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Effects of nitrogen fertilization strategies on nitrogen use efficiency in physiology, recovery, and agronomy and redistribution of dry matter accumulation and nitrogen accumulation in two typical rice cultivars in Zhejiang, China*

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Abstract: Field experiments were conducted in farmers' rice fields in 2001 and 2002 to study the effects of nitrogen (N) management strategies on N use efficiency in recovery (RE), agronomy (AE) and physiology (PE) and redistribution of dry matter accumulation (DMA) and nitrogen accumulation (NA) in two typical rice cultivars in Jinhua, Zhejiang Province. This study aimed mainly at identifying the possible causes of poor fertilizer N use efficiency (NUE) of rice in Zhejiang by comparing farmers' fertilizer practice (FFP) with advanced site-specific nutrient management (SSNM) and real-time N management (RTNM). The results showed that compared to FFP, SSNM and RTNM reduced DMA and NA before panicle initiation and increased DMA and NA at post-flowering. There is no significant difference between SSNM and FFP in post-flowering dry matter redistribution (post-DMR) and post-flowering nitrogen redistribution (post-NR). These results suggest that high input rate of fertilizer N and improper fertilizer N timing are the main factors causing low NUE of irrigated rice in the farmer's routine practice of Zhejiang. With SSNM, about 15% of the current total N input in direct-seeding early rice and 45% in single rice could be reduced without yield loss in Zhejiang, China.

Key words: Recovery N use efficiency (RE), Agronomic N use efficiency (AE), Physiological N use efficiency (PE), Nitrogen management, Rice, Accumulation and redistribution

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INTRODUCTION

Researches have revealed the poor fertilizer N use efficiency (NUE) of rice in China (Wang *et al*., 2001a; Peng *et al*., 2002). This could be partially due to high N input (Peng *et al*., 2002; 2006). New technologies in nutrient management in rice have been developed to increase nutrient use efficiency in recent years, such as site-specific nutrient management (SSNM) and real-time N management (RTNM). These advanced N management strategies could significantly increase NUE for rice in China (Wang *et al*., 2001b; Dobermann *et al*., 2002; Peng *et al*., 2006).

Since the pioneering work in the 1960s, crop growth model had developed rapidly with the in-depth understanding of physiological and ecological mechanisms and improving of computer science (Lin *et al*., 2003; van Ittersum *et al*., 2003). Several models of rice had been set up and have shifted from understanding and explaining towards practical application and operationalization (Bouman

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et al., 1996; ten Berge *et al*., 1997a; 1999b; Yan and Quan, 2002). However, existing rice models did not comprise overall environmental elements owing to faulty simulating technique and imperfect understanding of rice physiological and ecological mechanisms for different ecosystems or different rice varieties (Yan and Quan, 2002). The new findings in N management had not been wholly considered in rice models. The models have limitations on the whole, such as ambiguous or inadequately clear mechanism, imprecise quantitative indexes (Yan and Quan, 2002; Lin *et al*., 2003; van Ittersum *et al*., 2003). Moreover, rice cultivars have changed rapidly in recent years (Shan *et al*., 2001; Jiang *et al*., 2003; 2004). It is necessary to further understand physiological characteristics of the new varieties under different nutrient fertilization strategies in different areas. The objectives of this study were to (1) identify the possible cause of poor fertilizer NUE of rice through evaluating the effect of nitrogen fertilization strategies on recovery efficiency (RE), agronomy efficiency (AE) and physiology efficiency (PE) in two typical cultivars, and (2) specifically compare the dry matter accumulation (DMA) and N accumulation (NA) and their redistribution of the two cultivars between two advanced N management strategies (SSNM and RTNM) and farmers' routine N fertilizer practices (FFP). This study might provide information in developing and refining rice models in the area of Zhejiang Province.

MATERIALS AND METHODS

Field experiments

Field experiments were conducted at Shimen State Farm, Jinhua (29°7′ N, 119°39′ E, 64 m altitude) of Zhejiang Province in 2001 to 2002. A widely grown indica hybrid Shanyou63 (single rice from late May to early October) and a conventional indica Jinzao22 (double early rice from early April to middle July) were used. Some basic properties of the soils are shown in Table 1. For Shanyou63 transplanting spacing was 20 cm×20 cm with one seeding per hill. Plot size was 30 m^2. Phosphorus at 40 kg P/ha, potassium at 100 kg K/ha, and zinc at 5 kg Zn/ha were applied at basal fertilizer. For Jinzao22, direct sawn, plot size was also 30 m^2. Phosphorus at 15 kg P/ha was applied at basal fertilizer, potassium at 60 kg K/ha was applied at early tillering. The plots were kept flooded throughout the growing season. Pests, diseases, weeds were intensively controlled to avoid yield loss. Seven N treatments were arranged in randomized complete block design with four replicates.

