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Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China

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Abstract

Irrigated rice in China accounts for nearly 30% of global rice production and about 7% of global nitrogen (N) consumption. The low agronomic N use efficiency (AE_N, kg grain yield increase per kg N applied) of this system has become a threat to the environment. The objective of this study was to determine the possibility to improve the AE_N of irrigated rice in China by comparing the farmers' N-fertilizer practices with other N management strategies such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM). Field experiments were conducted in farmers' fields in four major rice-growing provinces in China in 2001 and 2002. The same experiment was repeated at the International Rice Research Institute (IRRI) farm in the dry seasons of 2002 and 2003. Agronomic N use efficiency was determined by the ‘‘difference method’’ using an N-omission plot. Maximum yield was achieved mostly at 60–120 kg N ha^{-1}, which was significantly lower than the 180–240 kg N ha^{-1} applied in farmers' practices at the Chinese sites. With the modified farmers' fertilizer practice, a 30% reduction in total N rate during the early vegetative stage did not reduce yield but slightly increased yield and doubled AE_N compared with the farmers' practice at the Chinese sites. The total N rate in RTNM and FTNM ranged from 30 to 120 kg ha^{-1} at the Chinese sites, but their yields were similar to or higher than that of the farmers' practice. Compared with the modified farmers' practice, RTNM and FTNM further increased AE_N at the Chinese sites. Overall, FTNM performed better than RTNM at the Chinese sites because the total N rate of FTNM was closer to the optimal level than RTNM. A quantum leap in AE_N is possible in the intensive rice-growing areas in China by simply reducing the current N rate and by allocating less N at the early vegetative stage.
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Keywords: Agronomic N use efficiency; China; Fixed-time adjustable-dose N management; Irrigated rice; Real-time N management

1. Introduction

China is currently the world's largest consumer of nitrogen (N) fertilizers. In 2002, annual N fertilizer consumption in China was 25.4 million metric tons or 30% of the global N consumption (FAO, 2004). About a quarter of this N was used for rice production in China based on statistics of 1997 (IFA, 2002); therefore, irrigated rice in China accounts for about 7% of global N consumption. China accounts for 30% of global rice production (FAO, 2004). The irrigated system produces over 95% of the rice in China (Maclean et al., 2002).

Crop yields in the world have continuously increased to meet population growth, partly because of the increase in fertilizer nutrient input, especially N fertilizer (Cassman et al., 2003). To maximize grain yield, farmers often apply a higher amount of N fertilizer than the minimum required for maximum crop growth (Lemaire and Gastal, 1997). Nitrogen use efficiency is relatively low in irrigated rice

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because of rapid N losses from ammonia volatilization, denitrification, surface runoff, and leaching in the soil–floodwater system (Vlek and Byrnes, 1986; De Datta and Buresh, 1989). The magnitude and nature of N losses vary depending on the timing, rate, and method of N application, source of N fertilizer, soil chemical and physical properties, climatic conditions, and crop status. In general, ammonia volatilization is the major pathway of N loss in irrigated rice (Zhu, 1997).

Nitrogen use efficiency is separated into different component indices by agronomists using N-omission plots (Novoa and Loomis, 1981). The yield increase that results from N application in comparison with no N application is defined as the agronomic N use efficiency (AE_N, kg grain yield increase per kg N applied). The apparent recovery efficiency of fertilizer-N (RE_N) is used to express the percentage of fertilizer-N recovered in aboveground plant biomass at the end of the cropping season. Cassman et al. (1996) reported that AE_N was 15–18 kg kg^{-1} in the dry season in farmers' fields in the Philippines. The average RE_N is 30% for irrigated rice in Asia (Dobermann and Fairhurst, 2000). Other indices include internal N use efficiency (IE_N, kg grain yield over total N uptake) and partial factor productivity of applied N (PFP_N, kg grain per kg N applied).

Available evidence indicates that the AE_N of rice production in China is very low, if not the lowest among the major rice-growing countries (Wang et al., 2001; Peng et al., 2002). This could be partially due to high N input. China's national average N rate for rice was 145 kg ha^{-1} in 1997 (IFA, 2002). Based on data from 1995 to 1997, the average rate of N application for rice production in China was 180 kg ha^{-1} (FAO, unpublished data, 2001). Nitrogen rates of 150–250 kg ha^{-1} are common. In Jiangsu Province, the average N rate reached 300 kg ha^{-1} in some counties (Q. Zhu, personal communication, 2001). Zhu (1985) reported that the RE_N was less than 30% for ammonium bicarbonate and 30–40% for urea in China. Li (1997) estimated that the RE_N for rice in China was around 30–35%. However, Li (2000) observed that the average RE_N of rice in Jiangsu Province was only 20%. This was further confirmed by Wang et al. (2001), who reported that the RE_N of the farmers' N-fertilizer practice was 18% in an on-farm experiment conducted in Zhejiang. In China, AE_N was 15–20 kg kg^{-1} from 1958 to 1963 and declined to only 9.1 kg kg^{-1} from 1981 to 1983 (Lin, 1991). Since then, AE_N could be even lower in China because of the increase in N rate (Peng et al., 2002). Wang et al. (2001) reported that AE_N of the farmers' N-fertilizer practice was 6.4 kg kg^{-1} in Zhejiang.

