Status of mineral nitrogen fertilization and net mitigation potential of the state fertilization recommendation in Chinese cropland

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ABSTRACT

The overuse of mineral nitrogen (N) fertilizer is widespread and affects greenhouse gas (GHG) emission in China. In 2013, the Ministry of Agriculture released the 'Recommendation for soil nutrient analysis-based mineral fertilizer application for corn, wheat and rice' (hereafter the Recommendation). The aims of this study were to estimate current mineral N fertilization and net mitigation potential (NMP) for the Recommendation in the three main crops in China. To estimate the NMP from the Recommendation concerning the fertilizer recommendation (FR) scenario, we designed a current situation (CS) scenario by conducting a field questionnaire survey across typical cropping regions in China. Our results indicate that annual N fertilization amount was 19.1 ± 1.2 (95% confidence interval) Mt N applied to the 66 M ha of Chinese cropland in the CS scenario and would decrease by about 7.1 Mt N in the FR scenario. This decrease might mitigate $37.4 \pm 5.2\%$ of GHG emissions including carbon dioxide (CO_2) from production and transport of N fertilizer, and nitrous oxide from soil due to N fertilization. Carbon (C) sequestration was $11.1 \pm 0.71 \text{ Tg C yr}^{-1}$ under both scenarios. The NMP was $23.9 \pm 3.4 \text{ Tg Ceq yr}^{-1}$ in the FR scenario and might offset $1.1 \pm 0.16\%$ of CO_2 emissions from fossil fuel combustion in 2011 in China. In conclusion, implementation of the Recommendation could be a sustainable and cost-effective N management system to mitigate GHG emissions in Chinese cropland.

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1. Introduction

Mineral nitrogen (N) fertilization contributes to global climate change by affecting greenhouse gas (GHG) emissions and mitigation (Lu et al., 2009; Schlesinger, 2009). The production and transport of N fertilizer emit carbon dioxide (CO_2) from the fossil fuel used (Lal, 2004; West and Marland, 2002). Moreover, the N fertilizer application to cropland results in more nitrous oxide (N_2O) emission from soil (Lal, 2007). However, N fertilization can also improve soil carbon sequestration (SCS) by increasing crop yield and residue input (Du et al., 2014). Therefore, altering N fertilization affects GHG emissions and mitigation in cropland.

Suitable N fertilization is difficult to predict, and hence excessive N fertilization is popular in Chinese croplands (Ju et al., 2009). This overuse of N fertilization reduces N use efficiency (Ma et al., 2008) and increases GHG emissions (Schlesinger, 2009). Some management systems have been developed to improve N fertilization practices (Jia et al., 2013; Ju et al., 2009; Peng et al., 2010). For example, site-specific N management reduces N fertilizer application by 32% compared with farmers' N management in rice (Peng et al., 2010). The 'Soil Testing and Formulated Fertilization system' was conducted at a national

scale, starting from 2005 and extended to 42.7 M ha of Chinese croplands in 2007 (Gao, 2008). Based on these studies, a fertilization system was released entitled 'Recommendation for soil nutrient analysis-based mineral fertilizer application for corn, wheat and rice' (hereafter the Recommendation) by the Ministry of Agriculture of the People's Republic of China (MOA, 2013). The Recommendation provides producing regions and crop yields specific criteria for suitable fertilizer management for each crop. Considering the regional heterogeneity of climate and cropping practices, the croplands were divided into four, five and five producing regions for corn, wheat and rice production, respectively (MOA, 2013). Therefore, the N fertilization suggestion in one province is available according to producing region and yield for each crop.

Any change in N fertilization has the potential to alter GHG emissions. However, the current status of N fertilization is little known in corn, wheat and rice throughout China. Furthermore, clarification is required concerning how implementation of the Recommendation would affect GHG emissions in cropland. Our hypothesis was that the implementation would decrease N fertilization and mitigate the resulting GHG emissions. Therefore, the objectives of this study were to estimate (1) the current mineral N fertilization and (2) net mitigation potential (NMP) of the Recommendation in these three crops in China. Thus, we conducted a field questionnaire survey across typical cropping regions in China during 2012–2013 and estimated the NMP of the Recommendation by designing two scenarios based on the survey and the Recommendation.

