Effect of Indigenous Nitrogen Supply of Soil on the Grain Yield and Fertilizer-N Use Efficiency in Rice

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Abstract: The effects of application of N fertilizer on wheat on the grain yield and N use efficiency (FNUE) of rice in the wheat-rice rotation system, as well as on the soil fertility were studies. N-fertilizer application on wheat significantly increased total N, ammonium-N and nitrate-N contents in paddy field, resulting in high indigenous N supply of soil (INS). Compared with low INS, the effect of N rate on the grain yield of rice was reduced significantly, and FNUE was decreased under high INS. These results indicated that high INS was one of the main reasons for the low FNUE in rice.

Key words: soil indigenous nitrogen supply; soil fertility; rice; yield; fertilizer use efficiency; nitrogen

Many reports have demonstrated that recovery efficiency (RE) of fertilizer-N in rice could reach 50%, even exceeded 80% under better crop management [1]. RE usually ranged from 30 to 50% in tropical paddy fields [2], Agronomic efficiency (AE) of fertilizer-N was equal to or higher than 20 kg grain/kg N in rice [3]. In China, RE in rice usually ranged from 30 to 35% and it was even much lower in some high-yielding area [4-6]. AE has decreased from 15-20 kg grain / kg N in 1958-1963 to 9.1 kg grain / kg N in 1981-1983 [7]. RE and AE probably continued to decrease with the increase of N-fertilizer rate in rice. Most indices of fertilizer-N use efficiency (FNUE) were calculated by the difference between grain yields or N uptake in plots received N-fertilizer and those did not receive N-fertilizer divided by N rate, thus, the grain yield or N uptake in zero-N plots is significantly related with FNUE.

Over the long term, the main aim of fertilizer management is to keep soil fertile, thus to enhance soil fertility. This method plays an active role in enhancing the soil productivity in China. Many experiments showed that grain yield in zero-N plots could reach 5-6 t/ha [8-10], even exceeded 8 t/ha [11]. Our research also found that the average grain yield in zero-N plots in twenty fields was 6.5 t/ha in two villages in Wuxi, Jiangsu Province in 2003-2004, it even reached 6.8-7.2 t/ha in Jiangdu [12], while in other rice growing countries, it was usually 3-4 t/ha [13]. These results indicated that indigenous soil N supply (INS) in paddy fields in China was rather high. However, it was not clear that how N-fertilizer management in the first crop affects INS in paddy fields and what effect of INS was on grain yield and FNUE. In this study, N fertilizer or no N fertilizer was applied in the first crop (i.e. wheat) to observe its effect on INS, grain yield and FNUE in rice. The objectives were to put forward the theoretical evidences for soil fertility management and increase grain yield and FNUE.

MATERIALS AND METHODS

Experimental design

The experiment was conducted on typical fields of wheat-rice rotation system in Gaoxu town, Jiangdu County, Jiangsu Province during 2001 to 2003 and repeated on the experimental farm of Key Laboratory of Crop Genetics and Physiology of Jiangsu Province, Yangzhou University during 2002 to 2004. Two factors, i.e. crops and N fertilizer, were designed. The crops were wheat (W, the first crop) and rice (R, the second crop). The varieties of wheat and rice were Yangmai 158 and Shanyou 63, respectively. The sowing date of wheat was 25-30 October, and the row

