Nitrogen application rates need to be reduced for half of the rice paddy fields in China

Dan Zhang [a, 1], Hongyuan Wang [a, 1], Junting Pan [a, 1], Jiafa Luo [b, 1], Jian Liu [c], Baojing Gu [d], Liu Shen [a], Limei Zhai [a], Stuart Lindsey [b], Yitao Zhang [a], Qiuliang Lei [a], Shuxia Wu [a], Pete Smith [e,*], and Hongbin Liu [a,*]

[a] *Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, P. R. China*

[b] *AgResearch, Ruakura Research Centre, 10 Bisley Road, Hamilton 3214, New Zealand*

[c] *Department of Plant Science, Pennsylvania State University, University Park, Pennsylvania 16802, USA*

[d] *Department of Land Management, Zhejiang University, Hangzhou 310058, People's Republic of China*

[e] *Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK*

∗Corresponding authors.

E-mail addresses: liuhongbin@caas.cn (H. Liu), pete.smith@abdn.ac.uk (P. Smith);

[1] These authors contributed equally to this work.

ABSTRACT

Increasing nitrogen (N) application to croplands in order to support growing food demand is a major cause of environmental degradation. However, evaluations of suitable N application rates based on environmental benefit have rarely been carried out for paddy-rice at a national scale in China. To address this challenge, we investigated the N application status in 1531 counties covering the main agroecological areas for rice growing in 2008, and conducted 12 field experiments containing 3 rice cropping systems with six N rates for 3 years (2011–2013). Results showed that the highest yields for rice were 5.8–8.6 Mg ha^{-1} with N rates of 209.4–289.8 kg N ha^{-1}. Compared with the N rate for the highest yield (YHN), the environmentally optimal N rate (EnON) was lower by 20–39% and the corresponding N loss was reduced by 21–45%, while ensuring 95–99% of the highest crop yield. In China, the N inputs to paddy fields exceeded the YHN and EnON rates by 10% and 45%, respectively. After adjusting the N rate to paddy fields to the EnON rate, the N amount used in China and the corresponding N lost would be reduced by 0.9 and 0.5 Tg N yr^{-1}, respectively, which enable highly efficient production of food with the lowest N loss possible. Thus, we suggest that N use rates for 45% of rice paddy fields in China, for which N application rates exceed the EnON rate, need to be reduced to mitigate environmental damage, and this can be done while still meeting China's food demand.

Keywords: Crop yield, rice, nitrogen rate threshold, nitrogen loss, food security, environmental benefit, non-point source pollution

1. Introduction

To meet the food and fiber demands of an increasing and gradually wealthier population, a series of policies were implemented to encourage synthetic fertilizer production and use in China during the last three decades (Li et al., 2013). However, nitrogen (N) fertilizer is substantially overused and misused in Chinese cropland, which is causing a series of environmental problems (Ju et al., 2009; Lu et al., 2015), such as greenhouse gas (GHG) emissions (Gu et al., 2012), eutrophication (Zhang et al., 2013), soil acidification (Guo et al., 2010), and a loss of biodiversity (Humbert et al., 2016; Zeng et al., 2016).

With the aggravation of environmental pollution, maintaining food production while reducing the detrimental effects of anthropogenic N application is an urgent priority for global food security and environmental sustainability (Erisman et al., 2011; Qiao et al., 2015). Ultimately, there is a need to balance the benefits derived from N applications with the associated environmental costs. The environmental cost assessment could provide guidance for emerging policy priorities in mitigating certain Greenhouse Gas (GHG) or reactive N (Nr) species, after quantifying both their release amounts and damage costs to ecosystems (Chen et al., 2011; Gu et al., 2012). However, previous studies have mostly focused on the optimal N rate to improve N use efficiency (NUE) and increase yield to its maximum potential (Xu et al., 2014), such as by testing the soil NO_3^--N content in the root zone (Cui et al., 2010), developing fertilizer recommendations based on soil testing, yield targets and crop responses (He et al., 2009) and fertilizer effect function equations (Sonar and Babhulkar, 2002), etc. Few studies have attempted to evaluate N input management and the associated environmental costs from rice production (Xia et al., 2016).

Rice is an important staple crop in China, playing a crucial role in food security. The global warming potential of GHG emissions and N loss from rice systems have been found to be several times higher than from either wheat or maize (Linquist et al., 2012). Thus, quantification of current N fertilization and improved N management practices and policies in Chinese rice production regions is of national and global interest (Wu et al., 2015). The rice planting area in China is extensive, with different crop rotations, such as a single rice crop per year in Northeast China, rice-upland rotation in the Yangtze River region, and double rice in South China. Furthermore, most Chinese farms are very small, with large variation in N rates, which makes it hard to determine the optimum N application rates for paddy-rice at a national scale in China (Zhang et al., 2013).

In this study, we investigated the current status of N management in 1531 counties, covering the primary agroecological regions of Chinese rice production in 2008, and conducted 12 field experiments with different N level practices for 3 years (2011–2013). The three questions we attempted to answer were: (i) What N rates achieve the highest rice yield and the optimal economic/environmental benefit for the single rice, rice-upland, double rice systems? (ii) What is the current level of N fertilizer application for paddy rice across China based on the above N rates? and (iii) What is the potential for reducing N application and N loss intensity using a reasonable management approach?

