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Yield, nitrogen use efficiency and balance response to thirty-five years of fertilization in paddy rice-upland wheat cropping system

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Abstract: Optimal soil nitrogen management is vital to crop production and environment protection. Little knowledge is available on crop yield, nitrogen uptake, use efficiency and balance in paddy rice-upland wheat cropping system of China. A thirty-five-year long-term field experiment was designed with nine treatments, including an unfertilized treatment (control), nitrogen (N), phosphorus (P), potassium (K) fertilizer, manure (M), and manure combined with mineral fertilizer treatments. Crop yield, N uptake, use efficiency, and N surplus or deficit amount were determined. The results indicated that rice, wheat yield and N uptake amount in the manure combined with mineral fertilizer treatments were higher than that in the manure alone or mineral fertilizer alone treatments. N use efficiency was the highest in the treatment with manure alone. Soil N input indicated a surplus in the mineral fertilizer in combination with manure treatment, but soil N input indicated a deficit in the control, NPK and M treatments. Considering crop yields, N use efficiency and N balance, recommended N application amount is almost 220 kg N/ha/year in the paddy rice-upland wheat cropping system. Taking into account labour and fertilizer sources, half mineral N and half organic N applications were recommended.

Keywords: crop output; fertilizer recovery rate; *Oryza sativa* L.; *Triticum aestivum* L.; long-term fertilizer experiment

Nitrogen (N) is one of the most important plant-available nutrients and is the most crucial crop yield-limiting factor in agricultural field (Yang et al. 2006). However, when unreasonably applied N fertilizer is neither completely assimilated by plants nor sequestered as soil organic N, it will result in N losses and cause environmental problems such as greenhouse gases, groundwater contamination, atmosphere pollution and water eutrophication, and biodiversity decline (Sainju et al. 2008, Lin et al. 2016). Increasing soil N use efficiency could reduce the use rate and farmers expenses on fertilizers and protect the environment from the negative effects of N loss (Mazzoncini et al. 2011, Ren et al. 2017). Nitrogen of agricultural field mainly originated from mineral fertilizers, organic manure, symbiotic N_2 fixation, and atmospheric wet and dry deposition (Gong et al. 2011). Organic manure such as compost has been considered an excellent soil amendment that can provide N and enhance N availability to improve crop yields (Smith and Siciliano 2015). The rice-wheat cropping system, which covers an area ranging from 9.5 to 13.5 million hectares, is mainly food production base in China (Hu et al. 2015). It is vital to keep sustainable crop yields, ensure China's food security and protect the agricultural environment. Long-term agricultural field experiments provide valuable information regarding the effects of nutrient inputs on crop productivity and

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soil environment (Cook and Trlica 2016, Schlegel and Havlin 2017, Hu et al. 2018a).

So far, there was little information about the effects of long-term organic manure and mineral fertilizer on crop N uptake, N use efficiency and balance in the rice-wheat system of China. This study aims at estimating the effect of thirty-five-year long-term fertilization on crop yield, nitrogen use efficiency and balance in the paddy-upland cropping system.

MATERIAL AND METHODS

Experiment site and design. An ongoing thirty-five-year field experiment in a rice-wheat rotation was initiated from rice cultivation in 1981, belonging to the National Fertilizer Experiment Monitoring Network at the Nanhu experimental Station, Hubei Academy of Agricultural Sciences in Wuchang District of China, located at latitude 30°28'N, longitude 114°25'E and altitude 20 m a.s.l. in Central China. The experimental site lies in a subtropical monsoon zone, which is characterized by hot summers and severe winters, and occasional snowfall during winter. The mean annual temperature is 13°C ranging from a minimum of 3.7°C in January to a maximum of 28.8°C in July. The mean annual precipitation is 1300 mm and the annual non-frost period is 240 days.

The soil at the experimental site is a yellow-brown soil, belonging to Albic Luvisol according to FAO classification. Soil properties at the beginning of the experiment in the topsoil were as follows: soil organic carbon 15.9 g/kg, total N 1.8 g/kg, total P 1.0 g/kg, total K 30.2 g/kg, available P 5.0 mg/kg (the Olsen method, Olsen et al. 1954), available K 98.5 mg/kg (the flame photometry method, Carson 1980), pH 6.30 in water, bulk density 1.29 g/cm^3.