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2. Materials and methods

2.1. Study region

This study was conducted in mainland China, where rice, wheat and corn are the main cereal crops. In 2011, these crops occupied 54% of the total sown cropland area and 89% of the total cereal yield (NBS, 2012). Chinese cropland is divided into four cropping regions according to heterogeneity of climate, cropping systems and cultivation (Lu et al., 2009): Northeast, North, Northwest and South China (Fig. 1). The cropping system is mainly single crops of corn, rice or wheat in one year in Northeast and Northwest China. The rotation is mainly corn–wheat in North China and mainly wheat–rice or even wheat–rice–rice in South China (Lu et al., 2009). However, other cropping systems may be adopted in some provinces due to climate and small-scale farmers' choices, for example both single and double cropping systems in Shaanxi in Northwest China.

2.2. Field survey

During 2012–2013, we conducted a survey with a field questionnaire for farmers concerning cropland management in main crops across 2011 throughout mainland China (Fig. 1). The survey questions included crop yields and mineral N fertilizations (Table A1 in Appendix). Meanwhile, the triangulation questions, including crop yield and fertilizer price, were designed to ensure questionnaires' validity (Table A1 in Appendix). The survey comprised four processes: (1) pilot survey: since there is huge

spatial heterogeneity in fertilization due to climate, soil and cropping system in China, sampling size was a big challenge in the present study. We conducted a pilot survey in the counties of Yanzhou, Tengzhou and Tongcheng which are located in major production regions of wheat, corn and rice (Text A1 in Appendix). The pilot survey showed that N fertilization rate was $251 \pm 51 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (mean $\pm$ standard deviation, $n = 52$). The sample size (n) of formal survey was estimated with Formula (1) (Townsend, 2002):

$$n = (\text{SD} * t_{n-1, 0.05} / 95\% \text{ CI})^2 \quad (1)$$

where SD is standard deviation of the N fertilization rate of the pilot survey, $t_{n-1, 0.05} = 1.96$ obtained from t -tables and CI is confidence interval. Therefore, the sample size of 410 was suitable using an acceptable $95\% \text{ CI} = 5$. To control the risk of uncertain factors, we adopted 850 as the sample size in the formal survey; (2) interviewer training: interviewers were solicited from China Agricultural University and trained concerning interview principles and respondent selection. They were also given detailed explanations of survey questions in a uniform questionnaire. The interviewer of the pilot survey served as not only the interviewer in the formal survey, but also the guiders in the training of the members solicited; (3) formal survey: in each province, two to five counties were randomly selected according to cropland area, with at least one village per county. In each village, five farmers were selected with a simple random sampling method during field-labor time by the interviewers. The interviewers spoke with the farmers selected and filled in the improved questionnaires based on the pilot survey. The

Fig. 1. The distribution of counties investigated in China mainland. The agricultural regions are Northeast China, North China, Northwest China, and South China.

interviewers copied the paper versions of questionnaires to electronic files and returned both of them; (4) data entry and cleaning: we distributed 850 questionnaires and obtained 779 valid questionnaires covering 141 counties and these questionnaires included 347 for corn, 288 for wheat and 375 for rice. The invalid questionnaires referred to these without fertilization status or with the values being threefold standard deviations more than the national mean of mineral N fertilization rates. All survey data were copied from MS Word to MS Excel files for further analysis.

2.3. Field data source

Multiple cropping systems are popular in Chinese cropland especially in North and South China. For single cropping systems, the sown area in a year equals the cultivated area, while multiple cropping systems can double or triple the cultivated area. When we discuss the GHG emission and mitigation of N fertilization, the study area is constricted to the cropland where corn, wheat or rice are planted (A_i), i.e. the effective cultivated area for the three crops. Therefore, A_i was calculated according to Lu et al. (2009) as follows:

$$A_i = CAT_i * (\sum SA_{ij}) / SAT_i \quad (2)$$

where for province i , A_i is the cropland area with three crops; CAT_i is the total cultivated area; SA_{ij} is the sown area of crop j ; crop j is corn, wheat or rice; and SAT_i is the total sown area of all three crops in 2011 (NBS, 2012). All units of these areas are 10^3 ha.

2.4. Scenario design

Two scenarios of N fertilization were designed in this study: the current situation (CS) scenario based on our survey and the fertilizer recommendation (FR) scenario based on the Recommendation. The Recommendation provides ranges of suitable N fertilization in accordance with producing region, cropping system and crop yields (MOA, 2013).

2.5. Data analysis

2.5.1. N fertilization amount

The amount of N fertilizer application per unit area for one crop in each province was calculated using Formula (3):

$$ANR_{ij} = \sum_n (\sum_p (CN_{F_p} \cdot AF_{nF_p})) / M_{ij} \quad (3)$$

where for province i , ANR_{ij} (kg N ha^{-1}) is the amount of N fertilizer applied per sown hectare of crop j , crop j is corn, wheat or rice; CN_{F_p} (kg N kg^{-1}) is the N content of fertilizer F_p ; AF_{nF_p} (kg ha^{-1}) is the amount of fertilizer F_p application in 2011 for the n th farmer; and M_{ij} is the number of farmers investigated for the CS scenario. F_p and AF_{F_p} are showed in Table A1 in Appendix.