2. Materials and methods

2.1. Study Areas

The distribution of the 12 in-situ field sites is shown in Fig. 1. According to the natural climatic conditions, cropping system used and cultivation history, the 12 sites covered three types of rice cultivation: (i) single rice, mainly distributed in Northeast China, which is dominated by a temperate monsoon climate with an average annual temperature of 2.9–8.7°C and an annual precipitation of 350–700 mm; (ii) rice-upland (wheat/rape/vegetable) rotation, mainly distributed in the Yangtze River Basin, which is dominated by a subtropical monsoon climate with an average annual temperature of 14.8–17.3°C and an annual precipitation of 950–1500 mm; (iii) double rice, mainly distributed in Southeast China, which is dominated by a subtropical monsoon climate with an average annual temperature of 17–21°C and an annual precipitation of 1200–2000 mm. The double rice cultivation consists of early and late rice with growing seasons from April to July and from July to November, respectively.

The number of study sites in each cropping system was mainly determined by the total rice planting area and the heterogeneity of environmental factors and management practices. Accordingly, 1, 8 and 3 field sites were set up for the single rice, rice-upland rotation and double rice systems, respectively. The planting areas of the above three systems in China were 4.6, 11.1 and 10.9 million ha, respectively (NBS, 2014). Compared with the latter two systems, the single rice system is commonly concentrated over relatively small areas with little variation in climatic conditions and soil type. Therefore, only one representative field site was chosen for the single rice system in this study. In view of the large variations in climatic conditions in the rice-upland crop growing regions and different crops (wheat/rape/vegetable) used for rotation with rice, 8 field sites were chosen for the study.

Fig. 1

2.2. Field measurements

The experiments were conducted over a three crop cycle during 2011–2013, with a total of 211 site-year observations across China. The experiments included a total of six fertilization treatments: zero N-fertilizer (CK), local farmers' practice (FT), and another four treatments with 50, 67, 83, and 133% of FT. Although each site had 6 treatments, the local farmers' practice treatment (FT) included a range of fertilization rates due to variations in the local practice among various regions. Consequently, the rates for the treatments with 50, 67, 83, and 133% of the local FT rates also varied. Prior to rice transplantation, soil was irrigated and plowed for better separation and homogeneity, followed by basal fertilization. Based on local farmers' practices, some sites also applied tillering topdressing and anthesis topdressing fertilization. Basic information about climate, soil properties, and fertilization for each site is shown in Tables S1–2. At each experiment site, the plots (20–40 m^2 in area) were arranged following a randomized complete block experimental design with three replicates. At maturity, grain yield and above-ground biomass were sampled and measured for each plot, with five replicate plants being randomly taken and mixed together for each plot. Their N concentrations were determined using the Kjeldahl procedure (Peng et al., 2011).

2.3. Survey of N used

Representative farmers were selected for a face-to-face, questionnaire-based household survey in the First National Pollution Census Program of China in 2008. A total of 15,310 farmers (1531 counties) were selected for surveying of the N rate and planting area, which covered the main agroecological areas for rice in 18 provinces across China. In each province, 10 to 152 counties that covered the main planting region were selected, and 10 individual farmers were randomly surveyed in each county. All of these in-house surveys were conducted by agricultural extension staff. The rice planting area for each county was provided by the local agricultural bureaus, which had a good knowledge of local production data. Before the survey informed consent was obtained from each farmer.

2.4. Calculations

The N surplus and PFP_N (N partial factor productivity, in kilograms of grain per kilogram of N applied) were calculated as following equation:

$$N_{surplus} = N_{input} - N_{uptake} \qquad (1)$$

$$PFP_N = Yield\ /\ N_{input} \qquad (2)$$

where $N_{surplus}$ is the N surplus (kg N ha^{-1}), N_{input} is the N fertilizer application rate (kg N ha^{-1}), N_{uptake} is the aboveground N uptake by rice (kg N ha^{-1}), PFP_N is the kilograms of grain per kilogram of N applied (kg kg^{-1} N), *Yield* is the rice yield under N_{input}.

The N losses (NH_3 volatilization, N_2O emission, N runoff and leaching) were calculated using the following equations (Chen et al., 2014; Wang et al., 2018):

$$N_{NH3} = 0.0002 \times N_{input}^2 + 0.1319 \times N_{input} + 8.9249 \qquad (3)$$

$$N_{N2O} = 0.74\text{e}\hat{}(0.011 \times N_{surplus}) \qquad (4)$$

$$N_{runoff} = 8.69\text{e}\hat{}(0.0077 \times N_{surplus}) \qquad (5)$$

$$N_{leaching} = 6.03\text{e}\hat{}(0.0048 \times N_{surplus}) \qquad (6)$$

$$N_{total\ loss} = N_{NH3} + N_{N2O} + N_{runoff} + N_{leaching} \qquad (7)$$

where N_{NH3} is the NH_3 volatilization loss (kg N ha^{-1}), N_{N2O} is the N_2O emission loss (kg N ha^{-1}), N_{runoff} is the N runoff loss (kg N ha^{-1}), $N_{leaching}$ is the N leaching loss (kg N ha^{-1}), $N_{total\ loss}$ is the total N loss from paddy soil though the above mechanisms (kg N ha^{-1}).

The N loss ratio was calculated using the following equation:

$$R_N = \frac{C_N - C_0}{N} \times 100\% \qquad (8)$$

where R_N is the N loss ratio (%), C_N is the total N loss at each non-zero N application rate (kg N ha^{-1}), C_0 is the total N loss at the zero N application rate (kg N ha^{-1}), and N is N fertilizer application rate (kg N ha^{-1}).