A field experiment was conducted with nine treatments (in a randomized complete block design with three replicates), and each plot was 40 m^2 (5 m width × 8 m length). The nine treatments were as follows: (i) unfertilized treatment, control; (ii) mineral N fertilizer treatment alone, N; (iii) mineral N and P fertilizers treatment, NP; (iv) mineral N, P and K fertilizers treatment, NPK; (v) manure treatment alone, M; (vi) manure plus mineral N fertilizer treatment, MN; (vii) manure plus mineral N and P fertilizers treatment, MNP; (viii) manure plus mineral N, P and K fertilizers treatment, MNPK; (ix) high amount manure plus mineral N, P and K fertilizers treatment, hMNPK. The unfertilized treatments that served as control did not receive any fertilizer, and only crop stubble and roots were input. The mineral N, P, and K fertilizers were applied by 150 kg N/ha, 32.7 kg P/ha, and 125 kg K/ha every year. The applied N, P and K fertilizers were used by urea, ammonium phosphate, and potassium chloride, respectively. The 22 500 kg/ha of organic fertilizers from pig dung compost every year were applied to M, MN, MNP and MNPK treatments, while 37 500 kg/ha were applied to hMNPK treatment. The pig dung compost averagely contained 282.1 g/kg organic carbon, 15.1 g N/kg, 9.1 g P/kg, 11.3 g K/kg and 69.0% water. Namely, 105 kg N/ha, 63 kg P/ha, 79 kg K/ha from pig dung compost every year were applied to the M, MN, MNP and MNPK treatments, while the 325 kg N/ha, 106 kg P/ha, 131 kg K/ha were applied to the hMNPK treatment. Sixty percent of inorganic fertilizers were applied during the rice growth season and the other 40% during the wheat growth season, while organic manure was applied equally (1:1) to the two crops. Forty percent of the N fertilizer was applied as a basal fertilizer, 40% was applied during the tillering stage and 20% during the booting stage in the rice growth season. Fifty percent of N fertilizer was applied as a basal fertilizer, 25% during the wheat seedling stage and 25% during the jointing stage in the wheat growth season (Table 1). Every year, the P, K fertilizer and manure were applied as basal fertilizers, before the plough. All basal fertilizers and manure were evenly sprinkled on the soil surface by hand and were incorporated into the plough layer by tillage as soon as possible. Tillage was done to 20 cm depth by the plough and followed by harrow. The fertilized and unfertilized plots were tilled uniformly.

Plant sampling and analysis. After crop grains matured, 1 m^2 rice or wheat plants from the boundary were manually harvested by sickle, removed from the fields and then sun-dried. The grains were separated from straws by a plot thresher. Both straws and grains were oven-dried at 65°C for 72 h and then ground through a 0.5-mm sieve to analyse soil total N concentrations. Samples from plant tissues and manures were analysed for total N by a micro-Kjeldahl method (Bremner and Mulvaney 1982). All the data were expressed by dry mass.

Calculation of nitrogen uptake.

$$N_{\text{total uptake}} = N_{\text{uptake in rice}} + N_{\text{uptake in wheat}} \quad (1)$$

$$N_{\text{uptake in rice}} = \text{Yield}_{\text{rice-straw}} \times N_{\text{rice-straw}} + \text{Yield}_{\text{rice-grain}} \times N_{\text{rice-grain}} \quad (2)$$

$$N_{\text{uptake in wheat}} = \text{Yield}_{\text{wheat-straw}} \times N_{\text{wheat-straw}} + \text{Yield}_{\text{wheat-grain}} \times N_{\text{wheat-grain}} \quad (3)$$

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Table 1. Application amount of mineral fertilizers and manure from 1981 to 2015

