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Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China

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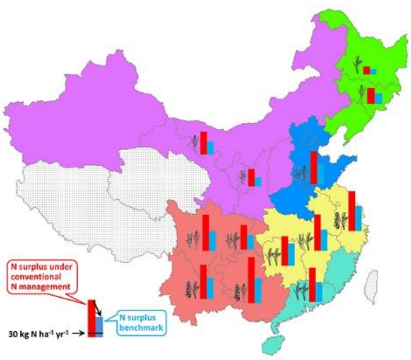
ABSTRACT: Nitrogen (N) surplus is a useful indicator for improving agricultural N management and controlling N pollution. Few studies have developed benchmark values for cropping systems in China, a country with the largest N fertilizer use in the world. We established N surplus benchmarks for 13 main cropping systems, at optimal N management, which accounted for about 50% of total N fertilizer consumption in Chinese agriculture, using results from >4,500 on-farm field experiments and a soil surface balance approach. The results showed that N surplus benchmarks for single cropping systems ranged from 40 to 100 kg N ha^{-1} yr^{-1} (average 73 kg N ha^{-1} yr^{-1}), while for double cropping systems ranged from 110 to 190 kg N ha^{-1} yr^{-1} (average 160 kg N ha^{-1} yr^{-1}), roughly twice that of single cropping systems. These N surplus benchmarks could be further reduced as declines of N deposition and reactive N losses towards to the "4R"s of nutrient stewardship through improving fertilization techniques and agronomic managements. Our N surplus benchmarks could serve as realistic targets to improve the N management of current conventional practices, and thereby could lay the foundations for a more sustainable N management in China.

KEYWORDS: N input, N output, N surpluses, N use efficiency, China, wheat, maize, rice, rapeseed



Abstract art

INTRODUCTION

Nitrogen (N) is a main nutrient, and needed to boost crop growth and development. It is delivered to the crop mainly through fertilizers, manure and the mineralization of organic matter and crop residues in soil. Nearly half of the world's population are currently nourished by crops grown with N fertilizers.[1, 2] However, improper use of N fertilizer may result in poor crop yield and/or crop quality, and lead to soil and environmental degradation, e.g., too little N is used in sub-Saharan Africa which results in low crop yields and soil N mining; too much N is used in China which leads to serious environmental pollution.[2, 3] Consequently, improving agricultural N management is crucial for producing more nutritious food for a growing global population, while maintaining or improving soil fertility and minimizing adverse environmental impacts. One of the key enabling steps for improving N management in cropping systems is the development of critical indicators and realistic benchmarks for evaluating the performance of N management.

Of the many indicators for assessing N management, two in particular may be useful for policy, i.e. nitrogen use efficiency (NUE) and N surplus. There are many functional definitions of NUE, e.g. agronomic efficiency, recovery efficiency, physiological efficiency and partial factor productivity,[4] and they have mainly focused on the efficiency of fertilizer N input. In contrast, the NUE concept used in the present study focused on the efficiency of all N inputs; it was based on a soil nitrogen balance calculation and included the main N inputs such as fertilizers, atmospheric deposition, and biological N fixation. Here, NUE is defined as the efficiency of all the N inputs transferring to harvested crop N, which is consistent with the definition used by the EU Nitrogen Expert Panel[5] and the approach used by Zhang et al.[2] NUE is a simple indicator commonly used by researchers, policy makers and international organizations to evaluate the relative transformation of N inputs into agricultural products.[6-8] Generally, for a given cropping system, low NUE over multiple years is an indicator of significant N losses to the environment.[6] NUE tends to decline with an increase of N input, and reducing N input would increase NUE, but might not achieve the target yield. Therefore, combining NUE with other indicators such as N removed in harvested product and N surplus in a set of integrated indicators will be critical for evaluating the performance of the N management in cropping systems.[5] In addition, estimations of changes in the soil N stock may be needed, because there is a risk that a high NUE is at the expense of soil N depletion, conversely, a low NUE may be the result of temporary soil N accumulation.[5, 9, 10]

The N balance is a summary table which lists the main N inputs and outputs of a cropping system. The difference between N input and harvested N output is defined as the N surplus.[11, 12] N surplus and NUE are different indicators for evaluating the performance of N management, but are related to each other. A benchmark for N surplus may be seen as a reference value for the N surplus under optimum N management in a given cropping system. Calculating N surplus provides important information about the use efficiency of N inputs.[11, 13, 14] The value of N surplus can be positive, indicating a risk of N loss to the environment or negative, indicating mining of soil N stock.[11] The N surplus is used as a management indicator by various countries and organization. For example, the mineral accounting system (MINAS) in The Netherlands was implemented at farm level in 1998 to achieve a step-wise decrease of the N (and phosphorus) surplus.[15] Lowering the N surplus in agriculture in The Netherlands has made a great contribution to improving the quality of groundwater and surface waters.[15] The decline of the nitrate concentrations in groundwater coincided well with the decline of the agricultural N surplus in Denmark, which was attributed to the initiation of the Danish environmental action plan since 1985, of which the restrictions of maximum N application rates for specific crops and minimum thresholds for utilization of N from animal manure are most important.[16]

To improve N management in crop production, the EU Nitrogen Expert Panel[5] proposed NUE as an easy-to-use indicator based on the N balance approach, but emphasized that NUE values need to be interpreted together with the quantity of N removed in harvested product (as a proxy for crop yield) and N surplus. They further suggested that these indicators are useful tools for decision makers to compare N management between farms, cropping systems or countries and to use this information to decide whether measures are needed to further improve the N management of specific farms and/or regions.