The economic and environmental benefits were calculated using the following equations:

$$ECB = Y \times Yp - AI \qquad (9)$$

$$ENB = Y \times Yp - AI - NrDC \qquad (10)$$

Where ECB is the economic benefit (¥ ha^{-1}), ENB is the environmental benefit (¥ ha^{-1}), Y is the rice yield under each individual N application rate (kg ha^{-1}), Yp is the price of rice (¥ ha^{-1}), AI is the agricultural input (fertilizer, labor, seed, diesel oil and pesticides, ¥ ha^{-1}), NrDC is damage cost due to Nr losses (¥ ha^{-1}). Data from Xia *et al.*, (2016) was used to assess the environmental costs (¥) of N loss. The prices of food products and various agricultural inputs are shown in Table S3.

2.5. *Scenario analysis*

Excessive amounts of N fertilizers are being used in paddy fields, which increases production costs and causes environmental degradation (Deng et al., 2011; Chen et al., 2014). In order to predict the potential for reducing N consumption and N loss intensity, we conducted a scenario analysis with three N management approaches: YHN (N application rate to achieve highest yield), EcON (economically optimal N application rate) and EnON (environmentally optimal N application rate).

Scenario YHN would involve reducing the N application rate to the YHN rate in regions where it is currently higher than YHN. Scenario EcON would involve reducing the N application rate to the EcON rate in regions where it is currently higher than EcON. Scenario EnON would involve reducing the N application rate to the EnON rate in regions where it is currently higher than EnON.

2.6. Statistical analysis

The statistical data analyses and graphs were prepared using SPSS 19.0 statistical software (SPSS China, Beijing, China) and Origin 8.5 software (Origin Lab Ltd., Guangzhou, China) packages. Spearman’s correlation coefficients were used to test for significant correlations between N application rate and rice yield, total N loss, N surplus, economic benefit and environmental benefit. A p value less than 0.05 was considered to be statistically significant.

3. Results

3.1. Yield response to N application rate

Based on the 12 experimental sites, the N rate response curves for both N surplus and N loss induced by N fertilizer fitted concave quadratic models ($P < 0.001$, $R^2 = 0.85$–0.99) (Fig. S1–2), and the response curves for the rice yield, economic benefit and environment benefit induced by N fertilizer fitted convex quadratic models ($P < 0.001$–0.05, $R^2 = 0.15$–0.84) (Fig. S3–5).

The highest rice yields for the single rice, rice-upland crop rotation, and double rice (early and late rice) were 8.64, 8.64, 5.81 (early rice) and 7.67 (late rice) Mg ha^{-1}, respectively, with N application rates ranging between 209.4 and 289.8 kg N ha^{-1} (Fig. 2). Among the three rice-cropping systems, the YHN rate was highest for the rice-upland crop, and lowest for single rice. Furthermore, the N losses at the YHN rate were 66.7–116.1 kg N ha^{-1}, accounting for 23–34% of the N input. Compared with the YHN rate, the EcON rate was 6–17% lower, without reducing production. This corresponded to a 6–25% reduction in N loss. If the environment remediation costs of N pollution are taken into account, the EnON rate and corresponding N losses would further decrease.

The EnON rate achieved 95–99% of the yield potential with a rate 20–39% lower than the YHN rate. At the EnON rate the total N losses from paddy soil were reduced 20–45%.

Fig. 2

3.2. N application rates at county level

The results of the county-level investigations showed that the total amount of N applied to rice paddy fields in the whole country was 5.3 Mt in 2008, accounting for 19% of China's total N fertilizer consumption. The average N application rate was 192.3 kg N ha^{-1} (189.6–195.2 kg N ha^{-1}) (Fig. 3), and those of single rice, rice-upland, early rice and late rice were 176.0, 216.2, 165.7 and 185.8 kg N ha^{-1}, respectively. Among the provinces, the variation in N rate was very large, varying from 136.5 kg N ha^{-1} to 376.9 kg ha^{-1}. The highest N inputs were observed in Jiangsu and Hainan provinces, up to 376.9 and 358.3 kg ha^{-1}, respectively. For Heilongjiang, Guizhou, Sichuan and Chongqing provinces, the N inputs were less than 160 kg N ha^{-1} (Table S4). In China, the N rate for 10% of the paddy fields exceeded the YHN rate, and for 45% exceeded EnON (Fig. 4a). It is clear that N fertilizer application far exceeded the YHN rate in the Southern Area of Northeast China and in the lower reaches of the Yangtze River.

Fig. 3 and Fig. 4

3.3. Potential for reducing N loss and N application

The total amount of N lost from paddy fields was estimated at 2.0 Tg N yr^{-1}, derived from the investigation data in China, which accounted for 38% of the total N input to rice fields (Fig 4b and Fig. 5). NH_3 volatilization was the main pathway for N loss from paddy fields, and accounted for 58% of the total lost. The N lost through N runoff, N leaching and N_2O emission accounted for 28, 8 and 6%, respectively. The N management approach of applying N at the YHN value, if adopted in the regions that N rate exceeded this value, could reduce N fertilizer use by more than 0.3 Tg per year. Compared with the current situation, applying N at the YHN value would reduce annual N loss by 17% (Fig 4c). Of this, the amount of N lost through NH_3 emission, N runoff, N leaching and N_2O emission would be reduced by 9, 32, 1 and 62%, respectively. Further, if the N rate applied to the paddy fields was adjusted to the EnON rate, the amount of N fertilizer used would reduce by 0.9 Tg N yr^{-1}, and the subsequent N loss would reduce by 0.5 Tg N yr^{-1} (Fig 4d), through NH_3 emission, N runoff, N leaching and N_2O emission reductions of 19, 41, 1 and 70%, respectively.