Treatment	Basal fertilizer							Supplementary fertilizer	
	N (kg N/ha)			P (kg P/ha)		K (kg K/ha)		urea (kg N/ha)	
	urea	ammonium phosphate	manure	ammonium phosphate	manure	potassium chloride	manure	first	second
Wheat									
Control	0	0	0	0	0	0	0	0	0
N	30	0	0	0	0	0	0	15	15
NP	24	6	0	13.1	0	0	0	15	15
NPK	24	6	0	13.1	0	49.8	0	15	15
M	0	0	52.6	0	31.7	0	39.2	0	0
MN	30	0	52.6	0	31.7	0	39.2	15	15
MNP	24	6	52.6	13.1	31.7	0	39.2	15	15
MNPK	24	6	52.6	13.1	31.7	49.8	39.2	15	15
hMNPK	24	6	87.8	13.1	53.0	49.8	65.6	15	15
Rice									
Control	0	0	0	0	0	0	0	0	0
N	36	0	0	0	0	0	0	36	18
NP	27	9	0	19.6	0	0	0	36	18
NPK	27	9	0	19.6	0	74.7	0	36	18
M	0	0	52.6	0	31.7	0	39.2	0	0
MN	36	0	52.6	0	31.7	0	39.2	36	18
MNP	27	9	52.6	19.6	31.7	0	39.2	36	18
MNPK	27	9	52.6	19.6	31.7	74.7	39.2	36	18
hMNPK	27	9	87.8	19.6	53.0	74.7	65.6	36	18

The supplement amount of nutrient from manure was calculated according to the average N, P, and K contents in the manure for thirty-five years. Manure was pig dung compost and averagely contained 282.1 g/kg organic carbon, 15.1 g N/kg, 9.1 g P/kg, 11.3 g K/kg, and 69.0% water

$N_{uptake\ in\ rice}$ and $N_{uptake\ in\ wheat}$ are harvestable nitrogen of rice and wheat of each treatment every year. $Yield_{rice\text{-}straw}$, $Yield_{wheat\text{-}straw,}$ and $Yield_{rice\text{-}grain}$, $Yield_{wheat\text{-}grain}$ are straw and grain yields of rice and wheat of each treatment every year. $N_{rice\text{-}straw}$, $N_{wheat\text{-}straw}$ and $N_{rice\text{-}grain}$, $N_{wheat\text{-}grain}$ are the nitrogen concentration of straw and grain of rice and wheat of each treatment every year.

Calculation of nitrogen use efficiency. Nitrogen use efficiency (NUE, %) was calculated in the following way:

$$NUE = [(N_{uptake\ in\ N\ added} - N_{uptake\ in\ control})/(total\ N_{fertilizer\ and\ manure\ applied})] \times 100 \quad (4)$$

$N_{uptake\ in\ N\ added}$ (kg N/ha/year) is the crop straw and grain N uptake in the added N fertilizer and manure treatments. $N_{uptake\ in\ control}$ (kg N/ha/year) is the crop straw and grain N uptake in the unfertilized control treatment. $N_{fertilizer\ and\ manure\ applied}$ (kg N/ha/year) is total applied N by mineral fertilizer and manure.

Calculation of soil N balance. Total N surplus or deficit amount of each treatment was calculated in the following way. The yields of each crop straws and grains were recorded from all plots every year. The rice harvestable nitrogen is equal to the rice straw yield multiplied by its nitrogen concentration plus the rice grain yield multiplied by its nitrogen concentration. The wheat harvestable nitrogen was calculated in the same way.

$$N_{surplus\ or\ deficit} = N_{input} - N_{output} \quad (5)$$

$$N_{input} = N_{fertilizer} + N_{manure} \quad (6)$$

$$N_{output} = N_{uptake\ in\ rice} + N_{uptake\ in\ wheat} \quad (7)$$

$N_{surplus\ or\ deficit}$ (kg N/ha/year) is total N profit or loss amount in the soil of each treatment every year. N_{input} (kg N/ha/year) is total N amount from mineral fertilizer and manure into the soil each treatment every year. N_{output} (kg N/ha/year) is harvestable nitrogen from rice and wheat each treatment every

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year. $N_{fertilizer}$ is the N from chemical fertilizer into soil and N_{manure} is the N from organic manure into the soil every year.

Statistical analysis. All data were subjected to statistical analysis of variance using the SPSS 18.0 software package (SPSS Inc., Chicago, USA) and were used to evaluate differences between different treatments. The difference obtained at $P < 0.05$ level was considered statistically significant using the *LSD* (least significant difference) test.