Site-specific N management such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) was developed to increase the N use efficiency of irrigated rice (Peng et al., 1996; Dobermann et al., 2002). In RTNM, N is applied only when the leaf N content is below a critical level. In this approach, the timing and number of N applications vary across seasons and locations while the rate of each N application is fixed. The leaf N content is estimated non-destructively with a chlorophyll meter (SPAD) or leaf color chart (LCC) (Tao et al., 1990; Peng et al., 1996; Balasubramanian et al., 1999; Yang et al., 2003). Evaluation of RTNM in Asia has generally shown that the same rice yield could be achieved with about 20–30% less N fertilizer applied, but increases in yield were seldom (Peng et al., 1996; Balasubramanian et al., 1999, 2000; Hussain et al., 2000; Singh et al., 2002).

Key components of FTNM are measurement of grain yield in nutrient-omission plots to obtain field-specific estimates of the indigenous N supply, a decision support system for predicting crop N requirement and the optimal amounts to be applied before planting, and in-season upward or downward adjustments of predetermined N topdressings at critical growth stages based on SPAD or LCC readings at a few critical growth stages (Dobermann et al., 2002). In this approach, the timing and number of N applications are fixed while the rate of each N application varies across season and location. Since 1997, FTNM has been evaluated in farmers' fields in eight major irrigated rice domains in Asia (Dobermann et al., 2002), including rice farms in Zhejiang Province, China (Wang et al., 2001, 2004). Across all sites in Asia, average grain yield increased by 11% and average RE_N increased from 31% to 40%, with 20% of all farmers achieving more than 50% RE_N (Dobermann et al., 2002). No study was conducted to compare RTNM and FTNM in farmers' fields at multiple sites.

The objectives of this study were to: (1) identify possible causes of low AE_N of irrigated rice in China, (2) evaluate different N management strategies for increasing AE_N, (3) determine whether N input in the early vegetative stage can be reduced by 30% in the farmers' fertilizer practice without a yield penalty in irrigated rice in China, and (4) compare RTNM and FTNM in farmers' fields across the five sites.

2. Materials and methods

2.1. General site characteristics

Field experiments were conducted in farmers' fields in the major rice-growing areas of China in 2001 and 2002. The experimental sites were located in Gaoxu Township, Jiangdu (32°30′N, 119°32′E, 21 m altitude); Shimen State Farm, Jinghua (29°7′N, 119°39′E, 64 m altitude); Huilongpu Township, Ningxiang (28°13′N, 112°28′E, 63 m altitude); Xiangang Township, Gaoyao (23°2′N, 112°41′E, 1.5 m altitude), of Jiangsu, Zhejiang, Hunan, and Guangdong provinces, respectively. These four provinces occupy about 33% of the total rice-planting area in China. Rice production in Jiangsu typically involves one crop of japonica rice per year. Two crops of rice, often hybrids, are typically grown per year in Jinghua of Zhejiang, and in Hunan and Guangdong. The experiments were conducted with only one rice crop per year at the Chinese sites. The same

Table 1
Soil chemical and physical properties at the beginning of the experiments at four sites in China and at the International Rice Research Institute (IRRI) farm

Site	pH	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Extractable K ($cmol_c\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	Clay (%)	Silt (%)	Sand (%)
Jiangsu	6.3	12.7	1.30	13	0.10	13.8	22.8	75.2	2.0
Zhejiang	4.5	16.1	1.68	29	0.12	5.4	13.5	58.5	28.0
Hunan	5.8	19.9	1.86	10	0.09	11.7	24.8	57.7	17.5
Guangdong	4.6	18.9	2.09	43	0.07	8.3	38.7	54.0	7.3
IRRI	6.2	15.1	1.60	10	1.25	37.4	63.2	29.0	7.8
Average S.E.	0.1	0.5	0.05	1	0.02	0.3	0.5	0.5	0.5

experiment was repeated at the IRRI farm (14°11′N, 121°15′E, 21 m altitude) in the dry seasons of 2002 and 2003. At the Zhejiang and Hunan sites, the experiment was repeated in the same field with the same treatment layout in the two years and the fields were fallow between the two growing seasons. At Guangdong, the experiment was repeated in the same field. The field was fallow during the winter growing season. Early-season rice was grown without N application before the field experiment in 2002. At Jiangsu, the experiment was repeated in an adjacent field and winter wheat was grown without N application before the rice-growing season in both years. At IRRI, the experiment was repeated in the same field and rice was grown in the wet season without N application before the field experiment in the dry season in both years. Soil chemical and physical properties are listed in Table 1.

2.2. Crop establishment and management

A widely grown indica/indica hybrid variety, Shanyou63, was used at the four sites in China. At IRRI, IR72, a common check variety in the tropics, was included in addition to Shanyou63. Because IR72 had grain yield similar to that of Shanyou63 and showed no different response to N treatments, only data of Shanyou63 are presented in this paper. Transplanting was done in June–August at the Chinese sites and in January at IRRI. Seedling age was 20–35 days at the Chinese sites and 14 days at IRRI. At the Chinese sites, seeding and transplanting started early and seedling age was shortened from northern to southern sites. Transplanting spacing was 20 cm × 20 cm with one seedling per hill. Plot size was 30 m^2. At the Chinese sites, phosphorus at 40 kg ha^{-1}, potassium at 100 kg ha^{-1}, and zinc at 5 kg ha^{-1} were applied at basal. At IRRI, phosphorus at 30 kg ha^{-1}, potassium at 40 kg ha^{-1}, and zinc at 5 kg ha^{-1} were applied at basal. The plots were kept flooded throughout the growing season. Pests, diseases, and weeds were intensively controlled to avoid yield loss.