The seven N treatments (Table 2) were different fertilize N management strategies, including control (N_1) and three fixed-N split treatments. The three fixed-N split treatments with total N rates of 60 (N_2), 100 (N_3) and 140 (N_4) kg N/ha with 20% applied at three-leaf stage, 35% at early tillering, 45% at panicle initiation in Jinzao22 and total N rates of 60 (N_2), 120

Table 1 Some basic properties of the soils

Variety	pH	Org. C (g/kg)	Total N (g/kg)	Olsen-P (mg/kg)	Xch. K (cmol/kg)	CEC (cmol/kg)	Sand (g/kg)	Silt (g/kg)	Clay (g/kg)
Jinzao22	4.85	25.2	2.47	12.83	0.15	7.04	387	469	144
Shanyou63	4.50	16.1	1.68	28.50	0.13	5.40	280	585	135

Table 2 Description of N treatments

Code	N treatments	
	Jinzao22	Shanyou63
N_1	Zero-N control	Zero-N control
N_2	Fixed-N split with total N rate of 60 kg/ha	Fixed-N split with total N rate of 60 kg/ha
N_3	Fixed-N split with total N rate of 100 kg/ha	Fixed-N split with total N rate of 120 kg/ha
N_4	Fixed-N split with total N rate of 140 kg/ha	Fixed-N split with total N rate of 180 kg/ha
N_5	Farmers' fertilizer practice (FFP)	Farmers' fertilizer practice (FFP)
N_6	Site-specific nutrient management (SSNM)	Site-specific nutrient management (SSNM)
N_7	Real-time N management using SPAD (RTNM)	Real-time N management using SPAD (RTNM)

(N_3) and 180 (N_4) kg N/ha with 35% applied at basal fertilizer, 20% at midtillering, 30% at panicle initiation and 15% at heading in Shanyou63. Control plots (N_1) received a full dose of phosphorus, potassium but no N.

FFP (N_5) was based on the common practice of the farmers near the sites. Total N rate was 140 kg N/ha with 40% applied before sowing, 20% at three-leaf stage, 40% at early tillering in Jinzao22 and total N rate was 200 kg/ha with 50% applied before transplanting, 35% at tillering, 15% at flowering (FL) in Shanyou63.

Treatment N_6 is SSNM, the timing of N application was fixed but the rate of N application was varied depending on leaf N status. N applications in Jinzao22 and Shanyou63 are described in Table 3, respectively. A chlorophyll meter (SPAD-502) was used to obtain SPAD values on ten uppermost fully expanded leaves in each plot.

Table 3 SPAD value for N application for N_6 in Jinzao22 and Shanyou63

Variety	Growth stage	*SPAD* value	N application (kg/ha)
Jinzao22	Three-leaf		20
	Early tillering	>34	25
		32~34	35
		<32	45
	Panicle initiation	>34	35
		32~34	45
		<32	55
Shanyou63	Basal		50
	Midtillering	>36	20
		34~36	30
		<34	40
	Panicle initiation	>36	30
		34~36	40
		<34	50
	Heading	>36	0
		<36	20

Treatment N_7 is RTNM, there was no basal N application. Weekly SPAD monitoring started at 10 d after transplanting (or 30 d after sown) and continued until flowering. If the SPAD reading was below 35, 45 kg N/ha was applied around the panicle initiation (PI) stage, 30 kg N/ha was applied for other growth stages in Shanyou63. If SPAD reading was below 34, 45 kg N/ha was applied from PI to booting stage and 35 kg N/ha was applied at other stages in Jinzao22.

Sampling and measurements

At transplanting (TP), midtillering (MT), panicle initiation (PI), flowering (FL) and maturity (MA) stages, five representative hills of the plants at each plot were separately sampled and divided into leaf blades, stems plus sheaths and grains. The samples were oven-dried at 70 °C till constant weight. Nitrogen concentration in plant tissues was determined by the Kjeldahl method (Lu, 1999). At maturity, rice was harvested and grain yield was expressed as 14% water content.

