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Region-specific nitrogen management indexes for sustainable cereal production in China

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Supplementary material for this article is available online

Abstract

Effective policy measures are required to control environmental problems caused by nitrogen (N) fertilizer use in intensive crop production systems in China. However, simply reducing the use of N fertilizer in all regions may be detrimental to food security. Here we reviewed N management policies and indicators, with a particular focus on European Union (EU), and designed an N index system for cereal crops in China. We suggest to use N surplus as an (environmental) evaluation index and N input as a guide to meet the dual challenge of food security and environmental sustainability, and propose crop and region-specific standards for these indexes. We inferred a mean critical N surplus of 75 kg N ha^{-1} for maize, 40 kg N ha^{-1} for wheat and 70 kg N ha^{-1} for rice. For N input, Maximum N (Max. N) and Minimum N (Min. N) input indices are proposed, to guide farming practices effectively. Max. N was based on the N demand of crops achieving their potential yield, in different regions, Min. N was based on the N demand of crops at their target yield, while associated N surpluses do not exceed the set critical values. To meet the dual challenge of food security and environmental sustainability, China needs to increase maize and wheat yields by 20%–40% (rice has achieved target yield) while reducing N input by 10%–20%. This requires an enormous increase in N use efficiency. The N management indexes proposed here can be used as benchmarks to monitor the progress at regional level. Max. N and Min. N may have to be updated regularly when potential and target yields, and thereby crop N demand, change. Also, critical N surpluses may have to change when insights in the impacts of these N surpluses change.

1. Introduction

Environmental pollution and soil acidification caused by nitrogen (N) fertilizer use in China have received significant attention during the last decade (Ju *et al* 2009, Guo *et al* 2010, Liu *et al* 2010, Zhang *et al* 2015, Yu *et al* 2019). In response, series of governmental policies have been released to improve N fertilizer management in intensive cropping systems. For instance, the central government has ordered local governments to ensure that the use of synthetic N fertilizer may not increase further by 2020, in the 'Action Plan for the Zero Increase of Fertilizer Use' (Ju *et al* 2016). However, a 'one-size-fits-all policy' may reduce crop productivity and thereby threaten food security, by neglecting regional differences in N demand. It may also lead to abandoning farms . Further, the governmental policy related to 'replacing inorganic fertilizer by organic fertilizer' in fruit, vegetable and tea cropping systems has led to incidental misuse and overuse of animal manure, due to a lack of guidance and knowledge (Farmer survey 2019). There is an urgent need for guidance in nutrient management, including benchmark indexes, to be able to improve the use of both synthetic and organic fertilizers and to meet the dual challenges of food security and environmental sustainability in China.

Table 1. Regulatory indexes for manure and fertilizer applications, used to implement the Nitrate Directive in some EU-countries (adopted from van Grinsven *et al* 2012).

	Denmark	France	Germany	UK	Netherland
Max manure input	√	√	√	√	√
Total N input	√	√		√	√
Max N surplus			√		
Max soil residue NO_3^-		√[1]	√[2]		

[1] In small highly sensitive areas (e.g. coastal areas with green tides).
[2] Implementation varies between states of Germany, e.g. maximum soil residue NO_3^- in autumn only in Baden Wurtemberg.

Table 2. Common nitrogen management indexes in cropland, their applied scales, and the possible benefits and limitations of the indexes.

Indexes	Applied scales	Benefits	Limitations
N application rate	Plot-Region	Reflect the farmers' input, Easy to regulate and monitor	Does not reflect risks of N losses directly
N surplus	Plot-Region	Easy to understand, Allows translating environmental targets into actionable goals for farmers	Difficult to monitor
NUE	Plot-Region	Reflect the efficiency of N used in cropping system	Does not reflect risks of N losses directly
Soil residue NO_3^-	Plot	Provides insight in the unused mineral N in soil, and in the risk of N leaching	High spatial and temporal variation and high monitoring costs
NO_3^- concentration in water	Plot-Region	Reflects groundwater and surface water quality	Difficult to monitor at regional scale, high costs.
NH_3	Plot-Region	Reflects impact on air quality	
N_2O	Plot-Region	Reflects impacts on climate change and air quality	
Total N losses	Plot-Region	Reflects impacts on resource use efficiency and the environment	