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spacing was 25 cm. The basic seedlings were 1.8×10^6 per ha. Rice seeds were sown on 8-10 May of next year, and transplanted on 8-10 June with one seedling at row spacing of 20 cm×20 cm. Two levels of N, i.e. N application and no N application were designed. For N application, N level in wheat was 600 kg urea/ha (276 kg N per ha), which was the conventional N rate in high-yielding practice, and applied according to the ratio of basal fertilizer : fertilizer applied at seedling stage : fertilizer applied at seedlings reviving stage : fertilizer applied at jointing and booting stages = 60 : 15 : 5 : 20. N level in rice in 2002 was 276 kg N/ha, the proportion of basal fertilizer, tillering-promoting fertilizer, spikelet-protecting fertilizer and grain-filling promoting fertilizer was 60%, 10%, 15% and 15%, respectively, and it was adjusted to 170 kg N/ha in 2003 and 2004 (the proportion of basal fertilizer, tillering-promoting fertilizer, spikelet-protecting fertilizer and grain-filling promoting fertilizer was 43.5%, 14.1%, 21.2% and 21.2%, respectively). There were total four treatments, i.e. W_0R_0 (no N application in both wheat and rice), W_0R_N (no N application in wheat, N application in rice), W_NR_0 (N application in wheat, no N application in rice) and W_NR_N (N application in both wheat and rice) (Table 1). Each treatment had four replicates. The plot size was 30 m^2. 300 kg/ha of super phosphate (P_2O_5 13.5%) and 200 kg/ha of KCl (K_2O 52%) were applied as basal fertilizer in both wheat and rice. And 20 kg/ha of $ZnSO_4 \cdot 7H_2O$ (Zn 23%) was additionally applied in rice before transplanting. Plots were separated by ridges covered with plastic films. From transplanting to two weeks before harvest, a shallow layer of water was kept in the paddy fields. Other managements were the same as those in high-yielding wheat and rice cultivation in local area.

Sampling and measurements

Soil nutrition

Total N content, available P, available K and organic matter were measured in 0-20 cm top layer of soil before each crop planting or after harvest. Ammonium-N and nitrate-N contents in the paddy fields at the mid-tillering, panicle initiation and heading stages were also determined by the standard Kjeldahl method and ultraviolet spectrophotometer method [14,15], respectively.

Table 1. Treatments and N input. kg/ha

Treat-ment	2001–2002		2002–2003		2003–2004	
	Wheat	Rice	Wheat	Rice	Wheat	Rice
W_0R_0	0	0	0	0	0	0
W_0R_N	0	276	0	170	0	170
W_NR_0	276	0	276	0	276	0
W_NR_N	276	276	276	170	276	170

Yield and its components

Two days before maturity, 0.5 m^2 of wheat and 12 hills of rice plants were sampled to determine yield components and biomass. The samples were reserved for N content determination. Plants from a 5-m^2 area in each plot were harvested at maturity for the determination of grain yield.

N content in rice leaves and plants

N content in rice leaves was determined by the standard Kjeldahl method [14] at the mid-tillering, panicle initiation, heading and maturity stages. N contents in grains and straws were also measured at maturity.

Grain quality

Amylose and protein contents in milled rice were analyzed using an Infratech 1241 Grain Analyzer from FOSS TECATOR. Other grain quality indices were measured according to the standard NY/T-593-2002 promulgated by Ministry of Agriculture, China.

RESULTS

Effect of N application in wheat growing season on soil nutrition

Soil nutrition status measured before wheat or rice planting and after harvest showed (Fig. 1) that total N content in soil decreased slightly after wheat harvest when no N-fertilizer was applied in wheat (treatment W_0R_0 and W_0R_N), however, it increased when N-fertilizer was applied in wheat (treatment W_NR_0 and W_NR_N), but it decreased in all the treatments after rice harvest. Total N content in four treatments (W_0R_0, W_0R_N, W_NR_0 and W_NR_N) resumed to same level after rice harvest and before wheat sowing. The results indicated that N application