Data analysis

The term NUE is used in different contexts by different workers (Craswell and Godwin, 1986). The following definitions are used here.

Post-flowering dry matter redistribution (post-DMR)=DMA at flowering−DMA in stems and leaves at maturity,

Post-flowering nitrogen redistribution (post-NR)=NA at flowering−NA in stems and leaves at maturity,

$RE=100\times\Delta TN/FN$,

$AE=\Delta GY/FN$,

$PE=\Delta GY/\Delta TN$,

where ΔTN was total aboveground plant N accumulation in the plot that received N fertilizer minus total aboveground plant N accumulation in the zero-N control, FN was the amount of N fertilizer applied, ΔGY was grain yield in the plot that received N fertilizer minus grain yield in the zero-N control.

Analyses were conducted on individual year data and then on 2001 and 2002 combined. Year was treated as the main unit with replication nested within years; the treatments were the subunits. Data were analyzed by the following analysis of variance (SPSS, version 11.5). Differences among treatment means were compared by least significant difference (*LSD*). For mean separations, *LSD* values were used at $P<0.05$.

RESULTS

Rates of N application and yield response

In SSNM and RTNM treatments, total fertilizer N rates which were determined by SPAD readings were 120 and 106 kg/ha in Jinzao22, 110 and 60 kg/ha in Shanyou63 in 2001 and 2002, respectively. The grain yields of Jinzao22 and Shanyou63 in different treatments was in the range of 4.0~5.9 t/ha and 6.3~7.1 t/ha, respectively (Table 4). The yield difference between N_1 and other N rates was significant; yield response to fertilizer N was obvious. Though fertilizer N rates of SSNM and RTNM were much lower than farmer's fertilizer practice (FFP), yields in SSNM and RTNM increased yield by about 12%, 8% in Jinzao22 and 8%, 5% in Shanyou63 compared with FFP. The difference in N rate between N_3 level and SSNM was not significant, yet yield in SSNM was higher observably than that in N_3 level in two cultivars (Table 4).

Table 4 N application and effects of different N managements on average rice yield of 2001 to 2002

Treatment	Yield (t/ha)		N application (kg/ha)	
	Jinzao22	Shanyou63	Jinzao22	Shanyou63
N_1	4.0c	6.3c	0	0
N_2	5.1b	7.0a	60	60
N_3	5.9a	6.9ab	100	120
N_4	5.7ab	6.9ab	140	180
FFP	5.2ab	6.6bc	140	200
SSNM	5.8ab	7.1a	120	110
RTNM	5.6ab	6.9ab	106	60

Grain yields followed by the same letter are not significantly different at 5% level

Effects of fixed-N split rates on DMA, NA and NUE

Increasing fixed-N split rates (N_1~N_4) enhanced DMA and NA at different stages in two cultivars, while there was no significant difference between N_3 and N_4 level (Figs.1 and 2). NA at N_3 and N_4 level tended to decrease from flowering to maturity in two cultivars (Fig.2). This indicated that high N rates increased N loss at post-flowering in two cultivars.

Carbohydrates stored in vegetative organs were partially redistributed to seeds during grain filling. Post-flowering dry matter redistributed from vegetative organs to seeds (post-DMR) of Jinzao22 and Shanyou63 was 809~2169 kg/ha, 2272~4789 kg/ha and accounted for 26%~44%, 25%~38% of the total dry matter at flowering stage, respectively. Post-flowering nitrogen redistributed from vegetative organs to seeds (post-NR) was 22~46 kg/ha in Jinzao22, 70~120 kg/ha in Shanyou63 and accounted for 68%~75%, 38%~72% of the total nitrogen accumulated in vegetative organs at flowering, respectively. Post-DMR and post-NR in Shanyou63 were higher than those in Jinzao22. This showed that DMA and NA from vegetative organs to seeds of Shanyou63 were more than those of Jinzao22. Post-DMR, post-NR, post-DMR/DMA at flowering stage (pre-DMA) and post-NR/NA at flowering stage (pre-NA) increased from N_1 to N_4 for the two cultivars except for post-DMR of Jinzao22 at N_4 level (Figs.3 and 4).