The earliest environmental policies regarding the management of N and phosphorus (P) in agriculture were established in the European Union. The Nitrate Directive (ND) has had the strongest influence on N fertilizer use in the European Union (van Grinsven *et al* 2012). The ND has greatly contributed to improved nutrient management and to a decrease of N losses to groundwater and surface waters by limiting the manure application rate, implementing balanced N fertilization and putting a ban on manure and fertilizer applications outside the growing season and near nitrate-sensitive water courses (Velthof *et al* 2014). However, progress has been slow and the overall effectiveness remains limited due to low acceptance among some member states. Also, increases in crop yields have stagnated since the implementation of the ND in 1991 (Eurostat 2018). Yet, it is relevant to briefly review the various measures of the ND and to find out which measures have been effective (table 1–2). Most EU member states have implemented 'balanced N fertilization' with crop and soil-specific N application limits (N quota, for both synthetic and organic fertilizers) to control N losses (van Grinsven *et al* 2012). However, N quota do not directly reflect the environmental impact, because higher N inputs may be used effectively by crops in high-yielding areas, under proper management practices, and then may result in low N losses (Zhang *et al* 2020). The EU member states are also monitoring N surpluses, especially in Germany, Denmark and The Netherlands (van Grinsven *et al* 2012). The N 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 (Oenema *et al* 2003, Ju and Gu 2017, McLellan *et al* 2018). However, it is not easy to implement an N input-output accounting system at farm level, because of the difficulty of quantifying the N inputs from different sources. A special case is the Mineral Accounting System (MINAS), implemented at farm level in The Netherlands from 1998–2006. The N and P input—output accounting system MINAS had farm-specific levy-free N and P surpluses, but farmers were charged if those levy-free N and P surpluses were exceeded. The system had high implementation costs and there was discussion about the levies and the levy-free surpluses and its regional differentiation (Schröder and Neeteson 2008). MINAS was abandoned in 2006, because the system did not comply with the legal requirements of N application limits of the ND, even though many farmers and policy makers started to acknowledge the nutrient management guidance provided by the system and its inherent flexibility (Schröder *et al* 2003). In addition, the idea to introduce this type of system was advised this year in the Netherlands in view of the Dutch N crisis (Advisory Board on Nitrogen Problems 2020).

Chinese agriculture is dominated by smallholders; there are about 200 million farm households, managing on average less than 1 ha of farmland, under diverse soil and climate conditions. The number and size of the

The N management indexes towards promised production & sound environment			
Indicators	Roles	Food Security	Environmental Sustainability
Critical N surplus	Evaluate N environmental risk	>0 No soil mining	< A critical level Limited N pollution
N input (Min & Max. N)	Guide farmers practices	> Min. N Meets the demand of Target yield[1]	< Max. N Below the demand of Maximum yield[2]

1. *Min. N = Harvest N of target yield + Critical N surplus*
2. *Max. N = Harvest N of yield potential + Critical N surplus*

Figure 1. The proposed Nitrogen Management Indexes System in cropland in China.

farms and the diversity in environmental conditions make the transition to improved N management not easy. The pressure to ensure food security and environmental sustainability is unprecedented. There is a great need for easy-to-implement, flexible and region-specific N management indexes for crop production. Consequently, the objectives of this study are to identify/design relevant N management indexes for crop production, to derive benchmark values for the proposed indexes, and to explore potential policy instruments. We focus on cereal production systems (wheat, maize and rice), because cereals cover 55% of the agricultural land and also consumes ca 50% of total N fertilizer use in China (Zhang *et al* 2016).

2. Material and methods

2.1. Developing N management indexes in China

There are a number of elements that need to be addressed for a sound agri-environmental management policy: (1) the objectives (what to achieve), (2) the policy instruments (how to achieve), (3) the target areas and scale (where to take actions), (4) the addressees (who has to take actions) (Oenema 2004). Taking China's specific agricultural conditions into account, five principles were established in designing the proposed N management indexes, i.e. they should:

(1) meet the dual demand of food security and environmental sustainability.

(2) suit the diverse environmental conditions of Chinese crop production systems, accounting for variations in crop types, climatic conditions (rainfall and temperature) and soil properties, which affect N losses to air and water bodies.

(3) be easily implemented as mandatory or incentive-based policy instruments.

(4) be feasible in terms of data acquisition and analyses.

(5) be suitable for both farm and regional scales and cover the national major cereal production areas. The main addressees are local governments and large farmers. Smallholders should be encouraged to follow the guidelines following training, but are not our primary addressees.

To meet the food security goal, a target yield that meets future grain demand is taken into account. Two key indicators were chosen, i.e., N surplus (kg N per hectare per cropping system) to evaluate the risk of N losses, and N input (kg N per hectare per cropping system) to guide farmers directly (figure 1). The N input should be equal to or higher than the N demand of the crop to produce a target yield, but lower than the N demand needed to achieve a potential yield under favorable conditions. Based on this consideration, the concept of Minimum N input (Min. N) for target yields and Maximum N input (Max. N) for potential yield was designed. In this study, the target yield is defined as the yield level that is needed to achieve the domestic food demand by 2030, which can be attained in farmers' fields. Potential yield is defined as the yield of an adapted crop variety when grown under favorable conditions without growth limitations from water, nutrients or diseases (Lobell *et al* 2009).