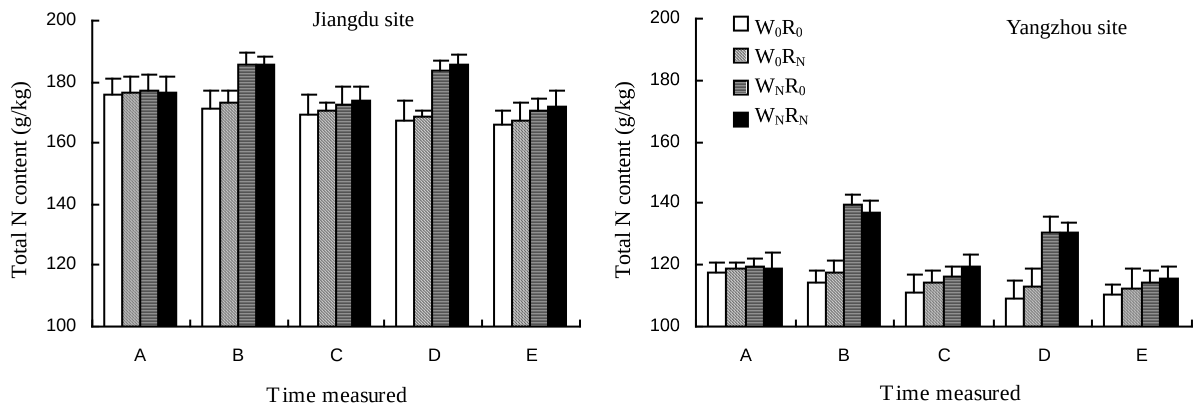

Fig. 1. Changes of total N content in soil at various stages.

A, Before wheat sowing in Jiangdu site in 2001 or in Yangzhou site in 2002; B, After wheat harvest in Jiangdu site in 2002 or in Yangzhou site in 2003 and before rice transplanting; C, After rice harvest in Jiangdu site in 2002 or in Yangzhou site in 2003 and before wheat sowing; D, After wheat harvest in Jiangdu site in 2003 or in Yangzhou site in 2004 and before rice transplanting; E, After rice harvest in Jiangdu site in 2003 or in Yangzhou site in 2004.

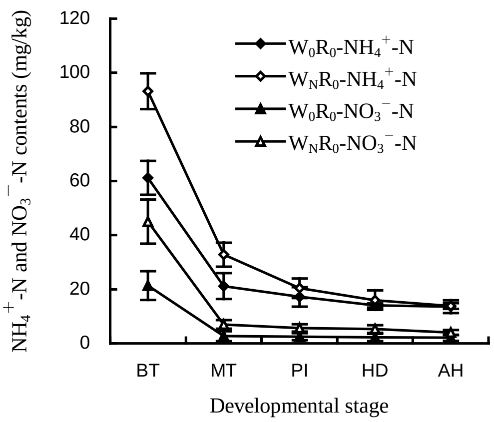

Fig. 2. Dynamic changes of NH_4^+-N and NO_3^--N contents in soil during rice developmental stage (Yangzhou site, 2004).

BT, Before transplanting; MT, Mid-tillering; PI, Panicle initiation; HD, Heading; AH, After harvesting.

during wheat growing season could increase indigenous N in paddy fields.

The results from Yangzhou site in the two years were identical with those from Jiangdu site, but total N content in soil in Yangzhou site was much lower than that in Jiangdu site.

The content of available P and K changed a little before or after wheat or rice planting, but plenty of P and K fertilizer were applied in each crop, thus, P and K would not be limited factors for wheat and rice growth. There were no obvious changes in organic matter content in soil (data not showed).

Ammonium-N content in treatment W_NR_0 (N was applied in wheat and no N was applied in rice) was much higher than that in treatment W_0R_0 (no N was applied in both wheat and rice) from the transplanting to mid-tillering stage. From panicle initiation to harvest, there was no significant difference between two treatments. Changes in nitrate-N content was similar to those in ammonium-N content, but its content was much lower (Fig. 2).

Effect of N application in wheat on N content in rice leaves

As shown in Fig. 3, N content in rice leaves decreased gradually from the mid-tillering to harvest stage. N content in treatment W_NR_0 was higher than that in treatment W_0R_0 at all growth stages except maturity, while that in treatment W_NR_N (N was applied in both wheat and rice) was higher than that in W_0R_N (no N was applied in wheat and N was applied in rice) at each growth stage.