RESULTS AND DISCUSSION

Crop yield. Rice and wheat yields are shown in Figure 1. Crop yield is significantly influenced by fertilization and fertilization years (Manna et al. 2005). On average, rice yield is increased by 29.1–53.4% compared to unfertilized control due to thirty-five years of fertilizer use and wheat yield is increased by 3.7–174.3% compared to the unfertilized control. Rice, wheat and total crop yields in the manure combined with mineral fertilizer treatments are higher than that in the manure alone or mineral fertilizer alone treatments.

Similarly, Chen et al. (2017), Gai et al. (2018) and Hu et al. (2018b) reported that rice and wheat and maize yields in the treatments receiving both manure and mineral fertilizers were significantly higher than those in the mineral fertilizers solely treatments for most of the experimental years. Nevertheless, the annual mean wheat yield of the organic manure treatment was significantly lower than that of the NPK fertilizer in a wheat-maize system (Xin et al. 2017). The trend of yield is positive for all treatments in wheat crop, and is consistent with the results reported by Choudhary et al. (2018).

Nitrogen uptake. Annual rice and wheat nitrogen uptake are shown in Figure 2. Annual rice and wheat N uptake amount were the highest in the hMNPK treatment. Rice and wheat N uptake amount were higher in the manure combined with mineral fertilizer treatments compared to the manure alone or mineral fertilizer alone treatments; they were higher in the manure alone or mineral fertilizer alone treatments than in the control treatment. Similarly, Shejbalová et al. (2014) reported that the grain and straw N uptake of spring barley in all fertilization treatments was higher than that in unfertilized control. Other researchers also reported improvement in nutrient uptake by crops when manure mixed with mineral fertilizers was applied (Yang et al. 2006, Duan et al. 2011b, Das et al. 2014).

Nitrogen use efficiency. Nitrogen use efficiency is represented with N recovered efficiency in the