The N surplus is calculated as the difference between total N input and total N output of cropland at plot or regional scale (equation (1)). The input includes the N in synthetic fertilizers, manure, biological N fixation and atmospheric N deposition. Total output refers to the N in harvested crop products (Liu *et al* 2010, Bouwman *et al* 2013).

The N input equals the sum of crop N harvest and N surplus (equation (2)), assuming that changes in N stock in soil can be ignored on the long-term (Ju 2015). To avoid excess N losses, the N surplus should be constrained to below an adopted critical level. This critical N surplus has also been used to calculate the corresponding N input (Ju and Gu 2017, McLellan *et al* 2018). Thus, Min. N is defined as the N harvest of a target yield (i.e., the minimum level that meets future food demand and is attainable by farmers), plus the critical N surplus (equation (3)), and Max. N is defined as the N harvest at potential yield (highest yield under favorable conditions without growth limitations), plus the critical N surplus (equation (4)). This concept was designed to encourage farmers to improve yield and limit N losses. Thus total N input should not be less than Min. N or greater than Max. N.

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

$$N_{input} = N_{har} + N_{surplus} + soil\ N\ change\ in\ stock\ (\approx 0\ in\ long\ run) \quad (2)$$

$$Min.N = N_{har\_target\ yield} + critical\ N_{surplus} \quad (3)$$

$$Max.N = N_{har\_potential\ yield} + critical\ N_{surplus} \quad (4)$$

Where N_{fer}, N_{man}, N_{dep} and N_{fix} refer to N from fertilizer, manure, atmospheric deposition and biological N fixation, respectively. N_{har} means harvested N in crops. *Min. N* indicates the minimum N input. *Max. N* indicates maximum N input. $N_{har\_target\ yield}$ and $N_{har\_potential\ yield}$ refer to the harvested N at the target yield and the potential yield, respectively.

2.2. Classification of subregions in Chinese crop production

To consider the variations in soil and climate conditions of different ecological subregions, we adopted the ecological zones classification of three cereal crops (maize, wheat and rice) in China, which are based on climate, geography, soil types and agricultural management practices (Wu *et al* 2014a, Wu 2014b, Wu *et al* 2015; see supplementary information section 1, figures S1–S3 is available online at stacks.iop.org/ERC/2/075002/mmedia). These ecological zones cover most cereal production areas in China including 1486 counties for maize, 2096 counties for wheat and 1383 counties for rice.

2.3. Critical N surplus for different cropping systems

The key task of sustainable N management in cropland is controlling the N surplus within a sound range, to avoid soil N 'mining' or excessive N emissions (EU Nitrogen Expert Panel 2015, Mclellan *et al* 2018). Many studies have shown that there is an exponential relationship between N surplus, defined as N fertilizer input minus crop N uptake in grain and straw, and reactive N losses such as nitrous oxide (N_2O) emissions and nitrate leaching, and that these reactive N emissions remain relatively low if this 'fertilizer based' N surplus is equal to or smaller than zero (van Groenigen *et al* 2010, Chen *et al* 2014, Zhao *et al* 2016, Omonode *et al* 2017, Cui *et al* 2018). Consequently, we calculated the critical (total) N surplus as the sum of N from manure, deposition (Xu *et al* 2018), biological N fixation and returned straw in cereal production, according to the definition shown as equation (1) (detailed information is given in the supporting information), using a 'fertilizer based' N surplus of zero, table S1. The corresponding reactive N emissions under the critical N surplus were calculated by using relationships between nitrate leaching, nitrous oxide emission and ammonia emission and N surplus as shown in table S2. The relationships were taken from Chen *et al* (2014), who used a national dataset of 373 observations from 64 experimental sites in China, covering all the agroecological subregions defined above. The corresponding reactive N emissions under the derived critical N surplus level were calculated to verify if they are within the safe boundary of environment. These safe boundaries were in turn derived from Liu *et al* (2020a).

2.4. Potential and target yields

Various crop grow simulation models are used in China for predicting potential yields of cereals, including APSIM (The Agricultural Production Systems sIMulator), Hybrid-maize and DSSAT (decision support system for agrotechnology transfer) and ORYZA (Yang *et al* 2004, Li *et al* 2017, Deng *et al* 2019, Liu *et al* 2020b). In this study, we used the Hybrid-maize model for maize (Liu *et al* 2020b) and the ORYZA model for rice (Deng *et al* 2019). For wheat, the simulated potential yields greatly varied between models; therefore, we estimated the potential yield from the highest recorded yields published in the literature based on 213 sites in China (Liu *et al* 2016). The varieties, climate

Table 3. Reactive N emissions at the critical N surpluses of main cropping systems.