In recent decades China has been successful in feeding 20% of the world's population with only 9% of the global cropland area.[17] Grain yield has increased substantially, with 57% of this increase being attributed to the use of synthetic fertilizer.[18] The country is now consuming around 30% of the global synthetic fertilizer,[19] and had an overall N surplus of 27.6 ± 4.3 Tg N for cropland in 2010,[20] which contributed to serious environmental pollution. More recently, Chinese agricultural scientists have made great advances in finding technical solutions to achieve relatively high crop yields with less environmental costs, under experimental conditions.[21-23] However, few studies have addressed the need for N management indicators at farm level.[24] There are currently no clear guidelines to restrict the overuse or misuse of N in farmers' practices, which is probably the main cause of severe N pollution from the agricultural sector over the last three decades.[25] In contrast, N management indicators in some Western countries are well established and have served as useful tools for farmers and policy makers to achieve better N management.[26]

Over the last three decades a large numbers of studies have been carried out to establish economic optimum N fertilizer application rates based on yield response curves in experiments for widely differing cropping systems across China.[21, 23] The results of these studies can be used now to establish N management indicators and N surplus benchmarks. The objectives of the present study are therefore: (1) to establish N surplus benchmarks for Chinese main cropping systems (wheat, maize, rice and rapeseed) at optimal N application rates; (2) to evaluate the N surplus and corresponding N harvest and NUE indicators under current farmers' practices; and (3) to propose effective ways for achieving the N surplus benchmarks through improved N management practices in crop production.

MATERIALS AND METHODS

Main cropping systems and regions. Based on the "Integrated Regionalization and Planning of Agriculture"[27] and "Integrated Regionalization of Farming Systems",[28] we divided Chinese cropland into 7 regions, each comprising several provinces, i.e. northeast (NE), northwest (NW), North China Plain (NCP), middle and lower Yangtze River (MLYR), southwest (SW), southeast (SE) and others. For 'others' there were no data available and so these regions were not included in the present study, i.e., Tibet, Qinghai, Taiwan, Hong Kong and Macao. The studied cropping systems of each region were identified according to the main Farming Systems in China[28] and data availability. In total, 4 crop types and 13 cropping systems were selected (Figure 1). In the above 6 regions, grain production for the above 4 crops account for >95% of total grain production in China.[28] The proportions of the wheat, corn, rice and rapeseed areas that were irrigated were 48%, 15%, 95% and 0, respectively.[29-32] The single cropping systems (i.e. one crop per year) are mainly in NE and NW. In NCP, MLYR, SW and SE, double cropping systems are dominant with two harvests per year.[33]

Figure 1. The studied main cropping systems in different regions of China. The basemap was download from Resource and Environment Data Cloud Platform (http://www.resdc.cn/).

Calculation of N surplus. The main external N inputs to these cropping systems are fertilizer N (both synthetic fertilizer and manure) and N from atmospheric deposition and biological N_2 fixation. Internal N transformations and minor N inputs (e.g., straw return, net soil organic matter mineralization, irrigation and seed) were not considered. We assumed that all straw was returned to the soil in all cropping systems, due to the governmental ban on straw burning and economic incentives to return straw since 2000.[34, 35] We cannot exclude the possibility that straw has been removed in some cases, but expect that our assumption here will not introduce large bias in the N surplus estimation. Irrigation N input can be large in some cropping systems, such as greenhouse vegetables in the North China Plain, but is small for the cropping systems of the present study.[36] Seed N is also very small and can be regarded as negligible compared to N input from fertilization.[37-39]

N output includes the N harvested in cereal grain. N surplus and NUE were calculated as:

$$N_{sur}=N_{fer}+N_{dep}+N_{fix}-N_{har} \quad (1)$$

$$NUE=N_{har} / (N_{fer}+N_{dep}+N_{fix}) \quad (2)$$

where N_{sur} and NUE are N surplus and N use efficiency, respectively; N_{fer}, N_{dep}, and N_{fix} represent the N input from fertilization, atmospheric deposition and non−symbiotic N fixation (all crops in the present study were non-leguminous crops), respectively; N_{har} is the N in harvested grain.

Approach for establishing N surplus benchmarks. Here we define the N surplus benchmark as 'the calculated N surplus value at economic optimum N management'. It has similar meanings in somehow with relevant references.[2, 5, 40, 41]

Data and information on economic optimum N management for wheat, rice and maize were obtained from previous studies across different agro-ecological regions in China.[31, 32, 42] On-farm experiments across the above regions (1575, 1177 and 1726 for wheat, rice and maize on a national scale, respectively) were conducted between 2005 and 2010. All the field experiments received the same treatments: no N fertilizer (N0), recommended N application rate (RN), 50% RN, and 150% RN. None of these experiments had inputs of animal manure or other organic N sources. The amount of N fertilizer for the RN treatment was determined by local agricultural extension employees. The RN was a starting point for setting the gradient of N fertilizer rates (0, 50% RN, RN and 150% RN) for each field experiment, which allowed reliable yield-N response curves to be established.