2.3. N treatments

At each site, eight N treatments were arranged in a randomized complete block design with four replicates. The eight N treatments in Table 2 were different fertilizer N management strategies, including three fixed-N split treatments. The three fixed-N split treatments had total N rates of 60, 120, and 180 kg ha^{-1} with 35% applied at basal, 20% at midtillering, 30% at panicle initiation, and 15% at heading at the Chinese sites, whereas they were applied in three equal splits at basal, midtillering, and panicle initiation at IRRI. Control plots received a full dose of phosphorus, potassium, and zinc but no N. The farmers' N-fertilizer treatment was based on the common practice of the farmers near the sites. At the Chinese sites, the farmers' fertilizer practice was modified by reducing the total N input in the farmers' N-fertilizer treatment by 30% and this reduction in N input was restricted to within 10 days after transplanting (DAT). At IRRI, the farmers' fertilizer practice was modified by adding N at basal in the farmers' N-fertilizer treatment.

In RTNM, if the SPAD reading was below 35, 30 kg N ha^{-1} was applied. If SPAD was below 35 around the panicle initiation stage, 45 kg N ha^{-1} was applied according to Peng et al. (1996). There was no basal N application in this treatment. A chlorophyll meter (SPAD-502, Soil–Plant Analysis Development Section, Minolta Camera Co., Osaka, Japan) was used to obtain SPAD values on five uppermost fully expanded leaves in each plot. Three SPAD readings were taken around the midpoint of each leaf blade, 30 mm apart, on one side of the midrib. Weekly SPAD monitoring started at 10 DAT and continued until heading.

Details of the FTNM approach were provided elsewhere (Dobermann and Fairhurst, 2000; Dobermann et al., 2002). Total N rate was based on the zero-N control grain yield and the yield target. Zero-N control grain yield was set to 5 t ha^{-1} for the Chinese sites and to 4 t ha^{-1} for IRRI, climatic yield potential to 10 t ha^{-1}, and yield target to 80% of climatic yield potential according to Dobermann and

Table 2
Description of N treatments

Code	N treatment
CK	Zero-N control
Fixed-60	Fixed-N split with total N rate of 60 kg N ha^{-1}
Fixed-120	Fixed-N split with total N rate of 120 kg N ha^{-1}
Fixed-180	Fixed-N split with total N rate of 180 kg N ha^{-1}
FP	Farmers' fertilizer practice
MFP	Modified farmers' fertilizer practice
RTNM	Real-time N management using SPAD
FTNM	Fixed-time adjustable-dose N management

Table 3
Method for determining the rate of N application in the fixed-time adjustable dose N management treatment (FTNM) at four sites in China and at the International Rice Research Institute (IRRI) farm

N split	Growth stage	N rate (kg ha^{-1})	
		China	IRRI
First N application	Preplant	50	35
Second N application	Midtillering	30 ± 10[a]	40 ± 10[a]
Third N application	Panicle initiation	40 ± 10[a]	45 ± 10[a]
Fourth N application	Heading	± 20[b]	± 15[b]
Total		100–160	100–155

[a] If SPAD is greater than 36, apply base amount −10 kg ha^{-1}; if less than 34, apply base amount +10 kg ha^{-1}; if from 34 to 36, apply base amount.
[b] If SPAD is less than 36, apply 20 kg ha^{-1} at the Chinese sites and 15 kg ha^{-1} at IRRI; otherwise, no need to apply N.

Table 4
Nitrogen application rate (kg N ha^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
FP	240	200	180	200	90
MFP	170	140	130	140	135
RTNM	75	75	90	30	135
FTNM	100	110	110	100	135
Year II					
FP	240	200	180	200	90
MFP	170	140	130	140	135
RTNM	105	45	75	45	150
FTNM	120	110	100	100	110

[a] See Table 2 for details of N treatments.

Fairhurst (2000) and Wang et al. (2001). The timing of N application was fixed but the rate of in-season N application varied depending on leaf N status (Table 3). The chlorophyll meter was used to determine leaf N status for making decisions on topdressed N application (Dobermann and Fairhurst, 2000). Strategies for splitting and timing of N applications were based on experience accumulated in the previous field studies.

2.4. Measurements

Soil samples were taken before transplanting in the first year. All soil samples were analyzed at the IRRI Analytic Service Laboratory. Plants were sampled from a 0.48-m^2 area (12 hills) at maturity. All plant samples were separated into straw, filled and unfilled spikelets, and rachis. Dry weights of each component were determined by oven-drying at 70 °C to constant weight. Tissue N concentration was determined by micro Kjeldahl digestion, distillation, and titration (Bremner and Mulvaney, 1982) to calculate aboveground total N uptake. Grain yield was determined from a 5-m^2 area at maturity and adjusted to a moisture content of 0.14 g H_2O g^{-1} fresh weight.

2.5. Data analysis

The framework of Novoa and Loomis (1981) was use to estimate RE_N and AE_N based on a comparison of crop performance in treatment plots with and without applied N. RE_N was calculated as the ratio of the increase in plant N accumulation at maturity that resulted from N fertilizer application to the fertilizer N rate, and AE_N was calculated as the increase in grain yield per unit of applied N. Internal N use efficiency was calculated as the ratio of grain yield to total N uptake. Partial factor productivity of applied N was the grain yield per unit N applied.

Data were analyzed following analysis of variance (SAS, 1982) and means of N treatments were compared based on Tukey's multiple comparison test at the 0.05 probability level.

3. Results

3.1. Rates and timing of N application

In the farmers' fertilizer practice, total N rate ranged from 180 to 240 kg ha^{-1} with three to five splits at the Chinese sites and was 90 kg ha^{-1} with two splits at IRRI (Table 4, Fig. 1). About 56% to 85% of the total N was applied in the first 10 DAT at the Chinese sites compared with none at IRRI in the farmers' practice (Table 5). As intended, the proportion of N applied in the first 10 DAT decreased substantially in the modified farmers' practice at the Chinese sites. The timing and rate of N application were the same in the two years for both FP and MFP.