Fig. 5

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4. Discussion

4.1. Rice yield

Grain yields at the same N application rate resulted in great temporal and spatial variation, and the yield ranges were −57% to 35% and −24% to 33% over time and space, respectively (Zhang et al., 2015). Although the highest yields of early (5.8 Mg ha^{-1}) and later (7.7 Mg ha^{-1}) rice in the double cropping system were lower, the highest yields (8.6 Mg ha^{-1}) in the single rice and rice-upland systems were achieved at the YHN rate, and were comparable to yield potentials in areas of the world with the most favorable conditions and intensive agronomic management, for example 9 Mg ha^{-1} in California (USA) (Grassini et al., 2013). However, high N surplus (36.3–176.1 kg N ha^{-1}) and low PFP_N (20.7–41.3 kg kg^{-1} N) were found when achieving maximum yields at the YHN rate (Table 1), indicating that inefficiency and environmental damage are associated with attempts to increase yields by increasing N inputs.

Table 1

Numerous studies have shown that the response of grain yield to N input fits a linear-plateau or convex quadratic model (Chen et al., 2011; Cui et al., 2013a; Zhang et al., 2015). Thus, a small decrease in the theoretical maximum achievable yield caused by reduction of N application rate will not severely reduce the grain yield in practice. For instance, no significant differences were observed in grain yield under N fertilizer application rates between 135–270 kg N ha^{-1} (Qiao et al., 2012). Through improved in-season root zone N management the required N rate was reduced from 300 to 160 kg N ha^{-1} without any yield losses (Lu et al., 2015). Our experiments demonstrated that the rice yield using the EnON rate achieved 95–99% of the highest rice yield potential, by reducing the amount of N applied by 20–39% compared with the YHN rate. More importantly, for all rice crops except early rice, when the EnON rate was used the N surplus dropped steeply by 39–79%, and PFP_N increased to 43.4–50.6 kg kg^{-1} N. These N use efficiencies are comparable to those of most ‘ecologically intensive’ systems worldwide (Chen et al., 2014).

With population and economic growth, demand for rice in China is expected to reach 218 Mt by 2030, by which time China’s population is expected to have stabilized (Chen et al., 2014). If farmers could achieve 95–99% of the highest rice yield potential using the EnON rate and using the same planting area as in 2008, by 2030 total production of rice would reach 221 Mt; exceeding the demand for direct human consumption. Such results imply that a substantial reduction in N input based on minimizing environmental damage would not significantly affect the rice yield.

4.2. Environmental effects

The Nr losses and GHG emissions from agriculture contribute substantially to atmospheric and water pollution in China and elsewhere (Chen et al., 2014). Using established empirical models, we evaluated total Nr losses and gas emissions per unit area (expressed as kilograms of N per hectare), and they showed a quadratic relationship with increasing N application rate. This showed that a decrease in N rate could reduce N loss. Our results demonstrated that the amount of N lost when the EnON rate was used was reduced by 21–45% from 74.8–112.3 kg N ha^{-1} to 59.1–70.4 kg N ha^{-1}, compared with the YHN rate. A root-zone N management strategy was also shown to reduce the required N application rate from 325 kg N ha^{-1} to 128 kg N ha^{-1}, while the intensity of Nr losses and GHG emissions was reduced by 80% and 77%, respectively (Cui et al., 2013b). This suggests that reducing N input is the most convenient and effective way to mitigate the environmental pollution derived from chemical fertilizer application.

Under current practice total Nr losses combined with gaseous emissions could be as high as 2.0 Tg yr^{-1}. If the EnON rate is widely adopted in the regions with a higher N rate, above the EnON rate, the N lost could be reduced by more than 0.5 Tg per year across China (Fig. 5), which would be equal to 10% of the total N input to rice fields. Enabling highly efficient production of food with the lowest possible environmental damage, the EnON rate can be used as a tool to guide use of N fertilizer for growing of rice.

4.3. Potentials for mitigation and management

Good infrastructure and readily available and relatively inexpensive N fertilizer facilitate application and promote overuse in China (Sutton and Bleeker, 2013). During the last decade, the global N fertilizer consumption increased by 22%, of which, a quarter (about 4.7 Mt) was attributed to China (FAO, 2017). Based on our survey, the average N application rate for rice production was not high, ca. 192 kg ha^{-1}, compared with the YHN rate (209–290 kg ha^{-1}) or the EnON rate (169–199 kg ha^{-1}). However, the average rice N surplus was 68 kg N ha^{-1}, which showed that farmers in China typically applied much more N than required by rice plants.