Effect of N application in wheat on rice yield

The results from Jiangdu site in 2002 showed that treatment W_0R_N significantly increased rice yield in comparison with treatment W_0R_0 (Table 2). The yield increase was 1541.1 kg/ha, and it was mainly due to the increase in number of panicles per unit area and number of spikelets per panicle. Compared with W_NR_0, W_NR_N increased number of panicles per unit area, significantly decreased other yield components (number of spikelets per panicle, grain weight and filled grain rate), though the yield was slightly

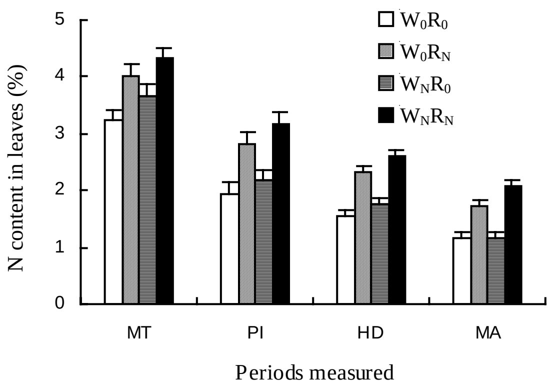

Fig. 3. Changes of N content in rice leaves (Yangzhou site, 2004) .

MT, Mid-tillering; PI, Panicle initiation; HD, Heading; MA, Maturity.

increased (only 242.6 kg/ha), it did not reach significant level.

The results of grain yield in 2003 tended to be similar to those in 2002 from Jiangdu site, and significant difference of yields was found among four treatments. The yield responses to the N level in rice were 1922.3 kg/ha and 534.5 kg/ha for no N and N application on wheat, respectively.

Changes in grain yields from Yangzhou site in the two years (2003 and 2004) were similar to those from Jiangdu site. The yield responses in treatments W_0R_N and W_NR_N to N rate in rice in 2003 were 2553.0 and 1824.3 kg/ha, and those were 3662.4 and 3047.3 kg/ha in 2004, respectively.

The grain yield in treatment W_NR_0 was significantly higher than that in treatment W_0R_0. The yield increase was mainly due to the increase of the numbers of panicles per unit area and spikelets per panicle. It was probably related to higher total N content before transplanting and higher ammonium-N and nitrate-N content before panicle initiation in the soil in treatment W_NR_0. These results further indicated that N application in wheat had significant effects on soil fertility and rice growth.

Compared with the yields at Yangzhou site and in W_0R_N treatment at Jiangdu site (2003), grain yield in W_NR_N significantly decreased at Jiangdu site in second season (2003). The yield decline was mainly due to lodging during late growth stage in W_NR_N, resulting in lower grain weight and filled grain rate, which was probably related to higher N content in soil at Jiangdu site.

Grain yields in 2003 were much lower than those in 2002 and 2004. Two reasons may explain this phenomenon: firstly, it kept heavy rain during early growth stage in 2003 and the plots were separated by ridges and not drained to avoid N loss, thus depressed the tiller growth and resulted in decreased number of panicles. Secondly, temperature was lower during grain filling stage in 2003, leading to lower grain

Table 2. Effects of N-fertilizer application in wheat on rice yield and its components.

Site	Year	Treatment	Panicles number per m^2	No. of grains per panicle	1000-grain weight (g)	Filled grain rate (%)	Yield (kg/ha)
Jiangdu	2002	W_0R_0	177.8	144.1	31.7	85.0	6896.5 c
		W_0R_N	240.7	150.1	30.8	75.9	8437.6 a
		W_NR_0	205.9	153.5	31.0	82.2	8050.0 b
		W_NR_N	266.4	141.0	30.6	72.3	8292.6 ab
	2003	W_0R_0	139.2	164.7	28.6	81.6	5355.0 d
		W_0R_N	198.1	180.1	28.1	72.6	7277.3 a
		W_NR_0	164.1	175.3	28.5	73.3	6004.4 c
		W_NR_N	196.9	179.7	27.6	67.0	6538.9 b
Yangzhou	2003	W_0R_0	128.2	179.3	28.6	82.1	5394.3 c
		W_0R_N	178.6	182.4	29.9	81.7	7947.3 a
		W_NR_0	136.9	183.8	29.3	80.2	5919.8 b
		W_NR_N	194.6	178.0	29.4	76.3	7762.1 a
	2004	W_0R_0	141.6	159.7	30.1	86.3	5874.7 c
		W_0R_N	224.6	176.6	28.9	83.2	9537.1 a
		W_NR_0	156.6	163.6	29.6	84.6	6415.8 b
		W_NR_N	240.9	171.2	28.5	80.5	9463.1 a

Lowercase letters represented significance at 0.05 level, by comparison of different treatments at the same site and in the same year.