	Critical N surplus kg N ha^{-1}	Emissions at the critical N surplus kg N ha^{-1}		
		NO_3^--N leaching	N_2O-N	NH_3-N
Maize	75	25	1.1	36
Wheat	40	14	0.54	28
Rice	70	6	0.74	35
Safe emissions		18	—	42

and soil characteristics were fully considered in these simulations, and the potential yield records were extracted according to our ecological zone classification.

The projected cereal food demand by 2030 in China is 657 million tons (Chen *et al* 2014), while the annual domestic production was about 600 Mt in 2014–2018 (National Bureau of Statistics of China, 2014–2018). It has been estimated that the food requirements for 2030 can be met by realizing 75%–80% of the potential yield on the current planting area (Chen *et al* 2014, Deng *et al* 2019). Such a yield level is close to the attainable yield level and in line with the standard definition of target yield (80% of potential yield; see e.g. Van Ittersum *et al* 2013), since yields above this target include a risk of negative marginal benefit and low economic profits for farmers (Cassman *et al* 2003). We used 75% of the potential yield as the target yield in this study.

2.5. Farmers' practices in different regions

Current farming practices related to N input and crop yield were mainly derived from a farmer survey conducted in 2019. This questionnaire survey was conducted to determine the prevailing practices regarding chemical and organic fertilizer inputs, crop straw management, and crop yield. We selected 11 provinces from the intensive wheat, maize, rice production regions. In total, 2200 farmers were randomly selected from 264 villages in 44 counties. The villages and counties represented farm households with high, medium and low farm income. The survey covered 60% of the defined cereal production areas in China (16 of the 27 ecological subregions). We supplemented the dataset for the remaining subregions (e.g., Southwest of wheat, Upper Yangtze River of rice) by using results from extensive surveys conducted in the period 2005 to 2014, which included 7.3 million farm households in 31 provincial administrative regions (Zhang *et al* 2019). The N surplus for each individual farm was calculated using equation (1). Manure N input was calculated by multiplying the manure application rate with respective N contents (Records of Nutrients in Organic Fertilizer in China 1999). The information on atmospheric N deposition and biological N fixation was derived from literature (section 2.3). For each ecological subregion, the arithmetic mean values of N input, N surplus, and yield of farmers were determined to reflect the current state.

2.6. N harvest by crops

The N uptake in harvested products (grains) was calculated by multiplying the grain yield by the grain N content, while considering variation in N content with changes in yield (N content of grain under different yield levels are provided in supplementary table S6). For all crops, grain N content decreased as yield increased; for maize, the grain N content ranged between 11.4 g kg^{-1} and 13.8 g kg^{-1} (Hou *et al* 2012, Yan *et al* 2016), for wheat between 20.1 g kg^{-1} and 24.1 g kg^{-1} (Yue *et al* 2012), and for rice between 11.8 g kg^{-1} and 13.3 g kg^{-1} (Zhang *et al* 2017). The N contents were all determined in long-term field experiments at different sites adopting the latest varieties and management practices, and are supposed to be representative. The straw was returned to the field in most cases, according to recent investigations and straw removal was thus not considered in our study.

3. Results

3.1. Benchmarking N surpluses

According to our calculation, the critical N surplus was 75 kg N ha^{-1} for maize, 40 kg N ha^{-1} for wheat, and 70 kg N ha^{-1} for rice (table 3, supplementary information section 2, table S1). At the critical N surplus, the corresponding seasonal reactive N emissions in maize, wheat and rice cropping systems were 6–25 kg N ha^{-1} for NO_3^- leaching, 0.54–1.13 kg N ha^{-1} for N_2O emissions, and 28–36 kg N ha^{-1} for NH_3 emissions (table 3). Most of these N losses are within the safe range regarding environmental impact on water and air quality, with the exception of NO_3^- leaching from maize (25 kg ha^{-1}), which slightly exceeded the critical level of 18 kg ha^{-1}.

Table 4. The N input indexes and associated yield levels of maize in different sub-regions in China.

	N input rates			Yield level			
Regions[1]	Min. N rate Kg ha^{-1}	Max. N rate Kg ha^{-1}	Farmers N rate Kg ha^{-1}	Target yield Mg ha^{-1}	Potential yield Mg ha^{-1}	Yield of farmers Mg ha^{-1}	N Surplus of farmers Kg ha^{-1}
NE1	177	211	236	8.2	10.9	8.8	122
NE2	186	222	276	8.9	11.8	10.4	151
NE3	228	260	252	11.4	15.2	8.8	138
NE4	184	217	231	8.7	11.6	8.7	119
NCP1	204	246	223	11.3	15.0	7.2	139
NCP2	210	254	310	11.8	15.7	6.4	236
NW1	179	214	256	8.3	11.1	7.2	162
NW2	223	269	251	11.9	15.9	9.7	135
NW3	250	304	259	14.1	18.8	8.7	147
SW1	227	255	283	11.0	14.7	5.4	213
SW2	220	250	222	10.8	14.4	5.6	150
SW3	206	234	298	9.7	12.9	5.6	226

Table 5. The N input indexes and associated yield levels of wheat in different subregions in China.