In RTNM, total N rate ranged from 30 to 90 kg ha^{-1} with one to three splits at the Chinese sites and was 135 kg ha^{-1} with four splits at IRRI in year I (Table 4, Fig. 1). In year II, total N rate ranged from 45 to 105 kg ha^{-1} with one to three splits at the Chinese sites and was 150 kg ha^{-1} with four splits at IRRI. The rate and timing of N application were different between the two years in RTNM at all five sites. IRRI had a higher total N rate and more times of N application than the Chinese sites in RTNM.

Table 5
The amount of N applied (kg N ha^{-1}) in the first 10 days after transplanting in the farmers' practice (FP) and modified farmers' practice (MFP) at four sites in China and at the International Rice Research Institute (IRRI) farm

Sites	Farmers' practice (FP)		Modified farmers' practice (MFP)	
	N applied	Percent of total	N applied	Percent of total
Jiangsu	168	70	98	58
Zhejiang	170	85	110	79
Hunan	100	56	50	38
Guangdong	135	68	75	54
IRRI	0	0	45	33

The timing and rate of N application were the same in two years for both FP and MFP.

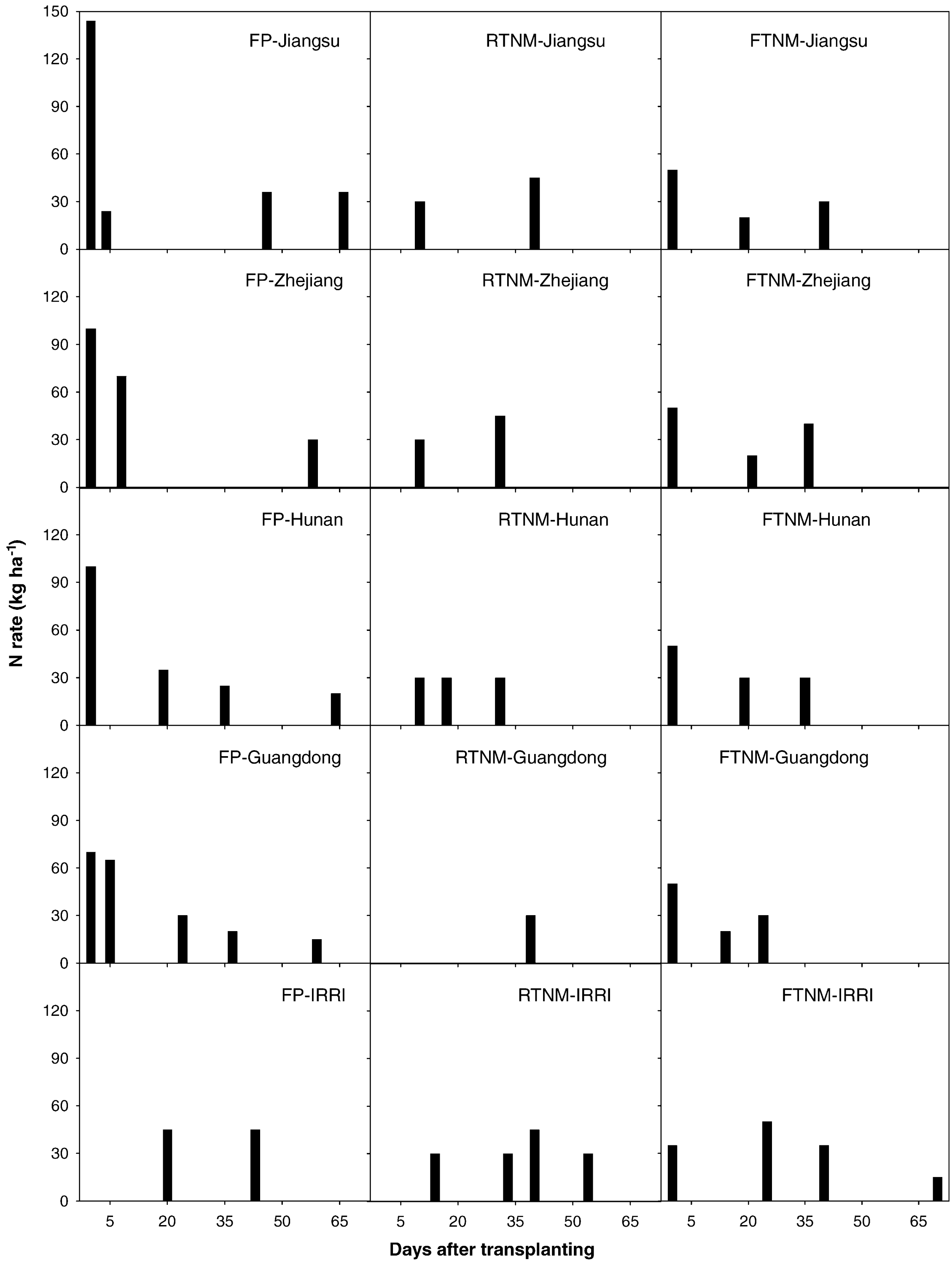

Fig. 1. Rate (kg N ha^{-1}) and timing (days after transplanting) of N application for farmers' fertilizer practice (FP), real-time N management using SPAD (RTNM), and fixed-time adjustable-dose N management (FTNM) at four sites in China in 2001 and at the International Rice Research Institute (IRRI) farm in the dry season of 2002.