Table 3. Effect of N-fertilizer application in wheat on N uptake and distribution in rice.

Site	Year	Treatment	N uptake in grains (kg/ha)	N uptake in rice straw (kg/ha)	Total N uptake (kg/ha)	Nitrogen harvest index
Jiangdu	2002	W_0R_0	63.3	20.8	84.1 c	0.75 a
		W_0R_N	127.1	74.0	201.1 a	0.63 b
		W_NR_0	81.9	31.2	113.1 b	0.72 a
		W_NR_N	123.1	89.2	212.3 a	0.58 c
	2003	W_0R_0	64.2	19.3	83.5 c	0.77 a
		W_0R_N	105.8	64.9	170.7 a	0.62 b
		W_NR_0	71.8	26.6	98.4 b	0.73 a
		W_NR_N	97.1	78.2	175.3 a	0.55 c
Yangzhou	2003	W_0R_0	62.2	21.1	83.3 c	0.75 a
		W_0R_N	104.7	60.4	165.1 a	0.63 b
		W_NR_0	67.7	27.7	95.4 b	0.71 a
		W_NR_N	101.8	68.5	170.3 a	0.60 b
	2004	W_0R_0	61.1	18.6	79.7 c	0.77 a
		W_0R_N	112.4	60.5	172.9 a	0.65 b
		W_NR_0	70.7	26.1	96.8 b	0.73 a
		W_NR_N	104.9	70.0	174.9 a	0.60 c

Nitrogen harvest index=N uptake in grains/total N uptake in rice plant.
Lowercase letters represented significance at 0.05 level, by comparison of different treatments at the same site and in the same year.

weight and filled grain rate.

Effect of N application in wheat on N uptake and use in rice

On N uptake and distribution

N uptake in rice was W_NR_N>W_0R_N>W_NR_0>W_0R_0, and N harvest index was reverse. The results were identical at different sites and in different years (Table 3), indicating N application in wheat had significantly effects on N uptake and distribution in rice plant.

On FNUE

Each index of FNUE, i.e. agronomic efficiency (AE), recovery efficiency (RE), physiological efficiency (PE) and partial factor productivity (PFP) of fertilizer-N in rice in the treatment of N application in wheat (W_NR_N) decreased to different extent when compared with that in the treatment of no N application in wheat (W_0R_N) (Table 4). It was more evident under N-abundance conditions in rice. For instance, when N level in treatment W_NR_N in Jiangdu site in 2002 was 276 kg N/ha, AE, RE and PE were 0.9 kg grain/kg N, 35.9% and 2.4 kg grain/kg N, being only 15.8%, 84.7% and 18.2% of those in treatment W_0R_N. In addition, RE in W_NR_N tended to decrease with the year increased.

The results from Yangzhou site in two years were identical with those from Jiangdu site.

Changes in main grain quality

Two treatments of N application in rice (W_0R_N, W_NR_N) increased brown rice rate, milled rice rate and head rice rate, especially for head rice rate, when compared with two treatments of no N application (W_0R_0, W_NR_0). N application also increased protein content, decreased amylose content in milled rice. In this study, N application increased chalky grain rate and chalkiness. Treatment W_NR_N (N was applied in both wheat and rice) decreased head rice rate, increased chalky rice rate and chalkiness, compared with treatment W_0R_N (no N application in wheat, N application in rice). The increase or decrease tended to be greater with the year increased (Table 5).