There were no significant differences in yield, DMA and NA at different stages, and post-DMR/pre-DMA and post-NR/pre-NA between N_3 and N_4 level in the two cultivars. So the fixed-N treatments with total N application 100 (Jinzao22) and 120 (Shanyou63) kg/ha could supply enough nitrogen and N rates at N_4 level was overfull.

RE, AE and PE were from 16%~33%, 8.02~20.14 kg/kg and 52~67 kg/kg in Jinzao22, and 26%~60%, 3.4~18.37 kg/kg and 9~28 kg/kg in Shanyou63 differing with N management, respectively. RE, AE and PE decreased with increasing N rate for the two cultivars from N_2 to N_4 (Fig.5).

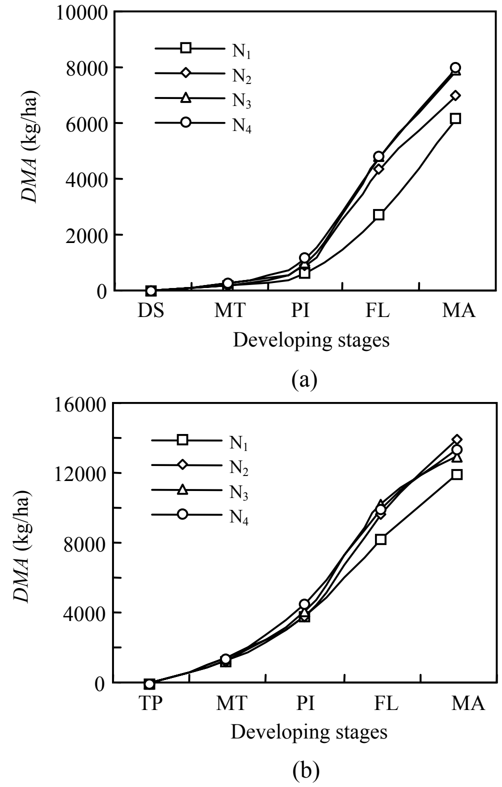

Fig.1 Effects of different N treatments on DMA at different stages in Jinzao22 (a) and Shanyou63 (b)
DS: Direct seeding; TP: Transplanting; MT: Midtillering; PI: Panicle initiation; FL: Flowering; MA: Maturity

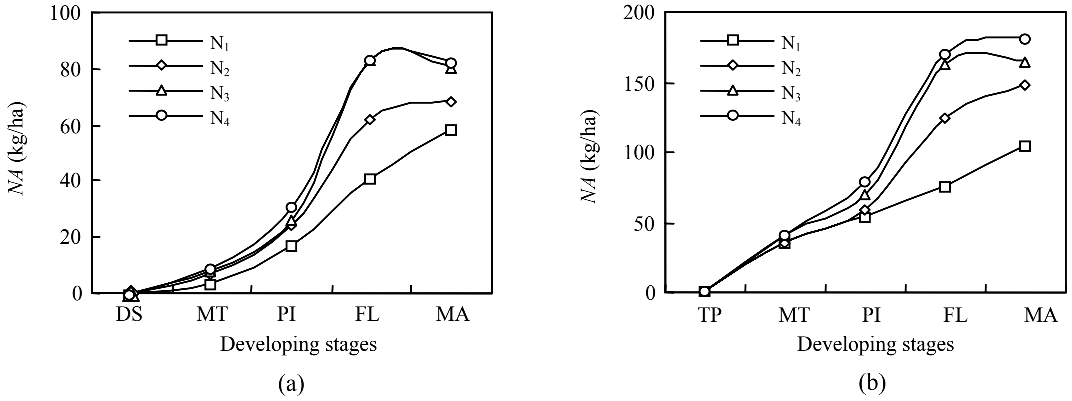

Fig.2 Effects of different N treatments on NA at different stages in Jinzao22 (a) and Shanyou63 (b)
DS: Direct seeding; TP: Transplanting; MT: Midtillering; PI: Panicle initiation; FL: Flowering; MA: Maturity