Therefore, the total amount of N fertilizer application (TNR, Mt N yr^{-1}) was calculated in each province using Formula (4):

$$TNR_i = \sum_j (ANR_{ij} * SA_{ij}) / 10^6 \quad (4)$$

where SA_{ij} (10^3 ha) is the sown area of crop j in province i .

Subsequently for the CS and FR scenarios, the annual amount of N fertilizer application for the three cereals per unit cropland area in each province (N_i , $\text{kg N ha}^{-1} \text{ yr}^{-1}$) was obtained using Formula (5):

$$N_i = TNR_i * 10^3 / A_i. \quad (5)$$

2.5.2. CO_2 emission

The production and transport of mineral N fertilizer require fossil fuel and emit CO_2 to the atmosphere. These CO_2 emissions were calculated using Formula (6):

$$EPT_i = (EPC + ETC) * TNR_i / 10^3 \quad (6)$$

where EPT_i (Tg C yr^{-1}) is the CO_2 -carbon (C) emission of mineral N fertilizer production and transport; EPC is the production emission coefficient of $2.143 \text{ t C t N}^{-1}$, provided by Chen et al. (2015); and ETC is the transport emission coefficient of $0.03 \text{ t C t N}^{-1}$, obtained from Zhang et al. (2013).

2.5.3. N_2O emission

The N fertilizer application to cropland increases N_2O flux from soil. The direct N_2O flux was estimated according to the method of IPCC (2006) and converted to CO_2 -C equivalents (EA , Tg Ceq yr^{-1}) using the global warming potential with a time span of 100 years:

$$EA_i = TNR_i * EFd_i / 28 * 44 * 298 / 44 * 12 * 10^{-3} \quad (7)$$

where EFd_i is the N_2O emission coefficient in province i . The coefficients are 0.0101, 0.00483, 0.00483 and 0.0119 in Northeast, North, Northwest and South China, respectively (Lu et al., 2008; Zheng et al., 2002).

2.5.4. Soil carbon sequestration

N fertilization can increase soil C storage by improving crop yield, followed by root and residue input. However, excessive N application does not increase yield and soil organic C content compared with optimum application (Brown et al., 2014; Hawkesford, 2014). Therefore, we assumed that the N fertilization in the FR scenario was sufficient for crop growth close to the maximum and hence SCS remained similar in both scenarios.

According to Lu et al. (2008, 2009), the SCS rate was suggested to have linear relationship with the N fertilization amount up to optimum fertilization (similar to FR scenario). Therefore, SCS was obtained using Eq. (8):

$$SCS_i = (a_i * N_i + b_i) * A_i / 10^6 \quad (8)$$

where SCS_i (Tg C yr^{-1}) is total C sequestration in province i ; a_i is the slope; and b_i is the intercept of the linear equation, with a and b given respectively as follows: 1.7385 and -104.03 for Northeast, 0.5286 and 1.5973 for North, 0.6352 and -1.0834 for Northwest and 1.1054 and 0 for South China (Lu et al., 2009).

2.5.5. Net mitigation potential

The total effective GHG emission in province i ($TEGE_i$, Tg Ceq yr^{-1}) was evaluated using Formula (9):

$$TEGE_i = EA_i + EPT_i - SCS_i. \quad (9)$$

In province i , the NMP_i (Tg Ceq yr^{-1}) and net mitigation rate (NMR_i , $\text{kg Ceq ha}^{-1} \text{ yr}^{-1}$) in the FR scenario were calculated as indicated in Formulae (10) and (11):

$$NMP_i = TEGE_{CS} - TEGE_{FR} \quad (10)$$

$$NMR_i = NMP_i / A_i \quad (11)$$

where $TEGE_{CS}$ and $TEGE_{FR}$ are TEGE in the CS and FR scenarios in province i , respectively.