	N input rates			Yield level			
Regions	Min. N rate Kg ha^{-1}	Max. N rate Kg ha^{-1}	Farmers N rate Kg ha^{-1}	Target yield Mg ha^{-1}	Potential yield Mg ha^{-1}	Yield of farmers Mg ha^{-1}	N Surplus of farmers Kg ha^{-1}
NE	146	179	154	4.7	6.3	4.6	57
NCP1	203	245	246	7.7	10.2	6.6	106
NCP2	197	231	241	7.1	9.5	6.6	101
NW1	195	225	241	6.9	9.2	5	135
NW2	162	199	349	5.4	7.2	6	222
SW	173	210	163	6.0	8	3.9	75
YR	183	223	244	6.5	8.6	5.1	135

Table 6. The N input indexes and associated yields of rice in different subregions in China.

	N input rate			Yield level			
Regions	Min. N rate Kg ha^{-1}	Max. N rate Kg ha^{-1}	Farmers N rate Kg ha^{-1}	Target yield Mg ha^{-1}	Potential yield Mg ha^{-1}	Yield of farmers Mg ha^{-1}	N Surplus of farmers Kg ha^{-1}
NE1-S	172	194	213	7.7	10.3	8.7	88
NE2-S	179	200	213	8.3	11.0	8.1	96
UYR-S	171	192	249	7.7	10.2	7.1	145
MYR-S	173	195	218	7.8	10.4	7.9	104
MYR-D	157	192	211	6.9	9.2	6.3	122
LYR-S	167	200	309	7.4	9.8	8.0	193
SC1-S	173	195	179	7.8	10.4	8.5	57
SC1-D	155	189	259	6.8	9.0	7.0	161
SC2-D	152	185	197	6.5	8.7	6.2	109
SW	157	192	182	6.9	9.2	6.9	85

The critical N surpluses and related reactive N losses are in the same range as those of the study of Liu *et al* (2020a) which derived the values using the planetary boundary concept (with the exception of N_2O emissions).

Currently, the average N surplus for maize, wheat and rice are 161, 119 and 116 kg N ha^{-1} respectively (tables 4–6; Results from surveys in 2014 and 2019). Hence, the average N surpluses were 65%–200% higher than the critical N surpluses. High N surpluses happened in all regions investigated for the three crops, with rice in South China as only exception.

3.2. N input indexes for three crops and associated management strategy

The average Min. N of maize was 208 kg N ha^{-1} (range 177–250 kg N ha^{-1}) and the Max. N was 245 kg N ha^{-1} (range 211–304 kg N ha^{-1}). For comparison, the average N input of farms across the different ecological zones was 263 kg N ha^{-1}, i.e., 7% higher than Max. N. The average maize yield on farmers' fields was 7.7 t ha^{-1} (arithmetic mean value of different regions), which was 55% of the potential yield and 36% less than the target yield (10.5 t ha^{-1} under Min. N). There were large regional differences, with some regions exceeding the Max. N, including Northeast spring maize (NE1, NE2, NE4), North China Plain summer maize (NCP2), Northwest rain-fed area maize (NW1) and most Southwest area maize fields (SW1, SW3), while the yields were still lower than the target levels except Northeast spring maize (NE). In these regions, current yields will have to increase by 36% to meet the target level, and N input will have to decrease by 20%–30% to meet Min. N. The current N application rate in other regions was less than the Max. N, but the yields will need to increase by 50% on average to meet the target level.

For wheat, the average Min. N was 180 kg N ha^{-1} (range 146–203 kg N ha^{-1}) and the Max. N was 216 kg N ha^{-1} (range 179–245 kg N ha^{-1}). The average N application of farmers' fields was 234 kg N ha^{-1}, which was 10% higher than Max. N. The average wheat yield of farmers' fields was 5.4 t ha^{-1}, which is 36% less than the potential yield (8.4 t ha^{-1}), and 17% less than the target yield (6.3 t ha^{-1}). Farmers' N input in regions such as North China Plain Rainfed Area (NCP2), Northwest (NW), and Yangtze River (YR) exceeded Max. N, while yields were still lower than the target level. In these regions, wheat yields will have to increase by 16% to achieve the target yields, and N inputs have to decrease by 27%–31% to achieve Min. N. The N application rate in other regions was below the Max. N, while the yields will need to increase by on average 24% to meet the target yields.