To determine the economic optimum N rates at the regional scale, a quadratic model (Table S1) was used to relate N input to grain yield in each on-farm experiment using SAS software (SAS Institute Inc., Cary, NC, USA). The quadratic model is typically used to describe N-yield response curves.[43] Next, the following variables were calculated at different N input levels: the yield increase (amount above the yield in the N0 treatment), gross return for the yield increase (yield increase times grain price), cost of N fertilizer (N rate times fertilizer price), and the net return on N application (gross return minus fertilizer cost). Finally, the average net return for each N increment across all N response curves was calculated. The N application rate with the largest average net economic return from N fertilizer input was defined as economic optimum N rate in a region.[31, 32, 42, 44] Although the fertilizer N price and market prices of rice, wheat and maize showed variations in space and time, the fluctuation of these parameters was small compared to other countries We therefore used an average fertilizer N price of US$0.59 kg^{-1} N, and mean grain prices of US$0.27, 0.29, 0.32 kg^{-1} for wheat, maize and rice, respectively (see sensitivity analysis below). This approach is also known as 'Maximum return to N' (MRTN; Sawyer et al.[44]), and used by Wu[31] and Wu et al.[32, 42] to calculate the economic optimum N rates used in the current study. The relationships of economic optimum N rate (for calculating N surplus benchmark), maximum yield N rate and the recommended N rate (RN) was further illustrated in Figure S1.

As there were no data for rapeseed in the aforementioned studies, we obtained data on economic optimum N management for this crop from Ren et al.[45] who estimated the economic optimum N rates for rapeseed in the Yangtze River Basin between 2007 and 2009 using 60 on-farm experiments. Since there was no sub-region data in Ren et al.[45], fertilizer N and yield from Ren et al.[45] were used in both of the SW and MLYR regions in the present study.

For calculating the N surplus benchmarks, N input from deposition was obtained from 22 rural sites in the Nationwide Nitrogen Deposition Monitoring Network (NNDMN)[46]. Each region in this study contains 2 to 6 monitoring sites in NNDMN. Regional N deposition rates were the average of measurements at all sites in each region. N input from biological N fixation was obtained from Bouwman et al.[47] N fixation rate associated with rice production was 25 kg N ha^{-1} yr^{-1}, and 5 kg N ha^{-1} yr^{-1} for wheat, maize and rapeseed. Grain N harvest for each crop was calculated by multiplying grain yield by grain N concentration: 1.9%, 2.3%, 1.4% and 3.9% of grain N content for rice, wheat, maize and rapeseed, respectively.[48]

Calculating reactive N (Nr) losses. Total Nr losses were related to N surplus but not equivalent to N surplus; we examined the correlations between N surplus, NUE and Nr losses. Reactive N (Nr) losses include NH_3 volatilization, N_2O emissions, nitrate leaching and runoff; N_2 loss was not included since N_2 has no harmful impacts on the environment. Details about calculation of the Nr losses can be found in SI and Table S2.

To compare N surplus and Nr losses under farmers' conventional N management with those under economic optimum N management, we collected data on fertilizer N rates and grain yields under farmer's conventional N management from the literatures (See SI for details data collection and calculation).

In the present study, we divided Chinese cropland into 7 regions, each comprising several provinces with the consideration of soil-climate similarity. There were differences of zoning method between the present study and literature data .[31, 32, 42, 46, 49] Details on merging the regional data from literature to the present study can be found in SI.

Fertilizer N input, crop yield, N harvest and Nr losses of different crops in China under optimum and conventional N managements were summarized in Table S3. For the double cropping systems in each region, the items of N input and N output were calculated as the sum of each crop to convert the data to cropping systems.

Sensitivity analyses. We did the sensitivity analysis to see how variation of fertilizer prices and product revenues affect the economic optimum N rates and the N surplus benchmarks, and predicted the changes of the crop yield, NUE, and Nr losses. As the crop price is quite stable in China due to the central government control[50] and the urea price range from 150 to 300 (fluctuation range: ±33%) USD per ton during 2000-2010 in China,[51] we therefore used a change of ±40% (only change of fertilizer price) for price ratio of fertilizer to crop to calculate the change of economic optimum N rates and corresponding crop yield based on the equation 3[52] and the N-yield response curves in Table S2, respectively. N surplus benchmarks and NUE were calculated by using the above equation 1 and equation 2. Nr losses were calculated by using the regional N loss models of Cui et al.[49] (See SI and Table S2 for more details).

$$X^{*}=X_{max}\times[1-2\times R\times X_{max}/(Y_{max}-Y_{0})] \quad (3)$$

where X^{*} is the economic optimum N rate; Y_{max} and X_{max} are maximum crop yield and corresponding N rate, respectively, which calculated from the N-yield response curves in Table S2; Y_0 is crop yield without N fertilizer application; R is the price ratio of fertilizer to crop