2.5.6. Statistical analysis

To test the validity of the survey, a paired-sample t -test was conducted between values from the field survey and the China Statistical Yearbook (NBS, 2012) for yields of corn, wheat and rice, respectively — there were no significant differences between them. It was impossible

to validate N fertilization rates with farmers' purchase records, but a *t*-test showed no significant difference between annual N fertilization rates in counties surveyed in the present study and statistical data for 2010 from Agricultural Information Institution, Chinese Academy of Agricultural Sciences. We also compared the annual N fertilization in the three crops in 31 provinces between this study and other studies (Fig. 5). Paired-sample *t*-tests were also performed to test the effects of the Recommendation on N fertilizer application rate and amount and TEGE. Difference at $P < 0.05$ was considered significant for *t*-tests.

An uncertainty of quantity could be expressed as a 95% confidence interval of individual estimate (IPCC, 2000). In this study, we only quantitatively estimated the uncertainties related to the amount of N fertilization surveyed. The uncertainty of N_i (U_{Ni} , kg N ha⁻¹ yr⁻¹), i.e., the 95% confidence interval of N_i , was calculated with Formula (12):

$$U_{Ni} = \sqrt{\sum_j (SA_{ij} \cdot U_{Nij}/A_i)^2} \quad (12)$$

where for province *i*, U_{Nij} is 95% confidence interval of ANR_{*ij*} of crop *j*. Furthermore, the uncertainties of EPT_{*i*} (U_{EPTi}), EA_{*i*} (U_{Eai}) and SCS_{*i*} (U_{SCSi}) were estimated using Formulae (13)–(15), respectively and showed in Table A2 in Appendix:

$$U_{EPTi} = \sqrt{((EPC + ETC) \cdot A_i \cdot 10^6)^2 \cdot U_{Ni}^2} \quad (13)$$

$$U_{Eai} = \sqrt{(EFd_i \cdot A_i / 28 \cdot 298 \cdot 12 \cdot 10^6)^2 \cdot U_{Ni}^2} \quad (14)$$

$$U_{SCSi} = \sqrt{(a_i \cdot A_i \cdot 10^6)^2 \cdot U_{Ni}^2} \quad (15)$$

Finally, the uncertainty of NMP (U_{NMPi}) was calculated using Formula (16) (IPCC, 2000):

$$U_{NMPi} = \sqrt{\sum (U_{Xi} \text{ in CS})^2 + \sum (U_{Xi} \text{ in FR})^2} \quad (16)$$

where U_{XCSi} in CS and U_{XFRi} in FR represents the uncertainties of EPT_{*i*}, EA_{*i*} and SCS_{*i*} in CS and FR scenarios, respectively.

3. Results

3.1. N fertilization amount

In 2011, the cropland area of corn, wheat and rice was 66 M ha with a total annual N fertilization of 19.1 ± 1.2 Mt N yr⁻¹ throughout China in the CS scenario (Table 1). The amounts were 2.6 (Northeast), 5.3 (North), 1.5 (Northwest) and 9.5 Mt N yr⁻¹ (South). There were seven provinces with N fertilization of more than 1 Mt N yr⁻¹ in China. In the FR scenario, the total N application significantly decreased by about 37% to 11.9 ± 0.3 Mt N yr⁻¹ in China ($P < 0.001$). The annual decreases were ranked as 5.6 Mt (South) > 3.7 Mt (North) > 1.8 Mt (Northeast) > 0.8 Mt (Northwest). The N application amount exceeded 1 Mt N yr⁻¹ only in Henan Province. These results indicated that though there were overlaps between the CS and FR scenarios for some provinces (Table 1), N fertilization overuse was widespread across China in the CS scenario.

Our results showed that the spatial patterns of N fertilization amount per unit area (N_i) varied greatly across China (Table 1, Fig. 2a). In the CS scenario, the average N_i was 187 (Northeast), 268 (North), 227 (Northwest) and 380 kg N ha⁻¹ yr⁻¹ (South). The N_i exceeded 300 kg N ha⁻¹ yr⁻¹ in 14 provinces: 12 in South and two in North China. In the FR scenario, the average N_i reduced to 123

Table 1
Cropland area (A_i), nitrogen (N) fertilization per unit area of cropland (N_i) and total amount (TNR_{*i*}) in the current scenario (CS) and the fertilizer recommendation (FR) in China mainland.