Average Min. N for rice was 166 kg N ha^{-1} (range 152–179 kg N ha^{-1}) and Max. N was 193 kg N ha^{-1} (range 185–200 kg N ha^{-1}). Average N input in farmers' fields across different ecological zones was 213 kg N ha^{-1}, i.e., 9% higher than Max. N. The average rice yield in practice was 7.5 Mg ha^{-1}, equivalent to 76% of the potential yield (9.8 t ha^{-1}), and similar to the target yield for most subregions. In most regions, Max. N was exceeded, including in Northeast China, Yangtze River and South China double rice zones, with a N reduction potential of 16%–24%. The N input in South China single rice and Southwest was less than Max. N, and yield targets were achieved. The N input should be reduced by 9% in Southwest when compared with Min. N.

4. Discussion

4.1. The novelty of the proposed N management indexes

Many countries including China have established crop-specific N fertilization recommendations, but due to the weak guidance, verification and control, possible N overuse cannot be controlled effectively (Schröder *et al* 2003, Ju *et al* 2009). To achieve the targets of meeting food security and limiting N pollution within safe boundaries, desirable management indexes need to be combined, implemented and enforced. By introducing a set of 3 complementary indexes regarding N surplus and N inputs (Max. and Min. N), this study established an N management index system towards better N management in cereal production in China (maize, wheat and rice). The concept of using crop-specific and yield-specific N input limits ('N quota') to limit the freedom of farmers on N use (van Grinsven *et al* 2012) has been widely adopted in EU countries. However, the methodologies for determining input limits varies among countries, which reflect different expectations on crops yields as well as different notions on the environmental impacts of the unused N. In this study, we adopted the potential yield concept and link the associated N demand to Max. N to encourage farmers to increase the yield level. In addition, to avoid yield losses caused by 'blind N reduction policies', Min. N was introduced to ensure the basic food production demand. The combination of an 'N floor and N ceiling' concept was tailored to the situation in China. The concept may be used also in other countries, so as to improve their food sovereignty and environmental protection.

In this study, a simplified approach was adopted to determine the critical N surplus, based on statistical relations between N surplus and reactive N emissions (Chen *et al* 2014). The validity of the critical N surplus thus derived was verified by calculating and comparing the corresponding emissions with safe levels reported by Liu *et al* (2020a). This approach is consistent with the precautionary principle of environmental policy, which stipulates that robust preventive measures should be adopted to reduce risks when there are strong uncertainties and variations in environmental impacts (Athanassoglou and Xepapadeas 2012). Other approaches such as using critical N emissions to calculate the N surplus may provide more precise critical values but can be very complex with great variations in different regional contexts. For instance, The Netherland uses a critical NO_3^- leaching, which is derived from the safe concentrations in leachate (11 mg NO_3^--N L^{-1}), to calculate the N surplus threshold (van Dijk and ten Berge 2009). This method needs to calculate water seepage by combining irrigation, rainfall, soil texture and slope and other hydrological parameters for each specific region. In addition, it still needs to be confirmed that other environmental impact, such as the air quality influenced by NH_3 emissions are below the set limits.

Evidently, both the concept of Min. N and Max. N and the critical N surplus, as derived in our study, need to be tested further in practice. This requires long-term monitoring at different sites, because of the annual

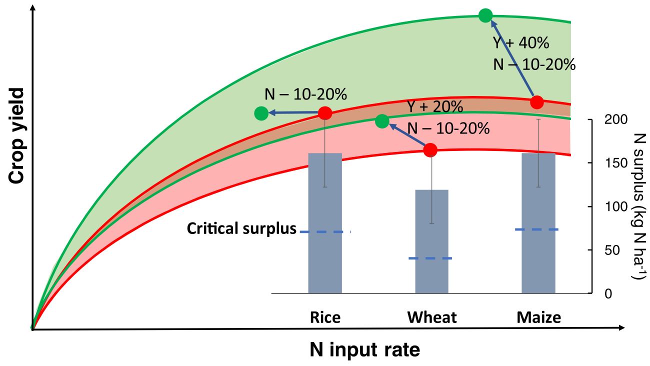

Figure 2. The average N surplus of farmers and improvement goals for three cereal crops. (The bars indicate current N surplus of three crops, dashed line indicates critical level of N surplus, red dots mean crop yield and N rate of farmers and green dots mean the target yield and N input rate).

variations and regional differences. Our approach for the derivation of a critical N surplus has been pragmatic, we have made use of an existing huge empirical database. Further studies are needed to estimate the uncertainties in the estimated critical N surpluses and to explore the sensitivity of the critical N surplus for changes in critical N emissions for different regions, and cropping systems (e.g. for single, double and triple crops in one year).