RESULTS

N surplus benchmarks for main cropping systems. With N inputs of 192−455 kg N ha^{-1} yr^{-1} and N harvests of 126−294 kg N ha^{-1} yr^{-1} under economic optimum N management, the N surplus benchmarks range from 40 to 190 kg N ha^{-1} yr^{-1} (Table 1 and Table 2). In NE and NW with single cropping systems, N surplus benchmarks are in the range of 40−100 kg N ha^{-1} yr^{-1}, with corresponding N input and N harvest values in the range of 192−224 and 126−154 kg N ha^{-1} yr^{-1}, respectively. The N surplus benchmarks of double cropping systems are in the range of 110−190 kg N ha^{-1} yr^{-1}, with N inputs and N harvests in the range of 358−455 and 211−294 kg N ha^{-1} yr^{-1}, respectively. The wheat-maize system in NCP and wheat-rice system in MLYR are the two most intensive double cropping systems in China,[23] with relatively high N input, N harvest and yield (Table 1 and Table 2). The N surplus benchmarks in the above two cropping systems have a similar value, 160 kg N ha^{-1} yr^{-1}. The N surplus benchmarks for rapeseed-rice systems in MLYR and rapeseed−maize in SW are higher than those for other cropping systems and regions; these differences may be attributed to the low NUE of rapeseed, which contributes to relatively large N surpluses[53] in the aforementioned two cropping systems.

Table 1. N surplus benchmarks for the main cropping systems of China as derived from economic optimal N management [a]

Regions	Cropping systems	N input		N harvest	N surpluses [d]
		Fertilizer N [b]	Other N [c]		
Northeast	Rice	127	65	154	38
	Maize	160	45	126	79
Northwest	Wheat	166	40	138	68
	Maize	184	40	128	96
North China Plain	Wheat–Maize	361	71	270	162
Middle and lower Yangtze River	Wheat–Rice	381	74	294	161
	Rice–Rice	337	94	263	168
	Rapeseed–Rice	377	74	264	187
Southwest	Wheat–Maize	313	45	211	147
	Wheat–Rice	294	65	250	109
	Rapeseed–Rice	343	65	252	156
	Rapeseed–Maize	362	45	213	194
Southeast	Rice–Rice	325	83	261	147

[a] the unit for all the numbers is kg N ha^{-1} yr^{-1}

[b] includes synthetic fertilizer and manure (but manure was not used in the experiments used here)

[c] including N inputs from atmospheric deposition and biological N fixation

[d] N surplus benchmark has been rounded to the nearest 10 kg ha^{-1} yr^{-1} for use in Table 2

Performance under economic optimum and conventional N management practices. The N input (including fertilizer N and other N) under conventional N management was in the range of 206 to 532 kg N ha^{-1} yr^{-1}, which is 7% to 27% higher than the N input under economic optimum N management. However, crop yield under conventional N management was 2 to

30% lower than that under economic optimum N management. This was because N input under conventional N management far exceeded the N rate for the maximum yield (extreme N over-fertilization) which led to either lodging or increased susceptibility to diseases or pests.[54] (Table 2) The harvested N under conventional N management (range 104 to 259 kg N ha^{-1} yr^{-1}) was 2% to 30% lower than that under economic optimum N management. The reason for higher N input with relatively lower crop yield in conventional N management compared to economic optimum N management could be attributed to farmers' lack of knowledge and market confusion as mentioned by Zhang et al.[55] As a result, N surpluses under conventional N management (range 59 to 349 kg N ha^{-1} yr^{-1}) were 34% to 96% higher than the N surpluses under economic optimal N management.

Expressing Nr losses on a yield-scaled basis (kg N (Mg of grain)$^{-1}$) provides an indication of Nr losses per ton of grain yield. Average yield-scaled Nr losses for conventional N management (7.4; range 2.4 to 13.0 kg N Mg^{-1}) were 42% higher than those at economic optimal N management (5.2; range 2.0 to 7.6 kg N Mg^{-1}). NUE at economic optimal and conventional N management were 52%–80% and 30%–71%, respectively. Average NUE of main cropping systems was 47% for conventional N management and 63% for economic optimum N management (Table 2).

Table 2 Nitrogen surpluses, NUE, and reactive N losses under economic optimum and farmer's conventional N management for different cropping systems and regions

