop, such as rice, wheat, maize, or staple grains [8, 25, 26, 28, 34, 43]. Some were focusing on the integrated N use in agriculture, without crop distinguishment [4, 20, 30]. In this context, heterogeneity among crops might be one potential contribution to the relevant researches and moreover, heterogeneity among regions was the emphasis of this work as well that seven regions in China were treated as the multi areas in the simulation of PEPEM analysis.

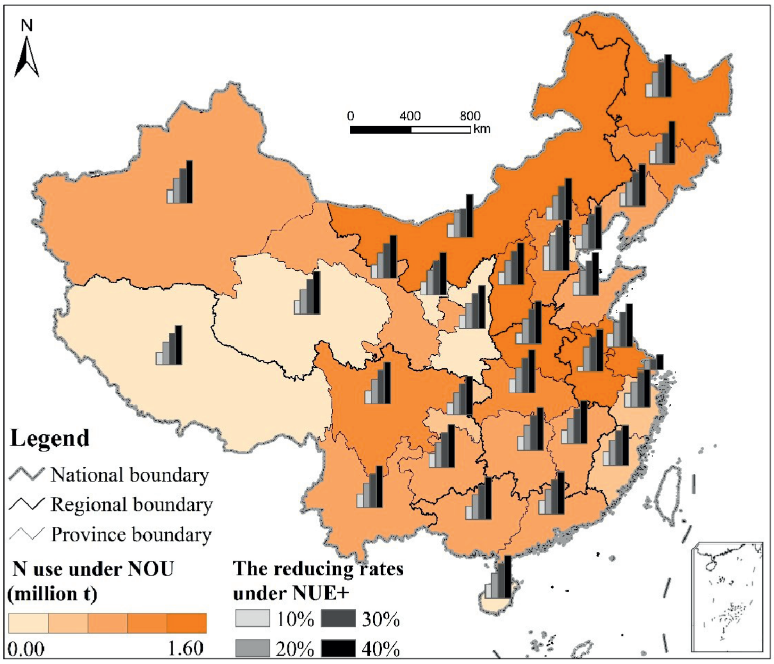

Fig. 4. N use in provinces under NOU and NUE+ scenarios.

Despite these potential contributions mentioned above, we acknowledge that there are several limitations in our study. First of all, the PEPEM simulation is one type of static modelling analyses that multi periods information would not be included within the model. Predicting analysis thereby, would be unavailable in this work. Though heterogeneities of both crops and regions were covered in model simulations, we did not conduct the intersectional analyses between crops and regions because of the data quality concern in each region and its induced bias in modelling. Consequently, the crop heterogeneities in each of the seven regions are still unclear, which might be the second shortcoming in this study. In terms of overcoming these limitations, the static simulation model should be reconstructed and adjusted to become a dynamic one at first through mathematical recursive methods, and then incorporate it with multi periods observations. As for the intersectional analyses, in future study we will continually search for suitable interpolation scheme to complete the datasets of crops in each region so that the bias of modelling could be mitigated.

Conclusion

Reducing agricultural nitrogen use has now become one of the top priorities for green and sustainable development of agriculture in China. By conducting a multi-crop multi-region price endogenous partial equilibrium model, this study evaluated the impacts from activities of nitrogen optimized utilization (NOU) and nitrogen use efficiency improvement (NUE+) on N use in Chinese agricultural sector. Seven main crops and seven geographical regions were taken into analysis. The NOU simulations indicate that: (1) after N use being optimized, total output of main crops in China would be increased by 3.62%, and crop acreage simultaneously would be saved by 8.21%; (2) NOU helps to reduce 7.73% N use in Chinese agricultural sector, so does in each region; (3) Soybean turns to be the only exceptional crop that NOU would enlarge its planting acreage and double the N use in production. As for the results of NUE+ simulations, (1) N use in Chinese agricultural sector would be continuously decreasing with the improvement of NUE, the reducing rates are 8.28%, 15.06%, 21.24% and 27.91% under NUE+10%, NUE+20%, NUE+30% and NUE+40% scenarios respectively, compared to the results of NOU; (2) among the crops, the reducing rates of soybean and peanut are far greater than those of others crops, especially that of maize, which is simulated as the least sensitive crop in N use to the NUE improvement; (3) Three of the seven regions, East, North and Central China, contribute over 60% of N use in the whole country. The reducing rates in North China are 1.5% to 2% higher than the average level, while on the contrary, N use in Northeast China performs least sensitivity under NUE+ scenarios.

Overall, this paper might have revealed several policy implications that help to solve the challenges of N overused in China. First of all, activities on optimizing nitrogen fertilizer utilization and improving nitrogen use efficiency are regarded as effective approaches to reduce N use in agricultural production, relevant policies and incentives are necessary and essential to achieve SDGs. On the other hand, various sensitivities to the NUE improvement among crops and regions disclose the heterogeneities in both crops and regions. Flexible adjustment strategies of crops' planting structures in different regions might be useful and inevitable in reducing agricultural nitrogen use in China. In order to have a deeper look at the reducing effects, future research will focus on reconstructing the PEPEM to be a dynamic model and analyze the intersectional analyses between crops and regions in multiple periods.

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Conflict of Interest

The authors declare no conflict of interest.

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