Cropping region	Province	A_i	N_i (kg N ha ⁻¹ yr ⁻¹)		TNR _{<i>i</i>} (Mt N yr ⁻¹)	
		(k ha)	CS	FR	CS	FR
Northeast	Liaoning	2760	238 ± 167	141 ± 20	0.66 ± 0.46	0.39 ± 0.03
	Jilin	4058	240 ± 29	130 ± 27	0.97 ± 0.12	0.53 ± 0.06
	Heilongjiang	7579	140 ± 56	113 ± 19	1.06 ± 0.43	0.86 ± 0.07
North	Beijing	152	314 ± 43	164 ± 21	0.05 ± 0.01	0.02 ± 0.002
	Tianjin	276	207 ± 50	135 ± 14	0.06 ± 0.01	0.04 ± 0.002
	Hebei	3971	289 ± 49	199 ± 39	1.15 ± 0.19	0.79 ± 0.08
	Shanxi	2518	138 ± 24	111 ± 19	0.35 ± 0.06	0.28 ± 0.02
	Inner Mongolia	3345	162 ± 31	111 ± 24	0.54 ± 0.10	0.37 ± 0.04
	Shandong	4644	289 ± 35	186 ± 20	1.34 ± 0.16	0.86 ± 0.05
	Henan	4996	370 ± 52	274 ± 68	1.85 ± 0.26	1.37 ± 0.17
Northwest	Shaanxi	2359	239 ± 19	119 ± 26	0.56 ± 0.04	0.28 ± 0.03
	Gansu	1935	185 ± 30	102 ± 23	0.36 ± 0.06	0.20 ± 0.02
	Qinghai	113	248 ± 37	113 ± 21	0.03 ± 0.004	0.01 ± 0.001
	Ningxia	454	296 ± 105	146 ± 26	0.13 ± 0.05	0.07 ± 0.01
	Xinjiang	1553	241 ± 90	182 ± 19	0.37 ± 0.14	0.28 ± 0.02
	Shanghai	104	441 ± 40	318 ± 28	0.05 ± 0.004	0.03 ± 0.001
South	Jiangsu	2969	505 ± 102	303 ± 45	1.50 ± 0.30	0.90 ± 0.07
	Zhejiang	779	323 ± 49	220 ± 48	0.25 ± 0.04	0.17 ± 0.02
	Anhui	3450	418 ± 46	227 ± 47	1.44 ± 0.16	0.78 ± 0.08
	Fujian	518	506 ± 135	237 ± 51	0.26 ± 0.07	0.12 ± 0.01
	Jiangxi	1728	345 ± 55	268 ± 67	0.60 ± 0.10	0.46 ± 0.06
	Hubei	2096	382 ± 53	262 ± 45	0.80 ± 0.11	0.55 ± 0.05
	Hunan	2000	466 ± 76	304 ± 71	0.93 ± 0.15	0.61 ± 0.07
	Guangdong	1310	402 ± 37	222 ± 46	0.53 ± 0.05	0.29 ± 0.03
	Guangxi	1861	270 ± 33	165 ± 28	0.50 ± 0.06	0.31 ± 0.03
	Hainan	297	255 ± 36	128 ± 20	0.08 ± 0.01	0.04 ± 0.003
	Chongqing	846	353 ± 148	201 ± 17	0.30 ± 0.13	0.17 ± 0.01
	Sichuan	2879	364 ± 245	205 ± 30	1.05 ± 0.70	0.59 ± 0.04
	Guizhou	1543	233 ± 136	125 ± 16	0.36 ± 0.21	0.19 ± 0.01
	Yunnan	2660	357 ± 93	136 ± 14	0.95 ± 0.25	0.36 ± 0.02
	Tibet	64	133 ± 209	106 ± 19	0.01 ± 0.01	0.01 ± 0.001
Country		65,818	290 ± 18	181 ± 8	19.08 ± 1.17	11.94 ± 0.3

The values of N_i and TNR_{*i*} are showed as mean ± 95% confidence interval.

Fig. 2. Nitrogen fertilizer amount ($\text{kg N ha}^{-1} \text{yr}^{-1}$) under the current situation (CS) scenario (a) and fertilizer recommendation (FR) scenario (b) in Chinese cropland.

(Northeast), 188 (North), 131 (Northwest) and 223 kg N ha⁻¹ yr⁻¹ (South) (Table 1, Fig. 2b). The N_i was lower than 300 kg N ha⁻¹ yr⁻¹ for all provinces except Shanghai, Hunan and Jiangsu.

3.2. CO₂ emission

The CO₂ emission was 40.9 ± 2.5 Tg C yr⁻¹ from production and transport of N fertilizer in the CS scenario in China (Fig. 3, Table A2 in Appendix). These emissions exceeded 2.5 Tg C yr⁻¹ in Henan, Jiangsu, Anhui and Shandong (3.96, 3.21, 3.09 and 2.88 Tg C yr⁻¹, respectively). In the FR scenario, the total emissions decreased by about 37% to 25.6 ± 1.2 Tg C yr⁻¹ in China. The emissions decreased by more than 1 Tg C yr⁻¹ in Henan, Shandong, Anhui, Jiangsu and Yunnan.