Regions	Cropping systems	Economic optimum N management							Farmer's conventional N management									
		N surplus bench-marks (kg N ha^{-1} yr^{-1})	NUE [a] (%)	Yield (Mg ha^{-1} yr^{-1})	Nr losses [b] (kg N ha^{-1} yr^{-1})			Yield-scaled Nr losses [b] (kg N Mg^{-1})	N input (kg N ha^{-1} yr^{-1})		N harvest (kg N ha^{-1} yr^{-1})	N Surplus (kg N ha^{-1} yr^{-1})	NUE (%)	Yield (Mg ha^{-1} yr^{-1})	Nr losses (kg N ha^{-1} yr^{-1})			Yield–scaled Nr losses (kg N Mg^{-1})
					NH_3	N_2O	L&R [c]		Fertili-zer N	Other N					NH_3	N_2O	L&R	
Northeast	Rice	40	80	8.13	16.5	0.5	5.3	2.7	141	65	147	59	71	7.75	17.9	0.5	5.6	3.1
	Maize	80	61	9.02	11.8	1.2	4.6	2.0	199	45	124	120	51	8.86	14.1	1.4	5.4	2.4
Northwest	Wheat	70	67	6.01	14.5	0.5	12.7	4.6	202	40	109	133	45	4.72	16.9	0.6	15.6	7.0
	Maize	100	57	9.16	13.2	1.3	5.1	2.1	238	40	104	174	37	7.42	16.3	1.6	6.3	3.3
North China Plain	Wheat–Maize	160	63	14.94	40.9	3.2	46.8	6.1	436	71	256	251	50	14.12	47.0	3.6	59.8	7.8
Middle and lower Yangtze River	Wheat–Rice	160	65	14.24	62.2	3.2	17.9	5.8	458	74	257	275	48	12.47	76.5	3.8	21.7	8.2
	Rice–Rice	170	61	13.85	66.4	2.6	19.7	6.4	390	94	259	225	54	13.60	77.0	2.8	21.9	7.5
	Rapeseed–Rice	190	59	11.06	50.8	3.2	30.4	7.6	442	74	214	302	41	9.25	63.3	3.6	33.7	10.9
Southwest	Wheat–Maize	150	59	12.25	31.3	2.7	29.0	5.1	395	45	165	275	38	9.33	37.9	3.3	41.7	8.9
	Wheat–Rice	110	70	12.24	49.1	1.8	13.0	5.2	345	65	224	186	55	10.96	57.2	2.1	14.5	6.7
	Rapeseed–Rice	160	62	10.45	44.6	2.3	27.8	7.1	404	65	209	260	45	8.98	52.5	2.7	31.4	9.6
	Rapeseed–Maize	190	52	10.46	26.8	3.2	43.8	7.1	454	45	150	349	30	7.35	33.2	3.9	58.6	13.0
Southeast	Rice–Rice	150	64	13.76	65.2	1.0	16.7	6.0	434	83	257	260	50	13.53	83.7	1.5	19.9	7.8

[a] NUE=N harvest/N input×100%

[b] Nr losses denote reactive N losses, Yield−scaled Nr losses=Nr losses/Yield

[c] L&R denote N leaching and runoff losses

Sensitivity analyses. The ±40% change of price ratio of fertilizer to crop gave a ±2-23 kg N ha^{-1} yr^{-1} (±2-6%) change of economic N rates and ±2-22 kg N ha^{-1} yr^{-1} (±6-15%) change of N surplus benchmarks in all cropping systems(Figure 2a and 2b). It led to <±0.05 Mg ha^{-1} yr^{-1} (<±0.3%) change of crop yield, ±1-3% (±1-5%) change of NUE and ±0-6 kg N ha^{-1} yr^{-1} (±1-6%) change of Nr losses (Figure 2c, 2d, 2e). The above analysis showed that the variation of fertilizer prices and product revenues have little effect on the economic optimum N rates, N surplus benchmarks, crop yield, NUE and Nr losses, given the low price ratio of fertilizer to crop in China.