4.2. Applicability of the N management indexes

The mean critical N surpluses proposed are 75 kg N ha^{-1} for maize, 40 kg N ha^{-1} for wheat and 70 kg N ha^{-1} for rice. These critical N surpluses are rather similar to the values (40–100 kg N ha^{-1}) proposed by Zhang *et al* (2019), which were derived from optimal management practices. Current N surpluses are 65%–200% higher than the proposed critical N surpluses. This indicates that current N management practices have to be improved to achieve both the critical N surpluses and the target yields. Only the current yield level for rice reaches the target yield (figure 2). The N management targets are really challenging, i.e., reducing N inputs by 10%–20% and increasing yield by 36% for maize and by 20% for wheat, simultaneously (figure 2). Evidently, farmers will have to increase the N use efficiency enormously, from 40% to 54%–63% for maize, from 50% to 60%–75% for wheat, and from 50% to 58% for rice. This is a formidable but imperative task; these target NUE levels are required for achieving sustainable N management (Zhang *et al* 2015).

Spatial variations in practices and challenges are also large. Current N application rates substantially exceed Max. N in some regions, with N surpluses being greater than 200 kg N ha^{-1} and NUE being only 25%–35%. These regions include the summer maize in North China Plain rainfed areas and rice in Lower Yangtze River areas (tables 4–6). For these 'hotpots', implementing the proposed N management indexes of Min. N and Max. N will be challenging.

4.3. Implementing N management indexes

The N management indexes are meant for regional and local governments to set targets for reducing the application rates of synthetic N fertilizers. The indexes provide scientific justification for improving N management practices and at the same time may be used to assess the performances of local managers and targeted farmers in their strive to improve the N management. Progress may be evaluated at county level, because of the administrative system (note, there are some 3000 counties). Currently, the Chinese government is promoting the application of green production measures through result-oriented subsidies, e.g., subsidies for improving cultivated land quality (Chen *et al* 2019, Fu *et al* 2020). The proposed N management indexes can be used to identify candidate farmers with advanced performance. For example, a bonus could be provided to farmers that have an N input close to Min. N and a grain yield close to the target yield. In addition, the proposed N management indexes will help extension staff to provide more focused and reliable fertilization recommendations that consider both economic and environmental targets.

To facilitate the implementation, some step-by-step incremental goals may be needed. For example, using 80–90 kg N ha^{-1} as an initial benchmark N surplus for cereal crops, combined with broadened levels for Max. N. Thereafter, the N surplus and Max. N can be adjusted downward concomitant with improvements in N management practices. We evaluated the reactive N emissions for a N surplus of 80 kg N ha^{-1}, and found that ammonia emissions are close to critical levels, but nitrate leaching may exceed the safe level by 1–8 kg N ha^{-1} in wheat and maize cropping systems (Chen *et al* 2014, Liu *et al* 2020a). In Germany, a N surplus benchmark of 90 kg N ha^{-1} was implemented in 2006, which was lowered subsequently to 60 kg N ha^{-1} from 2009 onward

(Wolter *et al* 2011). At the same time, N use efficiency improving technologies and management practices will have to be promoted and adopted among farmers, including the '4R' fertilizer management stewardship, implying that fertilizers should be applied at the right rate, with the right type at the right place and the right time, while these measures should be customized within regional- or site-specific conditions (Li *et al* 2019).

A major challenge is the monitoring of the N management indexes at farm scale. Two possible approaches may be employed to evaluate farmers' practices. The first is a 'Fertilizer Accounting System', which can be used to record farmer's practices with regard to nutrient inputs and outputs. It requires a tight administrative system, involving local governments, fertilizer distributors, middle men and farmers. This system has been implemented in United States through the Comprehensive Nutrient Management Plan and in some EU countries like Denmark, Netherlands and Germany (van Dijk and ten Berge 2009, Ministry of Environment and Food of Denmark 2017), where farm size is much larger, and the number of fertilizer distributors and middle men is much smaller. For example, the Fertilizer Accounting System administrated by the Danish AgriFish Agency has been adopted by Danish farmers. It can be either mandatory or voluntary. About 90% of Danish farmers have registered fertilizer accounts, accounting for 96% of the total agricultural area of the country, while the non-registered farms are obliged to pay a tax on the purchase of fertilizers (Ministry of Environment and Food of Denmark 2017). Similar policies instruments can be implemented in China, with priority for commercial farms or cooperatives.