DISCUSSION

Effect of INS on grain yield and FNUE in rice

INS sources include all N sources except N-fertilizer and in rice, INS sources mainly come from: the soil, irrigation water, rainfall and crop residues

Table 4. Effect of N-fertilizer application in wheat on fertilizer-N use efficiency in rice.

Site	Year	Treatment	Agronomic efficiency (kg grain /kg N)	Recovery efficiency (%)	Physiological efficiency (kg grain/kg N)	Partial factor productivity (kg grain/kg N)
Jiangdu	2002	W_0R_0	-	-	-	-
		W_0R_N	5.6**	42.4*	13.2**	30.6
		W_NR_0	-	-	-	-
		W_NR_N	0.9	35.9	2.4	30.0
	2003	W_0R_0	-	-	-	-
		W_0R_N	11.3**	51.3*	22.0**	42.8
		W_NR_0	-	-	-	-
		W_NR_N	3.1	45.2	7.0	38.5
Yangzhou	2003	W_0R_0	-	-	-	-
		W_0R_N	15.0*	48.1	31.2*	46.7
		W_NR_0	-	-	-	-
		W_NR_N	10.8	44.1	24.6	45.7
	2004	W_0R_0	-	-	-	-
		W_0R_N	21.5*	54.8*	39.3	56.1
		W_NR_0	-	-	-	-
		W_NR_N	17.9	45.9	39.0	55.7

Agronomic efficiency (kg grain/kg N)=[Grain yield in the plot received N fertilizer(G_N) – Grain yield in the zero-N control (G_0)]/The amount of N fertilizer applied (F_N); Recovery efficiency (%)=[Total aboveground plant N accumulation in the plot received N fertilizer (T_N) – Total aboveground plant N accumulation in the zero-N control (T_0)]/F_N; Physiological efficiency (kg grain/kg N)=(G_N – G_0)/(T_N – T_0); Partial factor productivity of fertilizer-N (kg grain/kg N)=G_N/F_N.

*, ** Significant at 0.05 and 0.01 levels, respectively, compared with different treatments at the same site and in the same year.

Table 5. Effect of N-fertilizer application in wheat on grain quality traits of rice. %

Site	Year	Quality trait	W_0R_0	W_0R_N	W_NR_0	W_NR_N
Jiangdu	2002	Brown rice rate	80.3 b	82.0 a	80.9 b	82.0 a
		Milled rice rate	70.1 b	72.1 a	70.2 b	72.0 a
		Head rice rate	27.8 c	45.3 a	40.8 b	44.9 a
		Chalky rice rate	80.9 a	82.4 a	80.6 a	82.5 a
		Chalkiness	18.8 b	19.8 ab	19.2 ab	20.0 a
		Protein content	7.6 c	11.2 a	9.0 b	11.2 a
		Amylose content	24.6 a	22.5 b	24.5 a	22.1 b
	2003	Brown rice rate	77.6 b	80.5 a	77.8 b	80.3 a
		Milled rice rate	64.9 b	69.0 a	64.6 b	68.8 a
		Head rice rate	31.7 c	44.3 a	40.1 b	39.1 b
		Chalky rice rate	71.8 b	74.0 a	71.8 b	75.8 a
		Chalkiness	15.7 b	16.7 b	16.1 b	18.8 a
		Protein content	7.3 c	11.5 a	8.2 b	11.9 a
		Amylose content	20.1 a	15.5 b	19.3 a	14.6 b
Yangzhou	2003	Brown rice rate	79.4 b	82.5 a	79.9 b	81.0 a
		Milled rice rate	68.1 b	72.2 a	69.2 b	71.8 a
		Head rice rate	32.5 c	44.5 a	38.8 b	42.1 a
		Chalky rice rate	80.3 b	81.4 b	80.2 b	84.7 a
		Chalkiness	19.8 c	22.3 b	20.2 c	24.3 a
		Protein content	7.5 c	11.1 a	9.2 b	12.0 a
		Amylose content	24.6 a	18.5 b	23.5 a	17.1 b
	2004	Brown rice rate	80.2 b	83.4 a	81.0 b	82.5 a
		Milled rice rate	70.3 b	73.1 a	71.0 b	72.4 a
		Head rice rate	37.2 b	46.5 a	39.3 b	44.3 a
		Chalky rice rate	82.9 b	83.2 b	81.8 b	87.2 a
		Chalkiness	23.2 b	25.3 b	23.9 b	27.8 a
		Protein content	7.7 b	10.8 a	8.6 b	11.3 a
		Amylose content	23.2 a	17.6 b	22.4 a	17.0 b