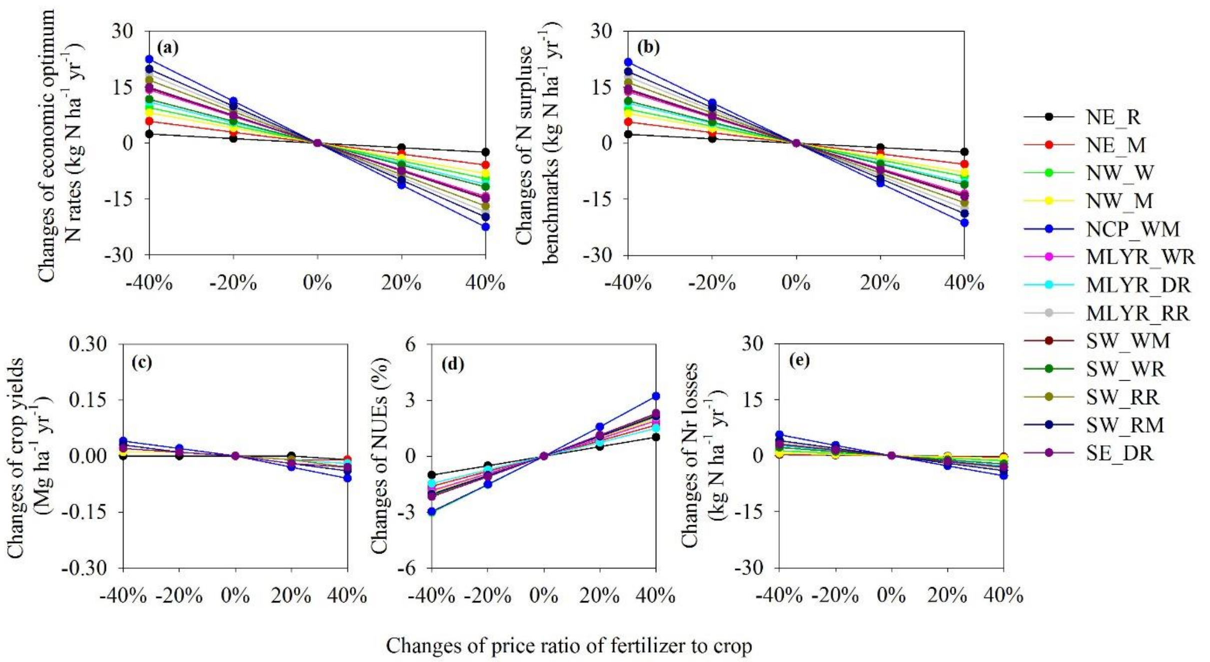


Figure 2. Sensitivities of economic optimum N rates (a), N surplus benchmarks (b), crop yield (c), NUE (d) and Nr losses (e) in response to ±40% change of price ratio of fertilizer to crop. NE, NW, NCP, MLYR, SW, SE denote the agro−ecological regions of northeast, northwest, North China Plain, middle and lower Yangtze River, southwest and southeast of China, respectively. M, R, W, WM, WR, DR, RR, RM denote maize, rice, wheat, wheat−maize, wheat−rice, double rice, rapeseed−rice and rapeseed−maize cropping systems, respectively.

Assessment of N management. We plotted N input and N output (harvested N) of the 13 main cropping systems of China under both economic optimum and conventional N management in Figure 3. The suggested minimum productivity level (N harvest=80 kg N ha^{-1} yr^{-1}) and suggested ranges for NUE (50%–90%) according to the EU Nitrogen Expert Panel[5] are also shown in Figure 3. The N harvest of the main cropping systems under both economic optimum and conventional N management were all above the minimum productivity level (80 kg N ha^{-1} yr^{-1}) suggested by EU Nitrogen Expert Panel.[5] Especially the N harvest values in double cropping systems (range 150 to 294 kg N ha^{-1} yr^{-1}) were much higher. Economic optimum N management greatly reduced N surpluses (range 38 to 194 kg N ha^{-1} yr^{-1}) compared to conventional N management, and increased average (arithmetic mean value) NUE from 47% for conventional management to 63% for economic optimal N management. The NUE of all cropping systems under economic optimum N management was within the desirable range suggested by the EU Nitrogen Expert Panel,[5] i.e., 50% to 90%, however, N surpluses of most cropping systems were higher than the suggested mean (80 kg N ha^{-1} yr^{-1})[5], except for single rice and single maize in NE, and single wheat in NW.

The N inputs of some double cropping systems under conventional N management were extremely high; the N input of the wheat−maize system in NCP, wheat−rice and rapeseed−rice in MLYR, rice−rice in SE all exceeded 500 kg N ha^{-1} yr^{-1}. NUE values of single rice and single maize in NE, rice−rice in MLYR, wheat−rice in SW under conventional N management were within the desirable range (50% to 90%), showing that high yield (high N harvest) were obtained together with a desirable NUE level. However, the N surplus in these 4 cropping systems was relatively high, which illustrates the importance of combining the above three indictors for evaluating the overall performance of N management. In the other cropping systems, high N harvests were associated with high N surpluses and low NUE; the N surplus in 7 of the 9 double cropping systems under conventional N management exceeded 250 kg N ha^{-1} yr^{-1}, while NUE was ≤50%.

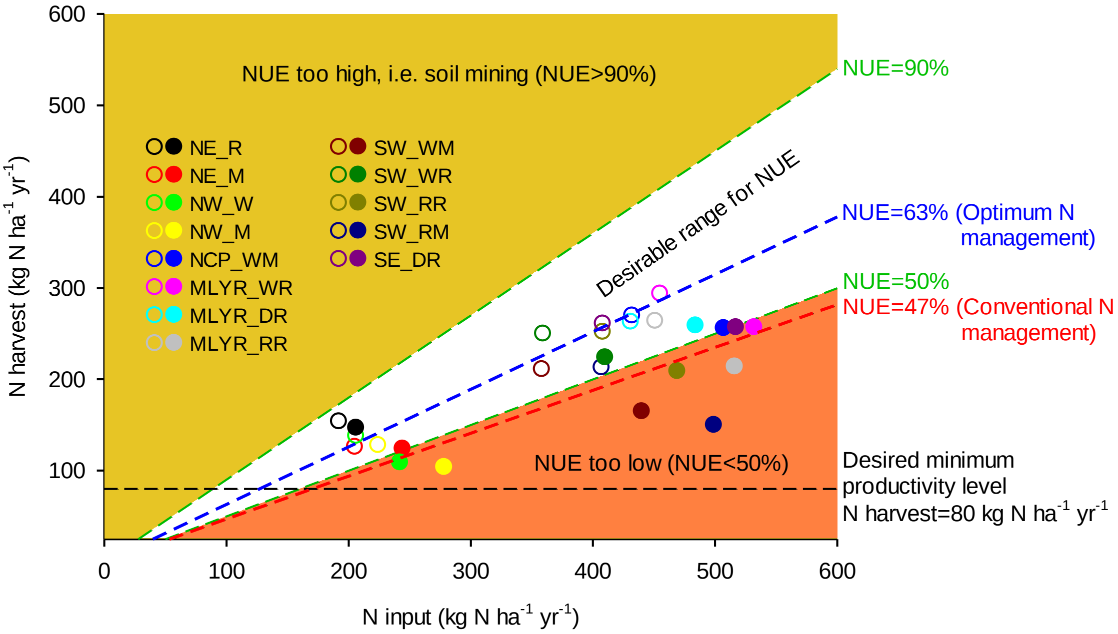


Figure 3. Comparison of mean N input and output in harvested cereals under economic optimum and conventional N management of main cropping systems and regions. N input include fertilizer N, N deposition and biological N fixation; NE, NW, NCP, MLYR, SW, SE denote northeast, northwest, North China Plain, middle and lower Yangtze River, southwest and southeast regions; M, R, W, WM, WR, DR, RR, RM denote maize, rice, wheat, wheat−maize, wheat−rice, double rice, rapeseed−rice and rapeseed−maize cropping systems. Open and solid circles denote data under economic optimum and conventional N management, respectively (modified from EU Nitrogen Expert Panel[5]).