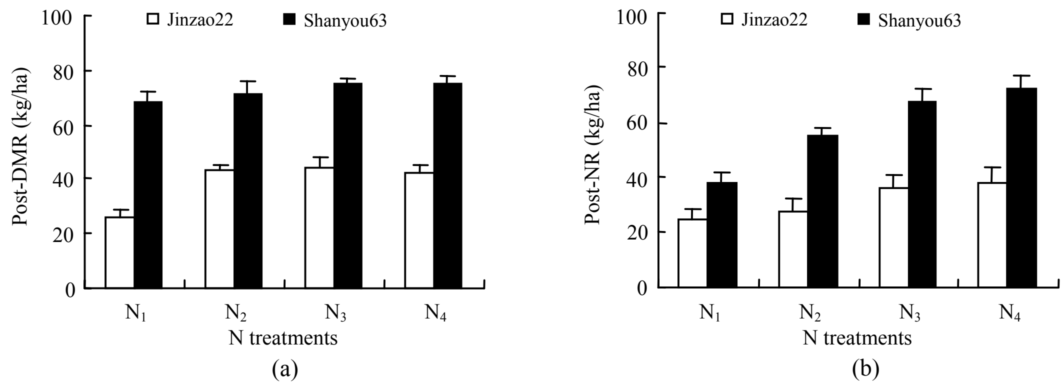

Fig.3 Effects of different N treatments on post-DMR (a) and post-NR (b) in two rice cultivars

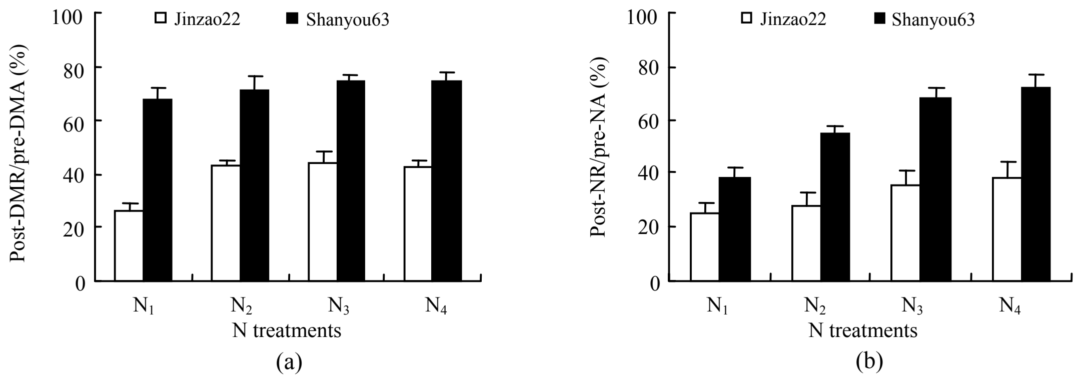

Fig.4 Effects of different N treatments on post-DMR/pre-DMA (a) and post-NR/pre-NA (b) in two rice cultivars
Pre-DMA: DMA at flowering; Pre-NA: NA at flowering

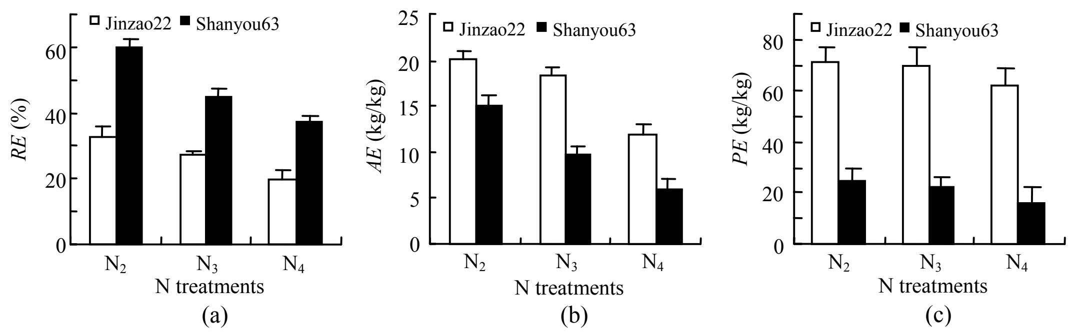

Fig.5 Effects of different N treatments on RE (a), AE (b) and PE (c) in two cultivars

Comparison of DMA, NA, post-DMR, post-NR and NUE in SSNM, RTNM and FFP

DMA at panicle initiation stage accounted for 21% and 37% of total DMA in Jinzao22 and Shanyou63 in FFP, which were 8%~9% and 8%~12% higher respectively than SSNM and RTNM. For Jinzao22, NA at PI accounted for 54%, 32% and 36% of total nitrogen accumulation in FFP, SSNM and RTNM, respectively. For Shanyou63, NA at panicle initiation accounted for 75%, 46% and 45% of total nitrogen accumulation and NA at post-flowering in FFP had negative values (Table 5). DMA and NA at panicle initiation stage in FFP were significantly higher than SSNM and RTNM, while DMA and NA from PI to MA were on the contrary, the cause was high proportion of total N input at early stage of rice growth in FFP, but in SSNM and RTNM N applications in the middle and late growth stages was stressed.