In FTNM, total N rate ranged from 100 to 110 kg ha^{-1} with three splits at the Chinese sites and was 135 kg ha^{-1} with four splits at IRRI in year I (Table 4, Fig. 1). In year II, total N rate ranged from 100 to 120 kg ha^{-1} with three splits at the Chinese sites and was 110 kg ha^{-1} with three splits at IRRI. The differences in rate and number of N applications were relatively small across the five sites and across the two years in FTNM compared with RTNM.

Table 6
Average grain yield, total N uptake, internal N use efficiency (IE_N), recovery efficiency of N (RE_N), agronomic N use efficiency (AE_N), and partial factor productivity of applied N (PFP_N) of N treatments across four sites in China and two years (2001 and 2002)

Treatment[a]	Yield (t ha^{-1})	N uptake (kg ha^{-1})	IE_N (kg kg^{-1})	RE_N (%)	AE_N (kg kg^{-1})	PFP_N (kg kg^{-1})
CK	6.4 d	95 e	61.2 a	–	–	–
Fixed-60	7.4 ab	135 d	50.0 b	66 a	17.2 a	124 a
Fixed-120	7.6 a	170 bc	40.4 de	62 a	10.4 bc	64 c
Fixed-180	7.3 bc	196 a	34.5 f	56 ab	5.1 d	41 e
FP	7.2 c	194 a	34.8 f	48 b	3.6 d	35 f
MFP	7.6 a	178 b	39.2 e	57 ab	7.7 cd	52 d
RTNM	7.4 ab	140 d	47.3 c	66 a	14.5 ab	123 a
FTNM	7.7 a	165 c	42.2 d	66 a	11.8 bc	72 b
Source of variation						
Year (*A*)	**	NS	**	*	*	**
Site (*B*)	**	**	**	**	**	**
N (*C*)	**	**	**	**	**	**
A × *B*	**	**	**	**	**	**
A × *C*	*	NS	NS	NS	NS	**
B × *C*	**	**	**	NS	NS	**
A × *B* × *C*	**	NS	NS	NS	NS	**

NS, nonsignificant. Within a column, means followed by different letters (a–f) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.
[a] See Table 2 for details of N treatments.
* Significance at the 0.05 probability level.
** Significance at the 0.01 probability level.

3.2. Yield response

For the four Chinese sites, N treatment had a significant effect on grain yield (Table 6). The farmers' fertilizer practice produced the lowest yield among the treatments that received N application. The fixed-N split treatments with total N rate of 60 and 120 kg N ha^{-1} produced yield similar to that of the modified farmers' practice, RTNM and FTNM. The modified farmers' practice increased yield by about 6% compared with the farmers' practice. At Jiangsu, the modified farmers' practice increased yield by about 10% compared with the farmers' practice (Table 7). At other sites, including IRRI, the difference in yield between the modified farmers' practice and farmers' practice was not statistically significant. There was no significant difference in yield between RTNM and FTNM at all five sites.

Jiangsu had a higher grain yield than the other sites in both years (Table 7). A higher yield potential was expected at Jiangsu probably because of longer total growth duration caused by lower air temperature than the other sites. The differences in yield among Zhejiang, Hunan, Guangdong, and IRRI were relatively small and inconsistent across the two years. At Jiangsu and Zhejiang, yield was not significantly different between the two years. At Hunan and Guangdong, yield was lower in 2002 than in 2001. At IRRI, year II had higher yield than year I.

At the zero-N control, Jiangsu recorded the highest yield of 7.5 t ha^{-1} in 2001 and 6.9 t ha^{-1} in 2002 (Table 7). At Zhejiang, Hunan, and Guangdong, the average yield of the zero-N control was 6.6 t ha^{-1} in 2001 and 5.7 t ha^{-1} in 2002. These yields were 1–4 t ha^{-1} higher than the yield of the zero-N control at IRRI. At Jiangsu, the maximum yield increase from applied N was 2.2 t ha^{-1} in 2001 and 3.0 t ha^{-1} in 2002, which was higher than at the other three Chinese sites, where the maximum yield increase from applied N was 1.3–1.6 t ha^{-1} when the N response was significant. At IRRI, the maximum yield increase from applied N was 2.5 t ha^{-1} in year one and 3.0 t ha^{-1} in year two.

Table 7
Grain yield (t ha^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Control	7.5 c	6.7 a	6.6 b	6.4 b	3.5 c
Fixed-60	8.9 ab	7.2 a	7.7 a	7.3 ab	6.0 a
Fixed-120	9.7 a	6.5 a	7.9 a	7.7 a	5.7 ab
Fixed-180	8.9 ab	6.7 a	7.4 a	7.7 a	5.2 b
FP	8.7 b	6.5 a	7.4 a	7.7 a	5.9 ab
MFP	9.5 ab	6.9 a	7.6 a	7.3 ab	5.8 ab
RTNM	9.0 ab	6.7 a	7.7 a	6.8 ab	6.0 a
FTNM	9.5 ab	6.8 a	7.9 a	7.6 a	5.8 ab
Mean	9.0	6.7	7.5	7.3	5.5
Year II					
Control	6.9 e	5.7 b	5.6 c	5.8 a	4.6 c
Fixed-60	8.6 d	6.7 a	7.1 ab	5.9 a	6.0 bc
Fixed-120	9.9 a	7.0 a	7.2 a	5.3 a	6.9 ab
Fixed-180	9.4 bc	6.9 a	6.3 abc	5.2 a	7.0 ab
FP	8.9 d	6.5 ab	6.2 bc	5.4 a	6.4 ab
MFP	9.9 a	6.8 a	6.8 ab	5.8 a	6.5 ab
RTNM	9.4 c	6.9 a	7.0 ab	5.9 a	7.6 a
FTNM	9.7 abc	7.0 a	6.9 ab	5.9 a	7.2 ab
Mean	9.1	6.7	6.7	5.6	6.5

Within a column for each year, means followed by different letters (a–e) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.
[a] See Table 2 for details of N treatments.