DISCUSSION

Establishing N surplus benchmarks. In the present study, we established N surplus benchmarks for China's 13 main cropping systems. Benchmarks were derived at economic optimal N management. The cropping systems accounted for about 50% of total N fertilizer consumption in Chinese agriculture in 2015.[56] Other important crops such as vegetables, fruits, potatoes and cotton were not included due to lack of reliable experimental data.

For the soil surface N balance approach, N outputs (N removed by products) are usually easy to obtain from yield and N concentration determinations. Nitrogen inputs may include many items, including fertilizer, manure, deposition, biological fixation, crop residue (straw), irrigation, seed etc., and these data are not always easy to obtain accurately. There is no accepted and universally applied protocol for establishing soil surface balances and the N input items considered differ therefore between studies. For instance, Norton et al.[6] compared N surplus and NUE of different countries, only considering synthetic fertilizer as N input. In the crop section of the farm−gate N balance in MINAS, synthetic fertilizer and manure are taken into account, while deposition and biological fixation are accounted for as natural processes.[57] Simplifications may make the N balance easier to calculate and use for policy orientation, but there is the risk of underestimating total N input.[57] At a global scale, Zhang et al.[2] calculated N surplus and NUE for cropping systems in different regions/countries, using synthetic fertilizer, manure, deposition and biological fixation as N input items.

The items of N input considered in the present study are the same as Zhang et al.[2] It is important to include atmospheric N deposition because China (especially central-east China) is a global hotspot of N deposition with annual deposition rates of 23–71 kg N ha^{-1} for rural area.[46, 58] Biological fixation is also an important N input item for some of the non−symbiotic N fixation crops (e.g., rice in the present study). Although N fixation was relatively small for maize, wheat, and rapeseed, we included N fixation in the N balance calculations of all crop systems in order to maintain uniformity with rice-based crop systems. The seed N input was neglected; it is lower than the associative N fixation rate. We also did not include animal manure or other organic materials because these are mainly used in vegetables and fruits production, and seldom in maize, wheat, rice and rapeseed production.[59]

We assumed that straw was returned to the field, thus, straw N in the output was offset by the input when calculated N surplus benchmark. Although the straw burning was banned and economic incentive for returning straw was provided by the Chinese government since 2000,[34, 35] it still has some cropping systems removing straw partly from the field in the practices. To address these situations, we assumed that 1/3 of the straw was removed in all cropping systems, and estimated how it affects N surplus benchmarks. The results showed the current N surplus benchmarks would be reduced 18-27 and 32-46 kg N ha^{-1} yr^{-1} for single and double cropping systems, respectively (Table S4). Therefore, for the cropping systems in which only part of straw was returned, the current N surplus benchmarks could be reduced around 20 kg N ha^{-1} per crop season.

By investigating the sensitivity of fertilizer price and product revenues, it showed that the economic optimum N rate and the N surplus benchmarks didn't depend strongly on them due to the low price ratio of fertilizer to crop in China.[31, 32, 42] Thus, the change of fertilizer price (much lower compared with other countries in general)[51] and the relative stable crop price[50] would cause little uncertainties of N surplus benchmarks.

Comparison of N surplus benchmarks. Losses of N are inevitable, especially in intensively managed crop systems, and the benchmark N surplus must reflect that. Our results show that the N surplus benchmarks for China's main single cropping systems range from 40 to 100 kg N ha^{-1} yr^{-1} (average 73 kg N ha^{-1} yr^{-1}), which is close to the N surplus benchmark of the Netherlands' MINAS (80 kg N ha^{-1} yr^{-1}), and the N surplus benchmark of 80 kg N ha^{-1} yr^{-1} for cropping systems proposed by the EU Nitrogen Expert Panel (Table 3). However, the N surplus benchmarks for Chinese main double cropping systems range from 110 to 190 kg N ha^{-1} yr^{-1} (average 160 kg N ha^{-1} yr^{-1}), which is roughly double that of single cropping systems (Table 3). There were large differences of N surplus benchmark in the 13 cropping systems, e.g. maize of single cropping system in northeast China (80 kg N ha^{-1} yr^{-1}) and the northwest China (100 kg N ha^{-1} yr^{-1}). The main reasons for this relatively wide range are variations in soil-climate conditions and crop management. The high soil organic carbon content in northeast China compared to the northwest China[35] suggest that the soil N supply was larger in northeast than in northwest. There are also differences in annual average temperatures and rainfall between these regions,[60] which may have contributed to differences in Nr losses and N surplus.