The second approach involves the monitoring of soil nitrate residue at harvest (Soil NO_3^- residue), which is a direct performance check. It has been shown that the nitrate residue in topsoil at harvest reflects N surplus, particularly in the drylands of northern China, where unutilized N remains in the soil in the form of NO_3^--N (Zhou *et al* 2016). According to long-term field observations in northern China in the wheat-maize rotation system, the accumulation of nitrate in the rooted topsoil (0–90 cm soil depth) at harvest is about 150 kg N ha^{-1} when N fertilizer input was applied at recommended rate (supplementary table S7, Cui *et al* 2008, Weng *et al* 2018). A meta-analysis study also revealed that the nitrate residue in the 0–1 m soil layer is about 100–150 kg N ha^{-1} (Zhou *et al* 2016). For a single crop, an average of 60–95 kg N ha^{-1} of soil residual nitrate in the 0–1 m soil layer was identified under the recommended N fertilizer application rate in long-term field experiments (Dai *et al* 2015, Xie *et al* 2018). The corresponding N surplus was about 80–90 kg N ha^{-1} for maize and 25–40 kg N ha^{-1} for wheat, which was consistent with the critical levels derived in this study. We suggest soil NO_3^- residues of maximally 150 kg N ha^{-1} and of 90 kg N ha^{-1} (0–90cm) for multiple- and single-cropping systems, respectively, to test if a reasonable N input management has been implemented. For proper evaluation, multiple years of observations (>3 years) will be needed, considering the large temporal and spatial variations.

The proposed Max. N and Min. N indexes are determined by crop yield levels, which are greatly influenced by climate and management conditions as well as by crop varieties (Lobell *et al* 2009). Therefore, the N management indexes need to be updated and refined regular to ensure their effective implementation. This could be facilitated by a national potential yield trials network and related databases, to be used also for improving and testing crop simulation models. In addition, the N input from biological N fixation, atmospheric deposition, and animal manure should be analyzed and reported to inform the nutrient management planning.

5. Conclusion

Crop and region-specific N management indexes have been derived from literature and data bases, so as to guide the necessary improvement of N management in cereal production in China (maize, wheat, and rice). The N management indexes are a combination of a critical N surplus and 'minimum' (Min. N) and 'maximum' (Max. N) N application rates. The critical N surplus is used as benchmark for evaluating the environmental impact of N use, Min. N and Max. N are used to guide farmers and to benchmark their N management practices. The indexes are interlinked and may have to be updated regularly, and in conjunction, because the N inputs are based on the N demand by the crops for different yield targets, and the critical N surplus reflect critical N emissions (which may become tightened over time).

The critical N surplus derived for maize was 75 kg N ha^{-1}, for wheat 40 kg N ha^{-1} and for rice 70 kg N ha^{-1}. Current N surpluses of farmers' fields were on average 65 to 200% higher than the critical N surplus levels. The Min. N derived for the three grain crops ranged from 166 to 208 kg N ha^{-1}, while Max. N ranged from 193 to 245 kg N ha^{-1}. Based on our analyses, yields of maize and wheat will have to increase by 20 to 40%, while yields or rice have to be sustained, and N inputs have to be reduced by 10 to 20%, to be able to achieve cereal grain food security and the set environmental targets impacts by 2030. To do so, an enormous increase in N use efficiency is required.

The N management N indexes are meant for regional and local governments to set targets for reducing the application rates of synthetic N fertilizers. At the same time, the indexes may be used to assess the performances of local managers and targeted farmers in their strive to improve the N management. Progress may be evaluated at county level. Monitoring involves fertilizer accounting and or measurements of soil mineral N in the top soil after harvests.

The reactive N emissions are derived by their relationship with the N surplus (NO_3^- leaching and N_2O) and N application rate (NH_3) given in table S2, according to the study of Chen *et al* (2014). The NO_3-N leaching and N_2O-N emission are calculated for a fertilizer-based N surplus of zero, whereas the NH_3-N emission is calculated at N fertilizer application rate that equals to crop N uptake (see table S3-S5). Safe emissions are derived from Liu *et al* 2020a.

The distinguished sub-regions are (Wu *et al* 2014a), Northeast China (NE1, NE2, NE3, NE4), North China Plain (NCP1, NCP2), Northwest China (NW1, NW2, NW3), and Southwest China (SW1, SW2, SW3), figure S1. See detailed information in supplementary information. The potential yields of maize have been derived from Liu *et al* 2020b. Yields and N inputs of farmers' fields have been derived from surveys conducted during 2014 and 2019.

The distinguished sub-regions referred to Wu 2014b, Northeast China NE, North China Plain (NCP1, NCP2), Northwest China (NW1, NW2), Southwest China SW and Yangtze River YP, figure S2. See detailed information in supplementary information. The potential yield referred to Liu *et al* 2016. Yield and N input rate of farmers are results from surveys conducted during 2014 and 2019.

The distinguished of subregions referred to Wu *et al* 2015, Northeast China (NE1, NE2), Yangtze River (Upper Yangtze River, UYR; Middle Yangtze River, MYR; Lower Yangtze River, LYR), Southwest China SW and South China (SC1, SC2), figure S3. The letter of S and D indicate the Single rice and Double rice respectively. For double rice, the results were calculated by averaging the early and late rice. See detailed information in supplementary information. The potential yields of rice referred to Deng *et al* 2019. Yield and N input rate of farmers are results from surveys conducted during 2014 and 2019.

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