Table 8
Total N uptake (kg ha^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Control	94 f	104 c	91 e	91 d	62 e
Fixed-60	136 e	137 b	134 d	137 bc	96 d
Fixed-120	190 c	163 ab	170 bc	160 ab	109 cd
Fixed-180	219 ab	175 a	211 a	182 a	140 ab
FP	233 a	173 a	196 ab	185 a	111 cd
MFP	202 bc	164 ab	187 ab	172 a	122 bc
RTNM	153 de	143 ab	151 cd	119 cd	144 a
FTNM	179 cd	155 ab	171 bc	156 ab	130 ab
Mean	176	152	164	150	114
Year II					
Control	99 f	84 d	85 d	115 d	69 e
Fixed-60	145 e	105 bcd	132 bc	153 bcd	100 d
Fixed-120	216 bc	132 abc	147 abc	180 abc	135 b
Fixed-180	242 a	146 a	177 ab	213 a	167 a
FP	241 ab	140 a	180 a	200 a	111 cd
MFP	238 ab	125 abc	165 abc	173 abc	135 b
RTNM	189 d	99 cd	131 c	137 cd	179 a
FTNM	208 cd	134 ab	138 abc	183 ab	135 bc
Mean	197	121	145	169	129

Within a column for each year, means followed by different letters (a–f) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.

[a] See Table 2 for details of N treatments.

3.3. N uptake

For the four Chinese sites, total N uptake was significantly different among the N treatments and the difference was consistent across the two years (Table 6). Among the five sites, Jiangsu generally had a higher total N uptake than the other sites when N was applied (Table 8). Overall, total N uptake was proportional to total fertilizer-N rate (Tables 4 and 8). At the Chinese sites, the farmers' fertilizer practice and a fixed-N split with total N rate of 180 kg N ha^{-1} usually had the highest total N uptake among the N treatments. The farmers' fertilizer practice had a 9% higher total N uptake than the modified farmers' fertilizer practice at the Chinese sites. The difference in total N uptake between RTNM and FTNM was not consistent across sites.

When N was not applied, total N uptake at the Chinese sites was 46% higher than that at IRRI (Table 8). There was no consistent difference in total N uptake in the zero-N control among the four Chinese sites. For Zhejiang, Hunan, Guangdong, and IRRI, where the two-year field experiments were conducted in the same fields and N treatments were assigned to the same experimental units, there was no consistent trend of a decline in total N uptake of the zero-N control from the first to the second year.

3.4. N use efficiencies

In general, IE_N was the highest when N was not applied and it decreased as the N rate increased (Tables 6 and 9). At the Chinese sites, the farmers' fertilizer practice and a fixed-N split with total N rate of 180 kg N ha^{-1} had the lowest IE_N among the N treatments. The modified farmers' fertilizer practice had a higher IE_N than the farmers' fertilizer practice at the Chinese sites, but the difference was not always significant. There was no significant difference between

Table 9
Internal N use effeciency (kg kg^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Control	73.1 a	57.0 a	65.1 a	63.2 a	61.9 ab
Fixed-60	62.4 b	40.9 b	51.8 b	54.3 b	63.6 a
Fixed-120	49.2 cd	35.6 cd	41.5 cd	45.1 cd	54.1 bc
Fixed-180	38.4 ef	32.2 d	32.8 e	40.6 d	42.5 d
FP	34.9 f	33.6 cd	34.5 e	42.4 cd	53.0 bc
MFP	42.8 de	36.7 bcd	37.0 de	46.4 c	50.1 cd
RTNM	53.0 c	37.7 bc	46.7 bc	54.4 b	45.0 cd
FTNM	48.0 cd	38.3 bc	42.1 cd	47.2 c	45.2 cd
Mean	50.2	39.0	43.9	49.2	51.9
Year II					
Control	62.8 a	60.1 a	55.9 a	52.2 a	62.5 a
Fixed-60	51.9 b	48.5 bc	44.9 b	45.2 ab	60.2 ab
Fixed-120	40.6 cd	44.2 bc	36.0 bc	31.4 d	52.2 c
Fixed-180	34.7 e	40.5 c	28.4 c	28.3 d	44.7 d
FP	32.9 e	42.2 c	28.7 c	29.5 d	55.3 bc
MFP	36.9 de	47.3 bc	31.6 c	34.8 cd	51.8 c
RTNM	45.4 c	55.0 ab	44.1 b	42.3 bc	45.5 d
FTNM	42.1 c	46.3 bc	37.4 bc	36.4 bcd	50.8 c
Mean	43.4	48.0	38.4	37.5	52.9

Within a column for each year, means followed by different letters (a–f) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.

[a] See Table 2 for details of N treatments.

RTNM and FTNM in IE_N except at Guangdong in 2001 and at IRRI in 2003. The differences in IE_N among the five sites were not consistent across the two years.

A significant difference among N treatments in RE_N was observed only at Jiangsu and at IRRI in both years (Table 10). Jiangsu had the highest RE_N while Zhejiang had the lowest RE_N among the Chinese sites. Overall, IRRI did not demonstrate a significantly higher RE_N than the Chinese sites. When data of the four Chinese sites were pooled, RTNM and FTNM had a significantly higher RE_N than the farmers' fertilizer practice (Table 6). There was no significant difference between RTNM and FTNM in RE_N at any site (Table 10).