The differences in rice cropping systems and farmers’ differing habits bring about large variations in regional N application rate, ranging from <100 to more than 400 kg ha^{-1} (Fig. 3). In China, 10% and 45% of paddy fields received a rate of N application exceeding the YHN and EnON rates, respectively. Generally, the average N application to rice-upland crops was higher than the others, especially in the lower reaches of the Yangtze River (Fig. 4a). This region is widely recognized as a high N input area with farmers having strong agricultural material consumption capacity. The other high N input region was the Southern Area of Northeast China, in which the optimal N application rate to achieve the highest yield was less than in other regions due to high soil fertility. Although the average N input of this region was 176.0 kg N ha^{-1}, there were many fields for which the N input exceeded the YHN rate. More importantly, there has been poor synchrony between crop N demand and N supply, because most farmers still believe that more fertilizer and higher grain yield are synonymous (Meng et al., 2016). The yield gap in these regions was much larger, and increased agronomic inputs cannot close this gap, because it already has gone past a point of diminishing returns, in the case of fertilizer applications in particular (Cui et al., 2016). For these regions, the Chinese government should adopt appropriate management measures and interventions to limit the amounts of chemical fertilizer used and regulate farmers' production behavior, such as reducing fertilizer subsidies, providing technical assistance, and implementing incentive programs (Good and Beatty, 2011).

On the other hand, for the 5% of regions for which the N input is lower than 100 kg N ha^{-1}, achieving 90% of the highest rice yield potential, government policies in China could provide fertilizer recommendations for higher yields. In summary, to achieve reasonable N management goals for chemical fertilizer use in rice fields, site-specific recommendations for N application are required.

5. Conclusions

Our results demonstrated that the economically optimal rice N application rate was 169–199 kg N ha^{-1}. Compared with highest yield N application, the N input for economically optimal rice N management would be lower by 20–39% and the corresponding reduction in N loss would be 21–44%, while ensuring 95–99% of maximum crop yield. This provides evidence for making policies and protection measures to reduce N application in order to produce higher agronomical benefits and lower environmental losses. Based on the above N rate threshold, 45% of rice fields in China have received excess N. Using the above practice, the amount of N fertilizer used and the corresponding N lost would reduce by 0.9 and 0.5 Tg N yr^{-1}, respectively. This indicates that a negligible reduction in rice production would enable highly efficient production of food with the lowest N loss possible.

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Table 1 Nitrogen surplus, PFP$_N$ and N loss ratio under three scenarios for YHN, EcON and EnON

Cropping system	Site No.	YHN			EcON			EnON		
		N surplus (kg N ha^{-1})	PFP$_N$ (kg kg N^{-1})	N loss ratio (%)	N surplus (kg N ha^{-1})	PFP$_N$ (kg kg N^{-1})	N loss ratio (%)	N surplus (kg N ha^{-1})	PFP$_N$ (kg kg N^{-1})	N loss ratio (%)
Single rice	1	36.3	41.1	23.1	27.8	43.7	22.5	7.8	50.6	21.1
Rice-upland	8	123.3	29.7	30.3	84.6	35.5	26.9	35.4	46.3	22.4
Double rice										
Early rice	3	20.7	20.7	34.3	155	22.6	32.6	108	28.2	28.6
Late rice	3	30.3	30.3	33.9	136	32.9	25.5	80.2	43.4	24.6

Note: YHN, EcON and EnON represent the N application rates to achieve the highest yield, optimal economic benefit and optimal environmental benefit, respectively. Nitrogen partial factor productivity (PFP$_N$) is kilograms of grain per kilogram of N applied (Chen, et al., 2014).

Figure legend

Fig. 1 Geographical distribution of the 12 monitoring sites in China. Double rice was subdivided into early and late rice.

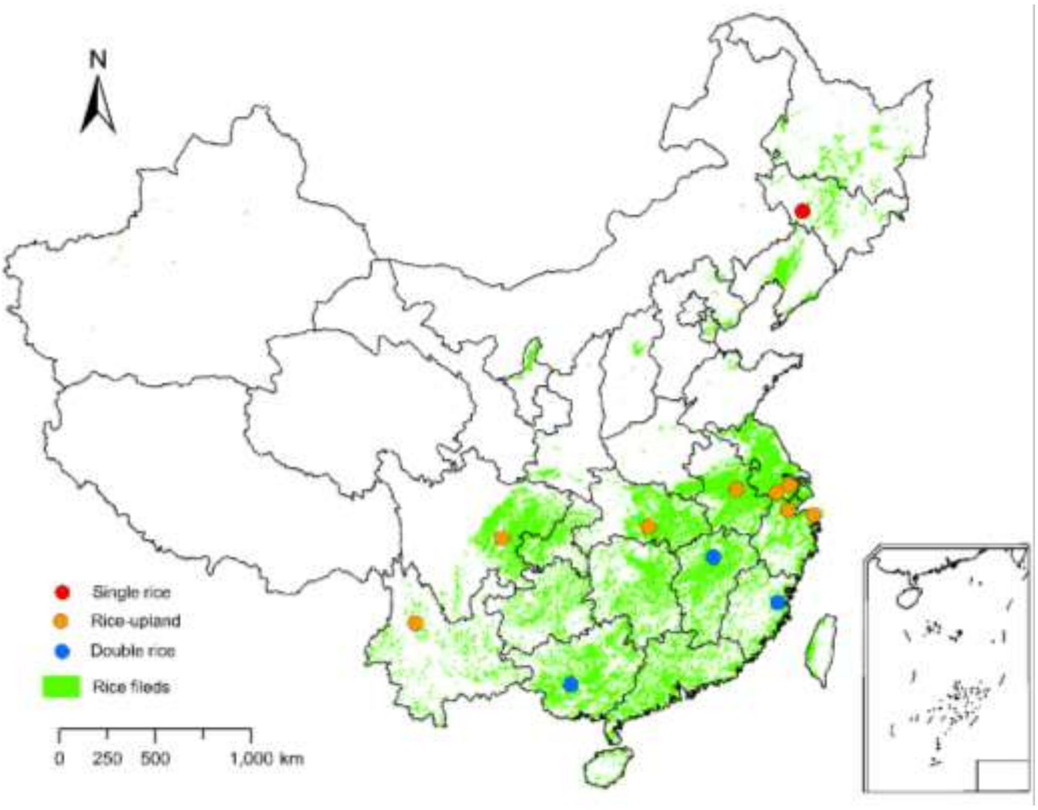
Fig. 2 Relationships between N fertilizer rate and rice yield, economic benefit or environmental benefit in the rice growing regions in China based on data from the 12 experimental sites. (a) Single rice; (b) Rice-upland crop; (c) Double rice (Early crop); and (d) Double rice (Late crop). The black points on the curves represent the highest rice yield, and corresponding yields for optimal economic and environmental benefits, and the red points represent the corresponding total N losses. The intersections of color thin-dash lines with the X axis indicate the corresponding N application rates.