There was no significant difference in post-NR among FFP, SSNM and RTNM for the two cultivars, except that for post-NR of Shanyou63 at RTNM was lower. It indicated that dry matter redistributed from vegetative organs to seeds at FFP was close to SSNM and RTNM in the same cultivar. In Jinzao22, post-DMR in SSNM and RTNM was lower than that in FFP. In Shanyou63, there was no significant difference between FFP and SSNM, but post-DMR in FFP was higher significantly than that in RTNM (Table 6).

RE, AE and PE in SSNM and RTNM increased significantly, in contrast to FFP. Increment of RE, AE and PE in SSNM and RTNM were 7%~9%, 5.57~6.29 kg/kg, 7~9 kg/kg in Jinzao22, and 14%~19%, 7.96~14.97 kg/kg, 12~33 kg/kg in Shanyou63, respectively (Table 7).

In RTNM, nitrogen application of Shanyou63 was 60 kg/ha, which was lower significantly than NA in rice at maturity. And it may produce a bad negative effect on soil fertility, so we consider that SSNM is superior to RTNM.

DISCUSSION AND CONCLUSION

In this study the fixed-N split treatments (N_1~N_4) indicated that RE, AE and PE of the two cultivars

Table 5 Comparison of DMA and NA in SSNM, RTNM and FFP

Items	Stages	Jinzao22			Shanyou63		
		FFP	SSNM	RTNM	FFP	SSNM	RTNM
DMA (t/ha)	Pre-PI	1.6a	0.9b	1.0b	5.2a	4.2ab	3.6b
	PI-FL	3.4a	3.6a	3.6a	7.2b	7.6a	7.1b
	Post-FL	2.6a	2.9b	3.3b	1.5a	2.3b	3.6b
NA (kg/ha)	Pre-PI	30a	23b	22b	104a	63b	50b
	PI-FL	20a	37b	31b	67a	97b	84b
	Post-FL	6a	13b	8b	−33a	−23b	−23b

Means in row followed by the same letter are not significantly different at 5% level

Table 6 Comparison of post-DMR and post-NR in SSNM, RTNM and FFP

Items	Jinzao22			Shanyou63		
	FFP	SSNM	RTNM	FFP	SSNM	RTNM
Post-DMR (kg/ha)	2187a	1971a	1638b	4389a	4146a	3430b
Post-NR (kg/ha)	35a	37a	36a	116a	111ab	96b

Means in row followed by the same letter are not significantly different at 5% level

Table 7 Comparison of NUE in SSNM, RTNM and FFP

Items	Jinzao22			Shanyou63		
	FFP	SSNM	RTNM	FFP	SSNM	RTNM
RE (%)	16a	23b	25b	26a	45b	40b
AE (kg/kg)	8.02a	13.59b	14.31b	3.40a	11.36b	18.37b
PE (kg/kg)	51a	60b	58b	13a	25b	46b

Means in row followed by the same letter are not significantly different at 5% level tended to decrease with increased N application, as reported in previous researches (Peng and Cassman, 1998; Timsina *et al*., 2001; Liu *et al*., 2004; Jiang *et al*., 2004; Peng *et al*., 2006; Mae *et al*., 2006). High N rate increased post-DMA and post-NR, which theoretically could result in large grain yield and large PE, RE and AE, however, high N rates did reduced them in the two cultivars, In this study, NA at flowering accounted for 99% and 100% of total nitrogen uptake under high N rates in Jinzao22 and Shanyou63 respectively, which resulted in high nitrogen concentration and accumulation in rice plant at flowering stage. It was reported that the decreased accumulation of nitrogen before flowering could be caused by nitrogen volatilization from plant tissues and death of partial leaf and organ at post-flowering stage, and that nitrogen volatilization was the main cause (Huang *et al*., 2004; Jin and Mian, 2005). In this study high N rate decreased NA at post-flowering in Jinzao22 and increased nitrogen volatilization in Shanyou63. High nitrogen concentration and accumulation at flowering stage was the basis of large post-flowering dry matter production and N redistribution. The negative effect caused by volatilization of large nitrogen concentration and accumulation at flowering stage was larger than the positive effect of post-flowering dry matter production and N redistribution at high N rate, so NUE decreased with increasing N rates. In addition, a high indigenous N supply of soil (INS) will result in higher N concentration in rice straw and produce the phenomenon of luxury consumption of N (Liu *et al*., 2004; 2005; Feng *et al*., 2006). In this study, the average grain yield in N omission plots of Jinzao22 and Shanyou63 were higher than 4 t/ha and 6 t/ha, respectively, indicating that the INS of the soil was high.