Jiangsu had the highest AE_N among the four Chinese sites (Table 11). Negative values of AE_N occurred at Zhejiang in 2001 and at Guangdong in 2002 because there was no yield increase from the applied N. Excluding these two cases, AE_N was similar among Zhejiang, Hunan, and Guangdong, with an average value of 11 kg kg^{-1}. At IRRI, AE_N averaged about 20 kg kg^{-1}. There was a significant difference in AE_N among N treatments except at Guangdong in both years and at IRRI in 2003. At the Chinese sites, AE_N was lowest in the farmers' fertilizer practice (Table 6). At IRRI, AE_N was lowest at the highest N rate of 180 kg ha^{-1} (Table 11). The modified farmers' practice generally increased AE_N compared with the farmers' practice at the Chinese sites. Both RTNM and FTNM had a significantly higher AE_N than the farmers' practice at Jiangsu in both years and at Hunan in 2001. At IRRI, the modified farmers' practice, RTNM, and FTNM, did not improve AE_N over the farmers' practice. There was no significant difference in AE_N between RTNM and FTNM except at Zhejiang in 2002.

Large differences in PFP_N among the N treatments were observed at the Chinese sites (Table 6) and at IRRI (Table 12). At the Chinese sites, a fixed-N split with total N rate of

Table 10
Recovery efficiency (%) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Fixed-60	69 ab	55 a	71 a	77 ab	58 ab
Fixed-120	80 ab	49 a	66 a	58 ab	40 b
Fixed-180	69 ab	39 a	67 a	51 b	44 ab
FP	58 b	34 a	58 a	47 b	55 ab
MFP	63 ab	43 a	74 a	58 ab	44 ab
RTNM	78 ab	52 a	67 a	96 a	61 a
FTNM	85 a	46 a	72 a	66 ab	51 ab
Mean	72	46	68	65	50
Year II					
Fixed-60	77 ab	35 a	79 a	64 a	53 ab
Fixed-120	98 a	40 a	52 a	54 a	56 ab
Fixed-180	80 ab	34 a	51 a	55 a	55 ab
FP	59 b	28 a	53 a	43 a	47 b
MFP	82 ab	29 a	62 a	42 a	49 b
RTNM	85 a	33 a	62 a	51 a	74 a
FTNM	91 a	45 a	53 a	69 a	60 ab
Mean	82	35	59	54	56

Within a column for each year, means followed by different letters (a and b) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.
[a] See Table 2 for details of N treatments.

Table 11
Agronomic N use efficiency (kg kg^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Fixed-60	24.0 a	8.2 a	18.0 a	15.5 a	41.7 a
Fixed-120	18.2 ab	−1.1 b	11.1 bc	10.6 a	18.1 bc
Fixed-180	7.7 c	0.2 b	4.7 d	7.4 a	9.5 c
FP	5.0 c	−1.1 b	4.6 d	6.6 a	26.2 b
MFP	11.7 bc	1.2 b	8.0 cd	6.6 a	16.5 c
RTNM	19.7 ab	0.2 b	12.4 b	11.6 a	18.4 bc
FTNM	19.6 ab	1.1 b	11.8 b	12.1 a	17.0 bc
Mean	15.2	1.2	10.1	10.0	21.1
Year II					
Fixed-60	27.8 a	16.5 b	25.4 a	2.0 a	23.2 a
Fixed-120	24.6 a	10.4 bc	13.6 bc	−3.9 a	19.3 a
Fixed-180	14.0 b	6.4 c	3.7 cd	−3.0 a	13.5 a
FP	8.2 c	3.8 c	3.1 d	−1.8 a	20.0 a
MFP	17.3 b	7.5 bc	9.0 bcd	0.0 a	14.0 a
RTNM	23.8 a	26.3 a	18.8 ab	3.3 a	19.9 a
FTNM	23.5 a	12.1 bc	13.0 bcd	0.9 a	23.0 a
Mean	19.9	11.8	12.4	−0.4	19.0

Within a column for each year, means followed by different letters (a–d) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.
[a] See Table 2 for details of N treatments.

Table 12
Partial productivity of applied N (kg kg^{-1}) of N treatments at four sites in China in 2001 (Year I) and 2002 (Year II) and at the International Rice Research Institute (IRRI) farm in the dry season of 2002 (Year I) and 2003 (Year II)

Treatment[a]	Jiangsu	Zhejiang	Hunan	Guangdong	IRRI
Year I					
Fixed-60	149 a	119 a	128 a	122 b	101 a
Fixed-120	81 d	55 d	66 d	64 d	48 c
Fixed-180	49 e	37 e	41 f	43 ef	29 d
FP	36 f	32 e	41 f	39 f	66 b
MFP	56 e	49 d	59 e	52 de	43 c
RTNM	120 b	89 b	85 b	225 a	45 c
FTNM	95 c	62 c	72 c	76 c	43 c
Mean	84	63	70	89	53
Year II					
Fixed-60	143 a	112 b	119 a	98 b	100 a
Fixed-120	82 c	58 c	60 cd	44 d	58 cd
Fixed-180	52 e	38 e	35 e	29 e	39 e
FP	37 f	32 e	34 e	27 e	71 b
MFP	58 d	48 d	52 d	41 d	48 de
RTNM	90 b	153 a	94 b	131 a	51 de
FTNM	81 c	64 c	69 c	59 c	65 bc
Mean	78	72	66	61	62

Within a column for each year, means followed by different letters (a–f) are significantly different at the 0.05 probability level according to Tukey's multiple comparison test.
[a] See Table 2 for details of N treatments.