Fig. 3 Distribution of N application rate in rice fields across China. Data is derived from the county-level investigations in 2008. County-rotation represents the total number of rotation systems in all counties under a certain range of N application rate. Most counties had more than one rotation system, so the total number of county-rotations (n value) was 2910 instead of 1531, which is the number of counties.

Fig. 4 Geographical distribution of N application and N loss from rice fields under different scenarios. (a) N application; (b) N loss at current situation; (c) N loss at YHN scenarios; and (d) N loss at EnON scenarios. Data is derived from the county-level investigations in 2008. YHN represents the N application rate to achieve highest yield, EcON represents the N application rate to achieve optimal economic benefit and EnON represents the N application rate to achieve optimal environmental benefit.

Fig. 5 N loss from rice under different scenarios. ”Current” represents the N loss in the current situation. “YHN” represents the N application rate to achieve the highest yield, “EcON” represents the N application rate to achieve the optimal economic benefit and EnON represents the N application rate to achieve the optimal environmental benefit.

506 Fig. 1


N
Single rice
Rice-upland
Double rice
Rice fileds
0
250
500
1,000 km

507

Fig. 2

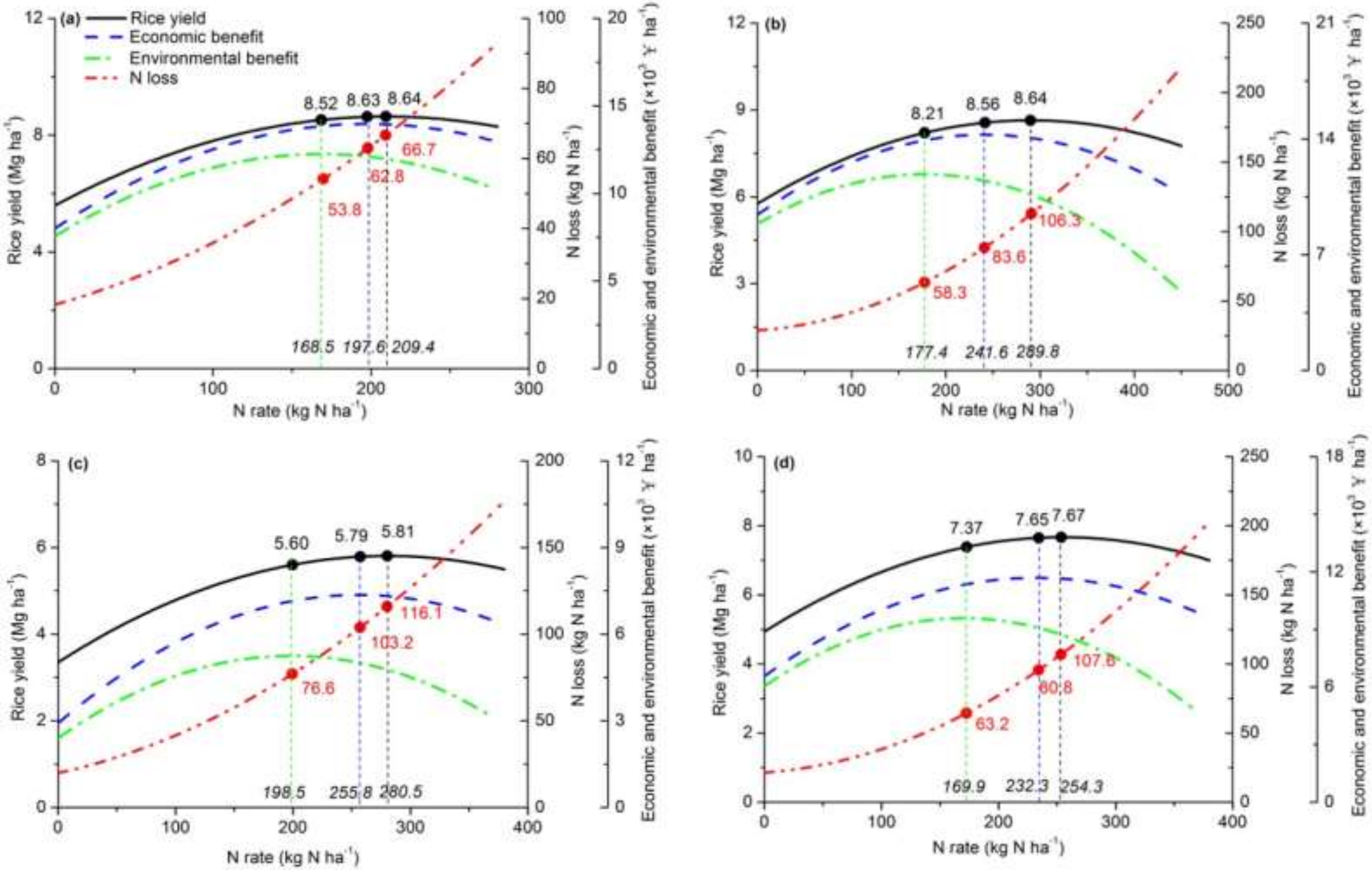

(a)
Rice yield
Economic benefit
Environmental benefit
N loss
8.52
8.63
8.64
66.7
62.8
53.8
168.5
197.6
209.4
Rice yield (Mg ha-1)
N rate (kg N ha-1)
N loss (kg N ha-1)
Economic and environmental benefit (×10³ ￥ ha-1)
0
4
8
12
0
100
200
300
0
20
40
60
80
100
0
5
10
15
20
(b)
8.21
8.56
8.64
106.3
83.6
58.3
177.4
241.6
289.8
Rice yield (Mg ha-1)
N rate (kg N ha-1)
N loss (kg N ha-1)
Economic and environmental benefit (×10³ ￥ ha-1)
0
3
6
9
12
0
100
200
300
400
500
0
50
100
150
200
250
0
7
14
21
(c)
5.60
5.79
5.81
116.1
103.2
76.6
198.5
255.8
280.5
Rice yield (Mg ha-1)
N rate (kg N ha-1)
N loss (kg N ha-1)
Economic and environmental benefit (×10³ ￥ ha-1)
0
2
4
6
8
0
100
200
300
400
0
50
100
150
200
0
3
6
9
12
(d)
7.37
7.65
7.67
107.8
90.8
63.2
169.9
232.3
254.3
Rice yield (Mg ha-1)
N rate (kg N ha-1)
N loss (kg N ha-1)
Economic and environmental benefit (×10³ ￥ ha-1)
0
2
4
6
8
10
0
100
200
300
400
0
50
100
150
200
250
0
6
12
18

Fig. 3

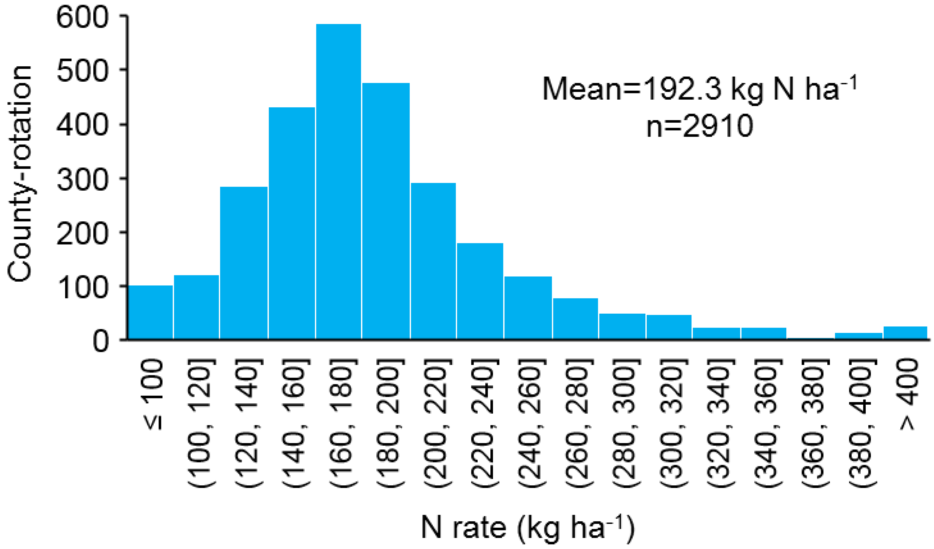

Mean=192.3 kg N ha-1
n=2910
County-rotation
600
500
400
300
200
100
0
≤ 100
(100, 120]
(120, 140]
(140, 160]
(160, 180]
(180, 200]
(200, 220]
(220, 240]
(240, 260]
(260, 280]
(280, 300]
(300, 320]
(320, 340]
(340, 360]
(360, 380]
(380, 400]
> 400
N rate (kg ha-1)