3.3. N₂O emission

The total N₂O emission was 22.2 ± 1.6 Tg Ceq yr⁻¹ in the CS scenario and decreased to 13.6 ± 0.4 Tg Ceq yr⁻¹ in the FR scenario throughout China (Fig. 3, Table A2 in Appendix). This emission decrease was more than 10% for all provinces. The emission decrease exceeded 1 Tg Ceq yr⁻¹ in Heilongjiang, Jiangsu and Anhui.

3.4. Soil carbon sequestration

The SCS was 11.1 ± 0.7 Tg C yr⁻¹ in both scenarios due to N fertilization throughout China (Fig. 3, Table A2 in Appendix). The SCS was more than 0.51 Tg C yr⁻¹ in two provinces in Northeast China (Heilongjiang and Jilin), three in North China (Henan, Shandong and Hebei) and

six in South China (Jiangsu, Anhui, Hunan, Sichuan, Hubei and Jiangxi). The sum of SCS in these provinces represented about 68% of China's sequestration. Meanwhile, SCS was lower than 0.25 Tg C yr⁻¹ in any province of Northwest China.

3.5. Net mitigation potential

The total NMP was 23.9 ± 3.4 Tg Ceq yr⁻¹ in the FR scenario (Fig. 3). The NMP exceeded 1 Tg Ceq yr⁻¹ in nine provinces: Jilin of Northeast China; Henan, Shandong and Hebei of North China; and Anhui, Jiangsu, Yunnan, Sichuan and Hunan of South China. The sum of NMP in these provinces contributed about 62% of the national NMP. The average NMR was 360 kg Ceq ha⁻¹ yr⁻¹ in China with a range of 72–974 kg Ceq ha⁻¹ yr⁻¹ across all provinces (Fig. 4). The NMR was more than 500 kg ha⁻¹ yr⁻¹ in seven provinces of South China: Jiangsu, Anhui, Fujian, Hunan, Guangdong, Sichuan and Yunnan.

4. Discussion

4.1. N fertilization amount

Our results indicate a spatial variation and overuse of N fertilization in corn, wheat and rice across China. The results were supported by other studies of fertilization of these three crops (Chai et al., 2013; Huang and Tang, 2010; Lu et al., 2009) (Fig. 5). The annual N fertilization in these other studies, calculated using the method of the present study, showed a very similar trend among 31 provinces, though the national-

Fig. 3. Greenhouse gas emissions and carbon sequestration in 31 provinces, municipalities, and autonomous regions in China mainland. For each province, the left column represents the values under the current situation scenario (CS), and the right column represents values under the fertilizer recommendation scenario (FR). EPT: greenhouse gas emission from production and transport; EA: soil N₂O emission; SCS: soil carbon sequestration. All units of these values are Tg Ceq yr⁻¹.

Fig. 4. Net mitigation rate (NMR, kg Ceq ha⁻¹ yr⁻¹) in fertilizer recommendation scenario in China cropland.

scale rate in the present study (290 kg N ha⁻¹ yr⁻¹) was higher than 287 (Chai et al. 2013), 272 (Huang and Tang 2010) and 212 kg N ha⁻¹ yr⁻¹ (Lu et al., 2009). Therefore, our survey was applicable to N fertilization in China at a large spatial scale. In this study, the annual N fertilization in South and North China was higher than in Northeast and Northwest China, which is consistent with the conclusion of Tian et al. (2011). This higher annual N fertilization is mainly attributed to

multiple cropping systems and higher economic levels in South and North China (Zhang et al., 2013). Meanwhile, excessive fertilization is widespread in Chinese croplands (Gao 2008; Zhang et al., 2008). From 2000 to 2011, the total N fertilizer applied to the three crops increased from 16 Mt N yr⁻¹ (Huang and Tang, 2010) to 19.1 ± 1.2 Mt N yr⁻¹ as determined in the present study. Ju et al. (2009) indicates that N fertilization could be reduced by 30%–60% without yield loss in South and

Fig. 5. Annual nitrogen fertilization (kg N ha⁻¹ yr⁻¹) in China's cropland of corn, wheat and rice in 2011 (this study), 2005 (Lu et al., 2009) and late 1990s (Chai et al., 2013; Huang and Tang, 2010).