In contrast to the top−down approach used by Zhang et al.[2], which derived N surplus benchmarks for global and regional mean N surpluses by model simulations[2, 65], we established N surplus benchmarks for China's main cropping systems using on−farm field experiments: this approach could be termed a bottom-up approach. The biggest difference between our study and the Zhang et al.[2] study is the data source. Our study used data from on−farm experiments in specific cropping systems in specific regions, whereas the Zhang et al.[2] study used data from the FAO and IFA statistical databases, and considered only one average Chinese cropping system. Zhang et al.[2] projected the total N surplus in China at 11 Tg N yr^{-1} for the year 2050, based on projected harvested N and target NUE. This translates to an N surplus benchmark of 65 kg N ha^{-1} yr^{-1}, based on a harvested area of 170 million hectares in 2010 in China.[61] Our estimated average N surplus (77 kg N ha^{-1} yr^{-1}) for main Chinese crops is close to the mean N surplus target for 2050 suggested by Zhang et al.[2], in which they set higher NUE targets in all crops. The economic optimum N rates between non-staple crops (e.g., fruits and vegetables) and staple crops were similar. This suggests that the N surplus target for 2050 suggested by Zhang et al.[2] could be realized through economic optimal N input management.

We recognize that our N surplus benchmarks are still higher than the actual N surplus values already achieved in some western countries, which would suggest that our N surpluses could be further reduced in the future. Atmospheric deposition currently is an important N input, accounting for 8 to 21% of the total N input under economic optimum N management.[46] It is likely that N deposition will reduce in the coming years due to the regulations and actions to deliver cleaner air in China.[62] Further, the Nr losses is still high even in the optimum N management, and still have much space to be reduced when toward the "4R"s of nutrient stewardship (using the right synthetic N fertilizer, at the right rate, right time, and in the right place)[63]. Hence, it is expected that N inputs may be reduced beyond economic optimal N inputs and that N surpluses may be reduced further in future.

Table 3 Comparison of N surplus benchmarks between China and other countries/regions

Countries or Regions	N balance approach	N surplus benchmarks (kg ha^{-1} yr^{-1})	References	Notes
Netherlands	farm–gate	80	Hanegraaf and den Boer[64]	80 kg ha^{-1} yr^{-1} was the levy free N surplus for arable land in 2003.
Europe	n.a. [a)]	80	EU Nitrogen Expert Panel[5]	Overal mean N surplus benchmark
World	soil surface	39	Zhang et al.[2]	39 kg ha^{-1} yr^{-1} is the global mean N surplus benchmark in 2050
China	soil surface	65	Zhang et al.[2]	Zhang et al.[2] proposed a N surplus of 11 Tg yr^{-1} for China in 2050, which translates to about 65 kg ha^{-1} yr^{-1}.
China	soil surface	40–100	this study	N surplus benchmarks for single cropping systems
China	soil surface	110–190	this study	N surplus benchmarks for double cropping systems

[a] n.a. denotes not available

N surplus and Nr losses. The N surplus is a combination of the total N losses and changes of the soil N stock over time, but includes also possible errors associated with the determination of N inputs and N outputs. We expect that N surplus is a proxy indicator for N losses, and that changes in soil N stock over time were relatively small because of the long-term cultivation of farmland.[9] However, the N surplus did not match with Nr losses in Table 2. For example, Northeast maize has an N surplus of 79 kg N ha^{-1} yr^{-1}, while the Nr losses sum to only 18 kg N

ha^{-1} yr^{-1}. There are three possible reasons for the difference between N surpluses and Nr losses. Firstly, the assumption of returning straw may lead to a slight overestimation of N surplus as discussed before. Secondly, we calculated only the Nr losses which have harmful environmental effects, so denitrification loss to N_2 was not accounted for in the N losses. Finally, the region evaluation of Nr losses by model simulation was more uncertain than the evaluation by site specific measurement. Nevertheless, the evaluation of Nr losses in the present study gave an integrated impression for different pathways of Nr losses, especially for the comparison of Nr losses between optimum and conventional N management.

Towards sustainable N management. To realize the proposed N surplus benchmarks for main cropping systems, N inputs (mainly synthetic N fertilizer) need to be reduced while maintaining or improving current crop yields (N harvest).[23] Reducing synthetic N fertilizer inputs must be done with complementary measures to minimize N losses. For instance, if we optimize the N application rate according to crop demand while applying the fertilizer with farmers' common practices (e.g. broadcast fertilizer with high N losses), large quantities of the applied fertilizer N will be lost to the environment, and the rest of the applied fertilizer N will not be enough to meet the crops' N demand (low harvested N), and N surplus will still be high.[66] The improvements could be expressed as full adoption of the "4R"s of nutrient stewardship[63]. and also include a better utilization of N from animal manures. By improving fertilization techniques and agronomic managements to realize the N surplus benchmarks, the target yields will be attained and the Nr losses will be minimized. We think that our N surplus benchmark will be a valuable tool for policy makers and agricultural extension workers to evaluate and improve the N management of current farmers' practices, and to lay the foundations for achieving the long-term goals for sustainable N management in China.

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Supporting Information Available

This file includes calculating N surplus under farmers’ conventional N management, calculating reactive N (Nr) losses, merging the regional data from literatures to the present study, and Figure S1 and Table S1-S4.

This information is available free of charge via the Internet at http://pubs.acs.org.

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