Fig. 4

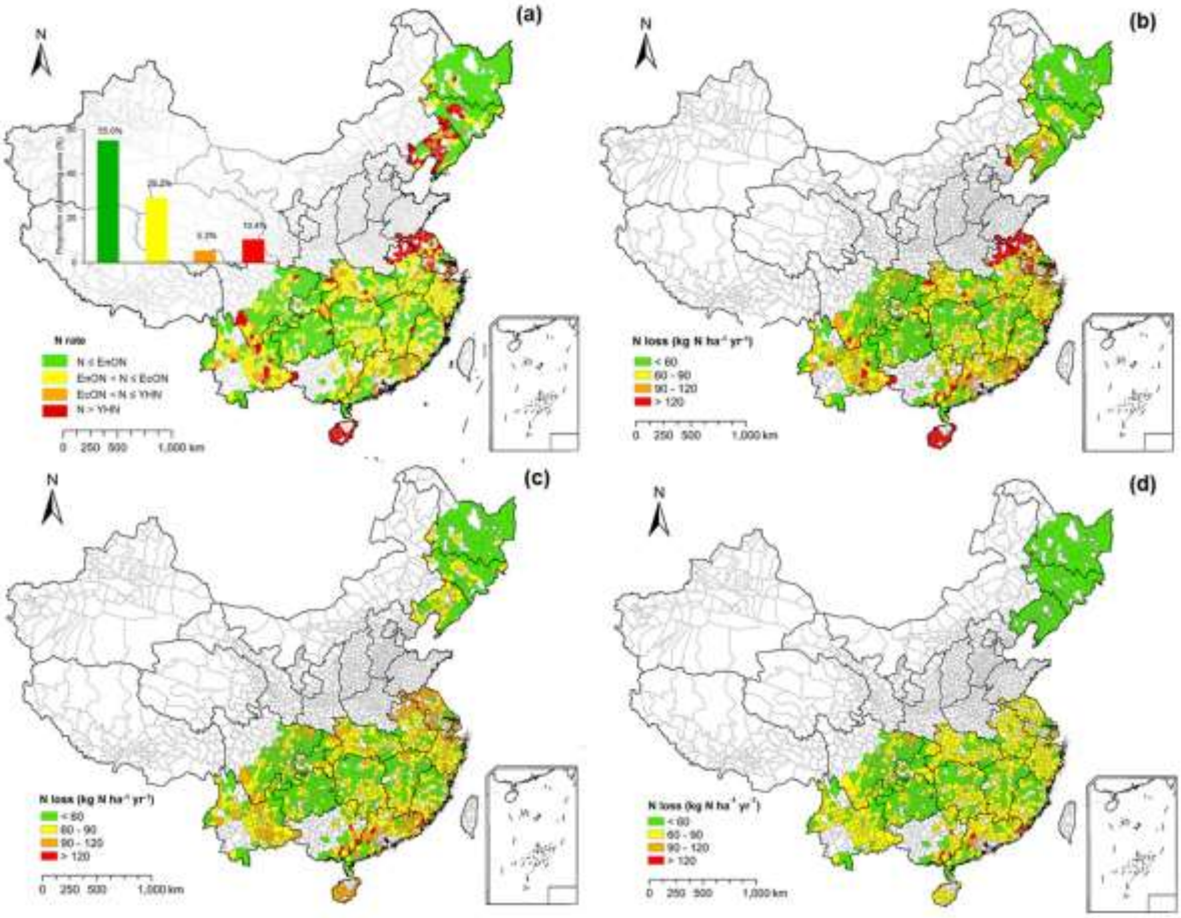
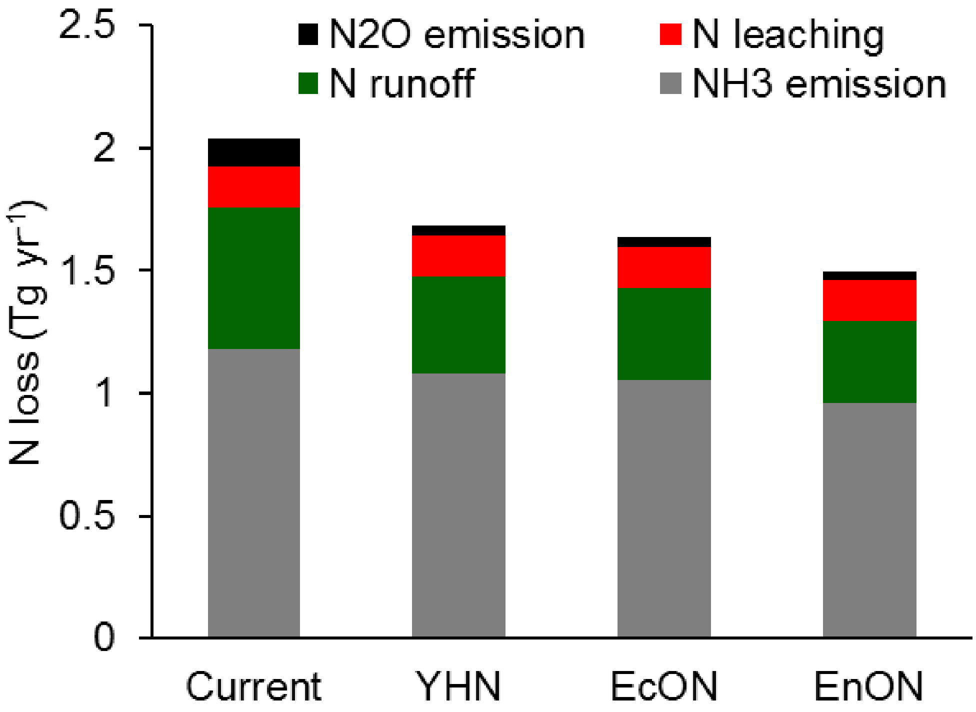

(a)
(b)
(c)
(d)
N
Proportion of planting areas (%)
0
20
40
60
55.0%
28.2%
6.2%
10.4%
N rate
N ≤ EnON
EnON < N ≤ EcON
EcON < N ≤ YHN
N > YHN
N loss (kg N ha⁻¹ yr⁻¹)
< 60
60 - 90
90 - 120
> 120
0 250 500 1,000 km

Fig. 5



N2O emission
N leaching
N runoff
NH3 emission
N loss (Tg yr^{-1})
2.5
2
1.5
1
0.5
0
Current
YHN
EcON
EnON