North China based on field experiments. During 2005–2007, an on-farm study also implied that optimal N fertilization decreased from 369 to 117 kg N ha⁻¹ yr⁻¹ without yield loss during wheat growing season, together with a reduction in N loss from 123 to 30 kg N ha⁻¹ yr⁻¹ in the North China Plain (Cui et al., 2011). According to quantitative relationships among core N fluxes in the crop root zone, the suitable N fertilization rate is 60% of the conventional rate in the North China Plain (Ju and Christie, 2011). These results are consistent with our estimation that the annual N fertilization in the FR scenario could be reduced by 35% compared to the CS scenario in the North China Plain. Therefore, implementation of the Recommendation might significantly reduce N fertilization without crop yield loss in China.

Our survey was across typical agricultural regions of China, but some factors may introduce uncertainties to the N fertilization estimation throughout the cropland. First, though annual N fertilization showed a similar trend among different studies, there were some exceptions due to sampling methods (Fig. 5). In the case of Shandong province, the average N fertilization of 289 kg N ha⁻¹ yr⁻¹ in this study was a little more than that of 252 kg N ha⁻¹ only for corn production in 2009 for 474 non-trained farmers (Jia et al., 2013). Furthermore, we also found that N fertilization for some farmers was lower than the national recommendation (Table 1). Therefore, it would be better if more surveys were conducted in the future. Second, other inputs of N sources, including straw and manure, can also increase soil N content (Basche et al., 2014; Maillard and Angers, 2014). Hence, N fertilization in the FR scenario may be overestimated compared to the optimum N fertilization. Finally, estimation in only three crops cannot draw a full picture of N fertilization in all cropland of China. Therefore, further research is required to widely investigate N fertilization across China, including inputs of other N sources and crops.

4.2. CO₂ emission

The reduction of N fertilization would also decrease the CO₂ emissions from production and transport of N fertilizer. Our study shows that this emission contributed to 60% of the total GHG emissions from N fertilization in the CS scenario. The NMP for transport and production in our study was 15.3 ± 3.4 Tg Ceq yr⁻¹ in the FR scenario, which was lower compared with 24 and 39 Tg Ceq yr⁻¹ for N application levels of 150 and 110 kg N ha⁻¹, respectively, in Chinese cropland using the same three crops (Chai et al., 2013). The production of N fertilizer in China consumes more fossil fuel than in developed countries due to low energy efficiency and outdated technology (Kahrl et al., 2010). Hence, improvements in N fertilizer production technology could mitigate 44 Tg Ceq yr⁻¹ in N fertilization to Chinese cropland using similar crops (Zhang et al., 2013). These studies indicate that implementation of the Recommendation, together with technical improvements in N fertilizer production, will mitigate even more CO₂ emissions from production and transport in China.

4.3. N₂O emission

Soil with N fertilizer input is one source of N₂O emissions on a global scale (Linquist et al., 2012; Venterea et al., 2011). Six field trials of wheat growth showed a linear relationship between mineral N fertilization (0–400 kg N ha⁻¹) and cumulative N₂O emissions measured using a closed chamber method in Germany (Lebender et al., 2014). Compared to no N addition in rice paddies, the N fertilization of 150 and 250 kg N ha⁻¹ increased N₂O emission by 2.5 and 6 times, respectively, during 2005–2007 in the Yangtze River Delta in China (Yao et al., 2012). A meta-analysis showed that the N fertilization of 181 kg N ha⁻¹ increased N₂O emission by 78% compared with controls in China's croplands (Sun et al., 2015). Using the DNDC model, the fertilizer-induced N₂O emission was estimated at 25 Tg Ceq yr⁻¹ in Chinese agricultural soils in 1990 (Wang and Li, 2000). Lu and Tian (2013) estimated that N-induced N₂O emission in the 1990s was 28.3 Tg Ceq yr⁻¹ using a

coupled biogeochemical model in Chinese cropland. The estimation of N₂O emission (22.2 ± 1.6 Tg Ceq yr⁻¹) in the present study (CS scenario) was lower than that in these other studies. The reason is that the study of Wang and Li (2000) aimed at all agricultural soils and the study of Lu and Tian (2013) at cropland with six crops, while we focused on croplands with only three crops. Our results showed that N₂O emission could be mitigated by 8.6 ± 1.7 Tg Ceq yr⁻¹ under a 37% reduction of N fertilization, which represents about 36% of the NMP in the FR scenario. A smaller decrease in N₂O emissions (5.5 Tg Ceq yr⁻¹) was found by Wang and Li (2000) under a 50% reduction of N fertilization (about 8.2 Mt) in 1990; while in the study of Chai et al. (2013), the mitigation potential in the late 1990s was 4.9 and 8.1 Tg Ceq yr⁻¹ under N fertilizer application levels of 150 and 110 kg N ha⁻¹, respectively, in China's cropland. These mitigation potentials differed between the present study and other studies due to different estimation methods of N₂O emission and periods of N fertilization; however, all these studies demonstrate that a reduction of excessive N fertilization can mitigate N₂O emissions from cropland.