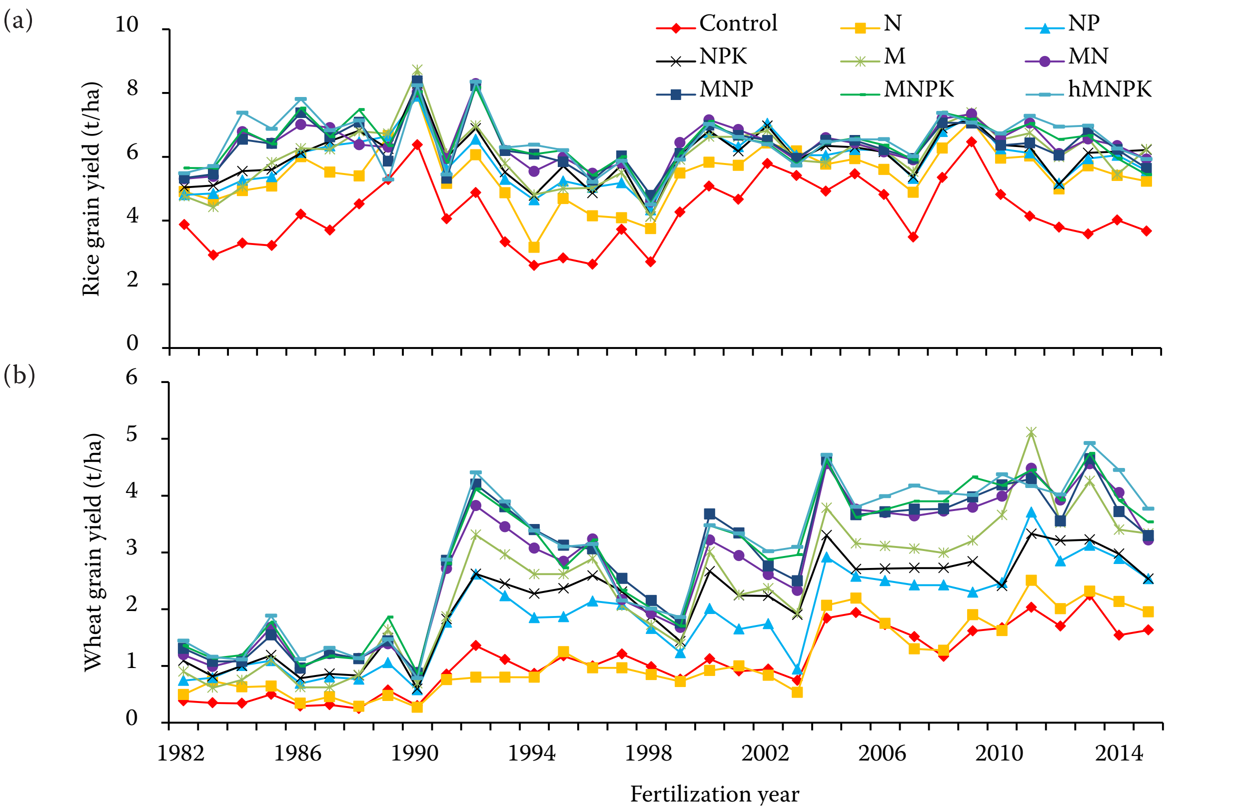

Figure 1. (a) Rice and (b) wheat grain yield in different fertilization treatments during thirty-five years periods

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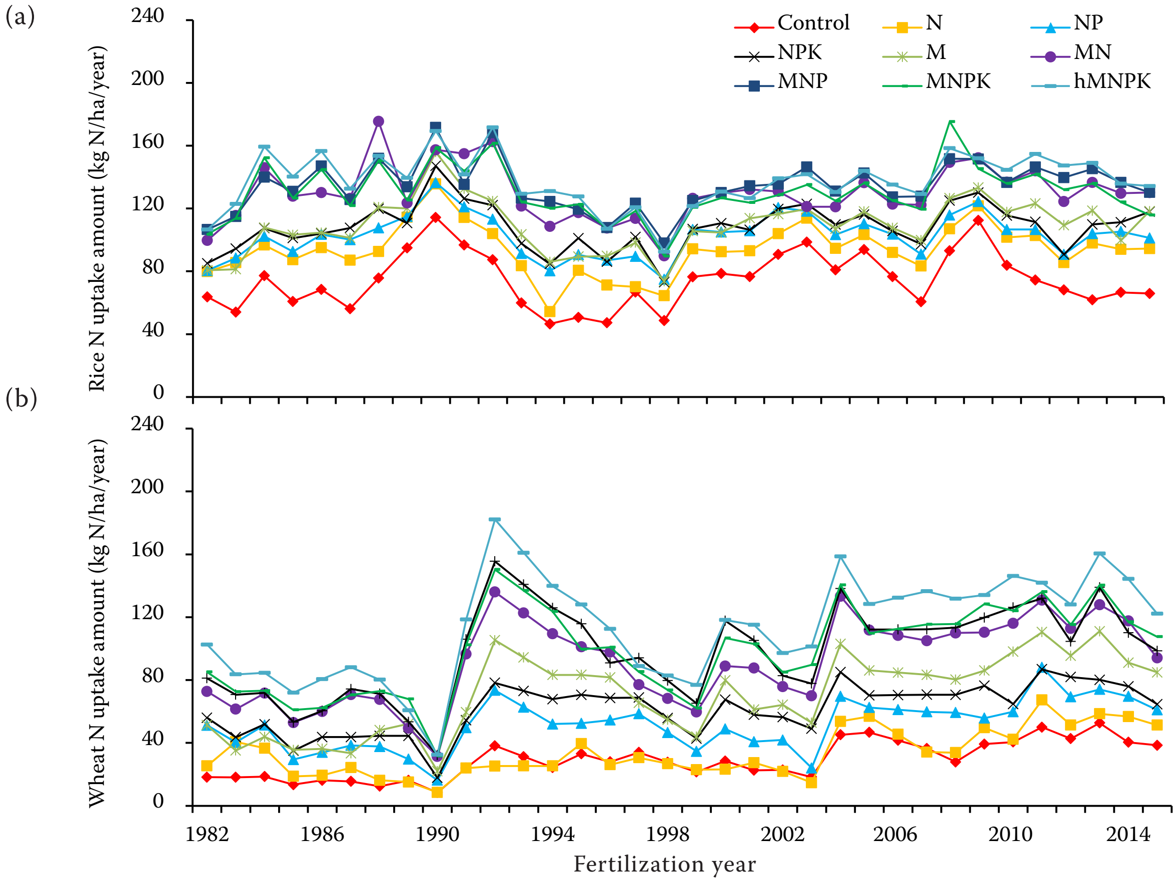