Within a row, data followed by the same letter indicate no significant difference at 0.05 level.

(such as straws returned to fields, crop roots and dead leaves) [16, 17]. In this experiment, straws of first crop wheat were not returned to the fields. Irrigation water and rainfall were same in one site in all the treatments. Thus, the difference of N supply in each treatment was mainly due to N supply ability in the soil.

The results of this experiment showed that N application and no N application in wheat growing season can create two INS statuses, i.e. high INS and low INS. INS had significant effects on rice growth, yield formation and N uptake and use in the second crop. Compared with low INS, high INS reduced the yield response to N rate, significantly decreased AE of fertilizer-N, and made RE tend to further decrease with the year increased, indicating high INS also can aggravate N loss. PE and nitrogen harvest index under high INS were lower than those under low INS, showing that most N was accumulated in non-productive parts, such as culms, sheaths and leaves, making rice 'luxury consumption of N'. This situation was more obvious when N rate was higher in rice.

Wheat-rice rotation is an important cropping system in the region of middle-lower reaches of Yangtze River, which plays an active role on stabilizing cereal production in this region. At present, N level in wheat has reached 270 kg N / ha, and it even exceeded 300 kg N/ha in some high-yielding area. High N input positively contributed to increasing wheat yield, but at the same time, it also increased N residue in the soil thus to increase INS. It was beneficial to fertilize the soil, but it was also the main reason leading to low FNUE in the second crop (rice). In this study, the contents of ammonium-N and nitrate-N were very low after rice harvest, which was identical with the results from Dobermann et al [18], but the mineral N content was high in paddy soil after wheat harvest, and it was much higher when N rate was high in wheat, which may stimulate N loss during the fallow of rice fields. We speculate that moderately reducing N rate or adjusting proportion and timing of N application without sacrificing grain yield to promote N uptake in wheat and to decrease N residue in soil thus to reduce INS in paddy soil was beneficial to increase grain yield and FNUE in rice. The results from other experimental sites during the past decades also demonstrated that INS didn't decrease in paddy fields significantly when continuously planting rice for 4-6 years [19,20]. We think that moderate reduction of N rate will not decrease or even increase grain yield in rice when INS was high in paddy soil. It was a valid approach to increasing yield and FNUE in rice by adjusting N rate and proportion according to INS status in paddy fields.

We also observed that it has been the fourth season that no N was applied in rice at Jiangdu site in 2003 and Yangzhou site in 2004, but the grain yields were still 5.3 to 5.8 t/ha, and didn't decrease significantly, which was identical with the results of zero-N plots in rice continuously planted for nearly 60 years in the International Rice Research Institute. These results not only indicated that paddy fields have strong self-adjusting ability of N, but also be related to the N from rainfall and irrigation water. The N content of rainfall and irrigation water was not measured in this study, thus the effects of rainfall and irrigation water on INS are worthy of further study.

We also found in the experiment that soil fertility resumed to the same level after rice harvest, indicated that N application in rice had no significant effect on wheat growth. The results of grain yield and FNUE in wheat in this experiment also proved it (data not showed).

Effect of INS on grain quality

The results showed that N application under high INS could increase chalky rice rate and chalkiness, thus to worsen appearance quality of rice, and it also decreased head rice rate to worsen milled quality, compared with under low INS. The trend also tended to be greater with the year increased. Thus, to decrease INS moderately or N rate under high INS were also beneficial to improve grain quality.

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