4.4. Soil carbon sequestration

The N fertilization can increase soil C storage by increasing crop productivity and resultant residue input (Lu et al., 2011b), but crop yield is also determined by photosynthetic efficiency, water supply and genetic properties (Hawkesford, 2014). An N fertilization threshold that enables crops to reach maximum yields exists. The fertilization exceeding the threshold does not increase yield and improve C sequestration rate compared to optimal fertilization (Hawkesford, 2014; Brown et al., 2014). The SCS induced by N fertilization in the present study (11.1 ± 0.7 Tg C yr⁻¹) was slightly lower than the 12 Tg C yr⁻¹ of Lu et al. (2009). This difference can be explained in two ways: one is that the N fertilization of the Recommendation in the present study was lower due to being based on national testing of soil for formulated fertilization technology (Chen et al., 2014), and the other is that excessive N fertilization cannot sequester more C to the soil in the present study.

Our result indicated that SCS presented a consistent spatial pattern with N fertilization across China. This result was also found in the effect of N deposition on SCS in Chinese terrestrial ecosystems (Lu et al., 2011a). The SCS estimations in the present study depend on the empirical formulae based on long-term experiments in the four cropping regions. This division of the cropping regions may mask some spatial heterogeneity of SCS properties across China. However, this method is a most suitable analysis according to current data availability. Furthermore, the soil pool has a finite capacity to store organic C (Six et al., 2002) and other organic inputs can increase soil C storage. These factors can increase uncertainties of SCS estimation in our study.

4.5. Net mitigation potential

Our results showed that implementation of the Recommendation might have a potential to significantly mitigate GHG emission by reducing N fertilization. In this study, the NMP of the FR scenario (23.9 ± 3.4 Tg Ceq yr⁻¹) was higher than that in similar crops in the studies of Chai et al. (2013) and Huang and Tang (2010), both of which estimated NMP by comparing with the N fertilization level in the late 1990s. In the study of Huang and Tang (2010), the NMP was 16 Tg Ceq yr⁻¹ under a 50% improvement of N use efficiency (6.6 Tg N yr⁻¹ reduction); while NMP was 19 Tg Ceq yr⁻¹ under the N fertilization of 110 kg N ha⁻¹ in each cropping season in Chinese cropland (Chai et al., 2013). The higher NMP in our study is mainly due to the almost 19% increase of N fertilization over 10 years across all Chinese cropland (NBS, 2012). The NMP of this study can offset 1.1 ± 0.16% of China's CO₂ emissions from fuel combustion in 2011 (IEA, 2013). Moreover, reducing N fertilization can decrease other adverse global effects, for example atmospheric N deposition (Liu et al., 2013) and soil acidification (Guo et al., 2010) due to excessive N fertilization. Therefore, the implementation of the

Recommendation could be an eco-friendly N fertilization management in China.

In this study, some factors might change during reducing the amount of N fertilizer (as in the Recommendation), for example, soil carbon sequestrations and N₂O emission factors. In addition, there are other practices of N fertilization that affect GHG emission and mitigation. These practices included choice of fertilizer type, fertilization timing and placement (Millar et al., 2010; van Kessel et al., 2013). All these can introduce uncertainties in the estimation of NMP of the FR scenario in the present study. The effects of these practices on GHG dynamics require further field experiments concerning fertilization. Based on these experiments, direct measurements of changes of soil C fractions and GHG emissions will improve preciseness and spatial heterogeneity of model datasets.

5. Conclusion

Our results indicate that N fertilization level was 19.1 ± 1.2 Mt N for the cropland of corn, wheat and rice throughout China in 2011. This amount could decrease by 7.1 ± 1.3 Mt N yr⁻¹ in the FR scenario. This decrease might mitigate 37% of the CO₂ emissions from production and transport of N fertilizer, and about 37% of N₂O emission from soil due to N fertilization. The NMP of the FR scenario could be 23.9 ± 3.4 Tg Ceq yr⁻¹ and might offset $1.1 \pm 0.16\%$ of China's CO₂ emissions from fossil fuel combustion in 2011. The overall results demonstrate that implementation of the Recommendation could be a sustainable and cost-effective N management system in China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.agsy.2016.03.012>.

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