de Datta (1986) reported that RE is usually 30%~50% in the tropics and PE in the tropics is about 50~70 kg rough rice per kg N absorbed. Yoshida (1981) estimated AE to be 15~25 kg/kg and Cassman and Pingali (1996) reported AE was 15~20 kg/kg in the dry season in the farmers' fields in the Philippines. NUE of the farmer's practice in irrigated rice in Zhejiang Province was reported by Wang *et al*.(2001a) and Feng *et al*.(2006). Wang *et al*.(2001a) measured AE in 21 farmers' fields for four seasons and found that the average AE of the farmers' practice was 6.4 kg/kg. Feng *et al*.(2006) reported that N use efficiency was so low that RE was only 21.55% in average in high-fertility paddy field in Northern Zheiiang Province, which was close to 19.9% in Jiangsu Province (Li, 2000). In this study, RE, AE and PE were 16%, 8.02 kg/kg, 51 kg/kg in Jinzao22 and 26%, 3.4 kg/kg, 13 kg/kg in Shanyou63 in FFP. SSNM and RTNM increased RE, AE and PE significantly in contrast to FFP (Table 7). Previous studies reported there was great potential for NUE improvement by changing accumulation and redistribution of dry matter and nitrogen under optimal nitrogen management in different cultivars (Jiang *et al*., 2003; 2004). We speculate the reasons that may explain the phenomena. In this study, DMA and NA at pre-PI in FFP were significantly higher than SSNM and RTNM for the two cultivars, while DMA at post-flowering was lower. Post-DMR and post-NR in FFP were higher or close to SSNM and RTNM. These results showed accumulation of dry matter and nitrogen before PI in the FFP was excessive, and will cause much invalid tillering and deficient nitrogen supplies in the middle and late rice growth stages. Yet SSNM and RTNM could not improve post-DMR and post-NR. So the disadvantage of FFP in Zhejiang was the improper timing of N applied, and N supply cannot be satisfied with N requirement, as reported in previous research (Zhang and Wang, 2002; Liu *et al*., 2004; Peng *et al*., 2006; Lin *et al*., 2006). Second, overfull N input in FFP was also the important factor causing low NUE of irrigated rice in Zhejiang. Some reporters believe that 30%~50% reduction in N application in most cases would be feasible and necessary in China (Yang *et al*., 2003; Liu *et al*., 2004; Feng *et al*., 2006). In this study, N input can reduce about 15% in Jinzao22 and 45% in Shanyou63; waste of N in single rice was more severe than direct-seeding early rice.

As dominant cultivars in Zhejiang, Shanyou63 and Jinzao22 have shown great differences in plant type, panicle size and grain yield under production practices. There were different NUE in different varieties under the different levels of N fertilizer (Jiang *et al*., 2003; Luan *et al*., 2005). In this study, RE of Shanyou63 was higher than that of Jinzao22 while PE was lower than that of Jinzao22 under the same condition (Table 7).

RE, AE and PE of the two cultivars tended to decrease and post-DMR, post-NR increased with increased N application under fixed-N split treatments for two cultivars. SSNM and RTNM increased DMA and NA at middle and late stages of rice, yet reduced DMA and NA before PI. SSNM and RTNM increased NUE significantly in contrast to FFP. The cause of low NUE of irrigated rice in FFP of Zhejiang was the high N input and improper timing of N applied. N input could be reduced about 15% in direct-seeding early rice and 45% in single rice without yield loss. SSNM was superior to other N treatments in two cultivars.

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