Figure 2. (a) Rice and (b) wheat nitrogen (N) uptake amount in different fertilization treatments during thirty-five years periods

crops. Annual rice and wheat N use efficiency are shown in Figure 3. Averagely, annual rice N use efficiency were 21.7, 31.6, 37.6, 65.9, 39.1, 42.0, 39.7, 35.6% and wheat N use efficiency were 5.7, 36.9, 53.8, 72.0, 54.4, 61.2, 61.6, 56.4% in the N, NP, NPK, M, MN, MNP, MNPK, hMNPK treatments, respectively. Rice and wheat N use efficiency were the highest in the manure alone treatment. Total N amount of manure alone was low, so N use efficiency in manure alone treatment was the highest of all other treatments. Islam et al. (2016) reported that increasing N rates had no significant effects on N uptake and declined N use efficiency. Shejbalová et al. (2014) also observed the highest N use efficiency of spring barley in the farmyard manure alone treatment in the long-term experiment in the Czech Republic. Gai et al. (2018) observed that additional manure amendment by existing N fertilizer application rate decreased N use efficiency by 50.8–59.1% compared to NPK alone application. Rutkowska et al. (2014) reported that potassium fertilization in long-term field experiment increased maize N use efficiency. In the present study, N use efficiency calculations only consider nutrient inputs derived from fertilizers; others however include also nutrients from the mineralization of soil organic matter and crop residues, not considered here (Lin et al. 2016).

Nitrogen balance. Annual rice and wheat N surplus or deficit amount of all soil treatments are shown in Figure 4. Averagely, rice N input to soil indicates N deficit in the control, N, NP, NPK, M treatments, whereas rice N input to soil indicates N surplus in the MN, MNP, MNPK, hMNPK treatments during a thirty-five-year period. The average annual rice N deficit amounts are 74.4, 3.9, 12.8, 18.2, 56.7 kg N/ha/year in the control, N, NP, NPK, M treatments, and average annual rice N surplus amount are 12.5, 8.3, 11.6, 40.2 kg N/ha/year in the MN, MNP, MNPK, hMNPK treatments, respectively. Averagely, wheat N input to soil indicates N deficit in the control, NPK, M treatments, whereas wheat N input to soil indicates N surplus in the N, NP, MN, MNP, MNPK, hMNPK treatments during a thirty-five-year period. The average annual wheat N deficit amount are 29.2, 1.5, 18.1 kg N/ha/year in the control, NPK, M treatments, and average annual wheat N surplus

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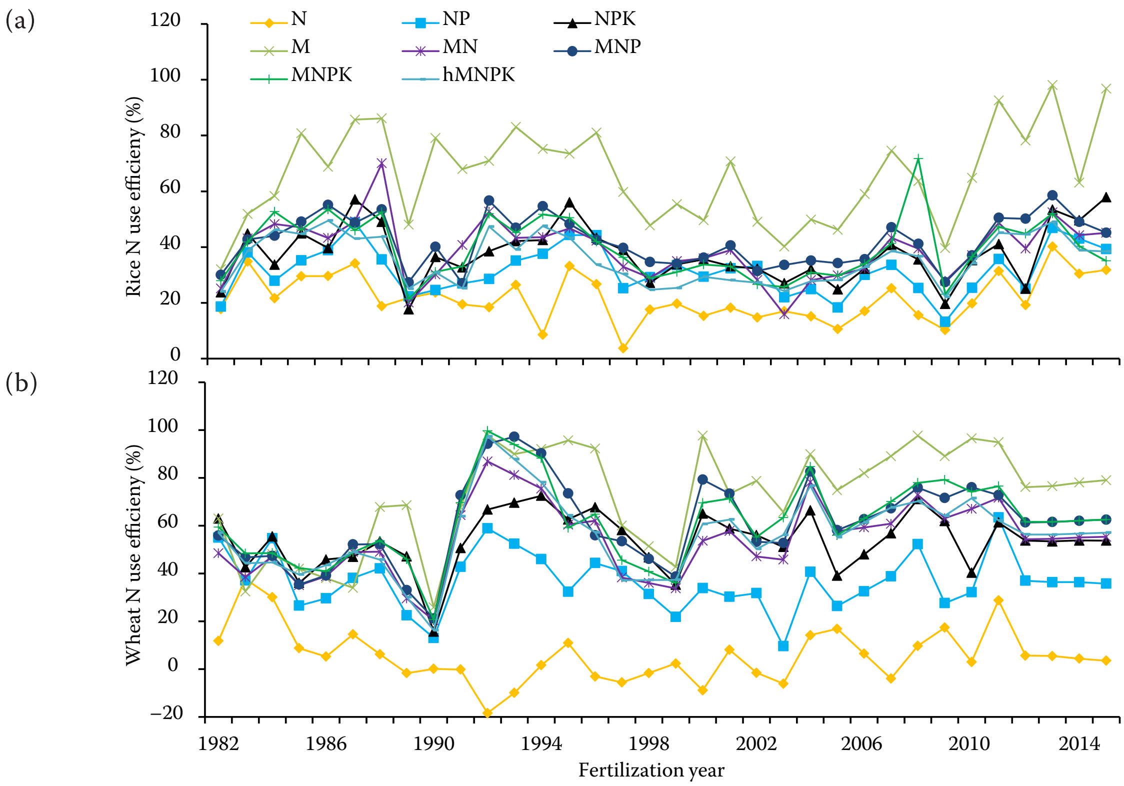

Figure 3. (a) Rice and (b) wheat nitrogen (N) use efficiency in different fertilization treatments during thirty-five years periods

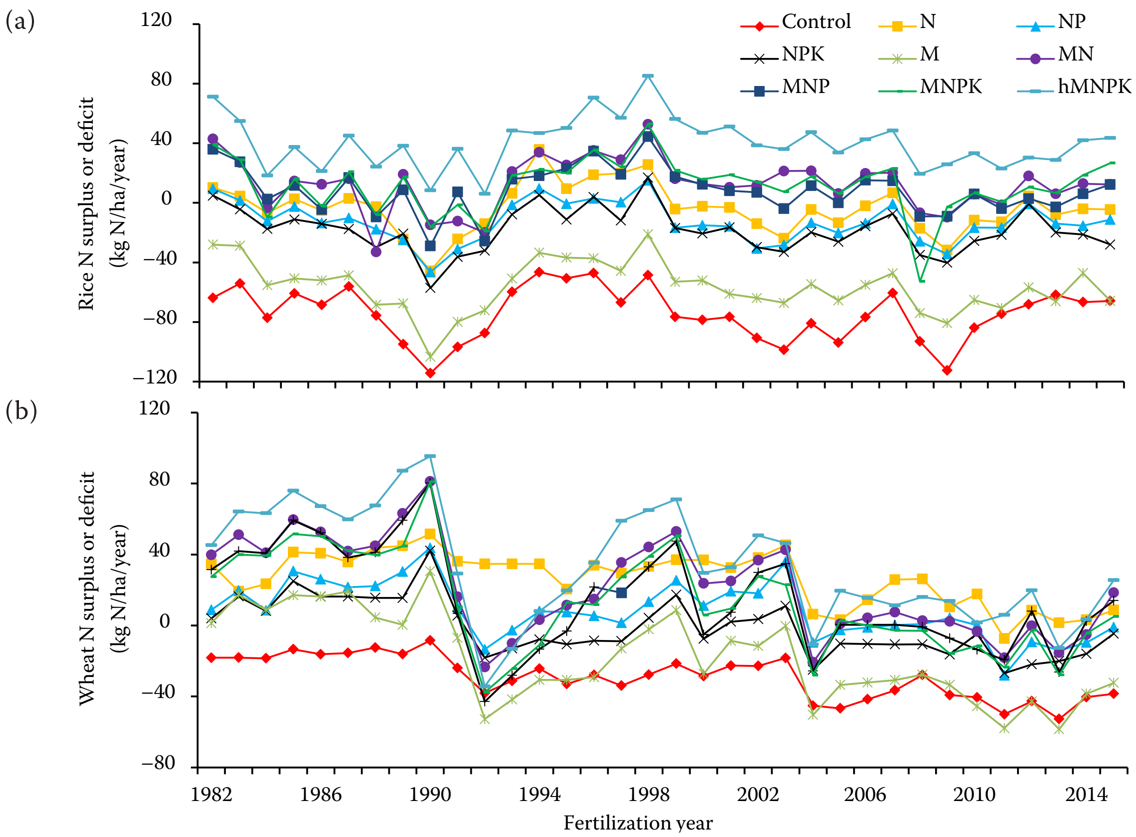

Figure 4. (a) Rice and (b) wheat nitrogen (N) surplus or deficit amount in different fertilization treatments during thirty-five years periods

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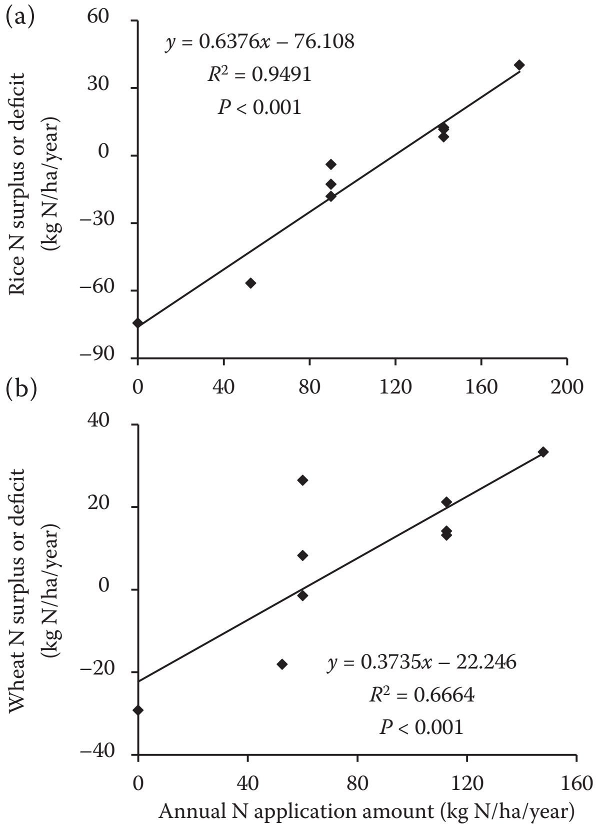

Figure 5. Linear regression relationship between (a) rice and (b) wheat nitrogen (N) surplus or deficit amount and annual N application amount for the duration of long-term fertilizer experiments

amount are 26.5, 8.3, 21.2, 14.2, 13.2, 33.3 kg N/ha/year in the N, NP, MN, MNP, MNPK, hMNPK treatments, respectively. These values indicate that mineral fertilizers combined with manure application are overdosed in the present study, especially in high amount manure treatment. Providing surplus inorganic or organic N application not only led to lower N use efficiency but also elevated the risk of N losses to the environment, over application of mineral fertilizer and organic manure should be avoided to achieve long-term agronomic and environmental sustainability (Cai et al. 2018, Gai et al. 2018). A significant linear regression exists between N surplus or deficit amount and annual N application amount (Figure 5a). The present results indicate that combined application of mineral fertilizer and manure significantly increased total N accumulation compared to the mineral fertilizer used alone. N deficient part originated from atmospheric nitrogen deposition, irrigation water and N fixation (Duan et al. 2011a, Gong et al. 2011, Lin et al. 2016, Qiu et al. 2016). Liu et al. (2015) reported that the atmospheric N deposition was 26.5 kg N/ha/year in the Hubei province of China. Therefore, crop recommended fertilization deserved to consider these factors.

In conclusion, the rice and wheat total crop yield and N uptake amount in the manure combined with mineral fertilizer treatments are higher than that in the manure alone or chemical fertilizer alone treatments. N use efficiency is higher in the manure alone treatment than that in treatments with manure combined with chemical fertilizer. However, surplus inorganic or organic N application not only led to lower N use efficiency but also elevated the risk of N losses to the environment; over-application of mineral fertilizer and organic manure should be thus avoided. Considering crop yields, N use efficiency and N balance, recommended N application amount as almost 220 kg N/ha/year in the paddy rice-upland wheat cropping system. Taking into account labour and fertilizer sources, half inorganic N and half organic N application were recommended.

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