60 kg N ha^{-1} and RTNM had the highest PFP_N and the farmers' practice had the lowest PFP_N among the N treatments. At IRRI, a fixed-N split with total N rate of 60 kg N ha^{-1} had the highest PFP_N among the N treatments. At the Chinese sites, PFP_N was significantly higher in RTNM than in FTNM.

4. Discussion

The low AE_N of the farmers' N-fertilizer practice in irrigated rice was first reported by Wang et al. (2001) in Jinhua, Zhejiang Province. They measured AE_N in 21 farmers' fields for four seasons and found that the average AE_N of the farmers' N-fertilizer practice was 6.4 kg kg^{-1}. In this study, the low AE_N of the farmers' N-fertilizer practice in irrigated rice was confirmed in the other three provinces in China in addition to Zhejiang. At Zhejiang in 2001 and Guangdong in 2002, there was no significant yield response to applied N. Negative values of AE_N occurred in these two cases. Because AE_N was calculated by the ''difference method'' using yield of the omission-N plot, the negative values of AE_N indicate that the N-treated plot had a lower yield than the zero-N control. This was possible when excessive N application caused mutual shading, lodging, and pest damage in the N-treated plot. Excluding Zhejiang in 2001 and Guangdong in 2002, AE_N of the farmers' fertilizer practice at the Chinese sites ranged from 3.1 to 8.2 kg kg^{-1}, which is consistent with the values reported by Wang et al. (2001).

Much evidence suggests that farmers have overapplied N fertilizer to the rice crop at the study sites in China. First of all, maximum yield was achieved mostly at the N rate of 60–120 kg ha^{-1}, which is significantly lower than the 180–240 kg applied in the farmers' fertilizer practice at the Chinese sites. Second, the 30% reduction in total N rate in the farmers' practice increased yield in seven out of eight comparisons at the Chinese sites although the increase was significant only at the Jiangsu site in 2002. Third, the total N rate in RTNM and FTNM ranged from 30 to 120 kg ha^{-1} at the Chinese sites; however, the yield of RTNM and FTNM was higher than that of the farmers' practice except at the Guangdong site in 2001. Fourth, the yield increase from applied N was less than 3 t ha^{-1} at the Jiangsu site and less than 2 t ha^{-1} at the other three Chinese sites. If AE_N of 20 kg kg^{-1} can be achieved, the total fertilizer-N requirement would be 150 kg ha^{-1} at the Jiangsu site and 100 kg ha^{-1} at the other three Chinese sites. These N rates are substantially lower than the amount of N applied by farmers at the Chinese sites. The high input rate of fertilizer N was the most important factor that caused low AE_N of irrigated rice at the Chinese sites.

Another factor that caused low AE_N of irrigated rice at the Chinese sites was the improper timing of N application. A large proportion of total N was applied in the first 10 DAT in the farmers' fertilizer practice at the Chinese sites. In RTNM, however, no N was applied before 10 DAT and no significant yield reduction was observed in RTNM compared with the farmers' practice. In the modified farmers' fertilizer practice at the Chinese sites, a 30% reduction in the total N rate in the farmers' practice took place only within 10 DAT. Again, no significant yield reduction was observed in the modified farmers' practice compared with the farmers' practice. The high grain yield and total N uptake from the zero-N control at the Chinese sites compared with the IRRI site suggests that the soil at the Chinese sites could provide a sufficient amount of N for early vegetative growth of the rice crop. These results suggest that a reduction in the proportion of N applied at basal and during the early vegetative stage could be an effective way to improve the AE_N of irrigated rice at the study sites in China.

When N input was excessive in the farmers' N-fertilizer practice at the Chinese sites, the low AE_N was associated with poor IE_N, not with RE_N. This suggests that the fertilizer N absorbed by the crop was not converted into grain efficiently at the Chinese sites, where a high N rate resulted in luxury N consumption by the rice plants. A higher RE_N was observed at the Chinese sites, regardless of N treatment, compared with that of previous studies. Wang et al. (2001) reported RE_N of 18% in the farmers' N-fertilizer practice and 29% in FTNM in Zhejiang. The reason for the higher RE_N in this study was unclear. The optimal IE_N for irrigated rice is 68 kg kg^{-1} (Witt et al., 1999). In this study, most N treatments had an IE_N below this optimal level except for the zero-N control at Jiangsu in 2001. This suggests that there was room to improve N use efficiency at the Chinese sites and at IRRI in N-treated plots. When N was not applied, there was no significant difference in IE_N between the Chinese sites and IRRI. At the optimum N rate, RE_N, IE_N, and PFP_N were comparable between the Chinese sites and IRRI. Therefore, there is no intrinsic barrier to achieving high AE_N in irrigated rice in China. It is possible to achieve an AE_N as high at the Chinese sites as at IRRI with improved N management strategies.

In this study, doubling AE_N was achieved in the modified farmers' practice by a 30% reduction in the total N rate of the farmers' practice at the Chinese sites, except at Guangdong in 2001. RTNM and FTNM further increased AE_N at the Chinese sites. A similar improvement in AE_N was achieved even in the fixed-N split treatments with a total N rate of 60–120 kg N ha^{-1}. Hence, a quantum leap in AE_N is possible in irrigated rice at the study sites in China by simply reducing the current N rate and by allocating less N at the early vegetative stage. RTNM and FTNM would be useful in fine-tuning the optimum total N rate and better distributing N throughout the growing season for further improvement in AE_N. These strategies are also useful for managing season-to-season and field-to-field variability in crop N demand and soil N supply for achieving maximum AE_N.

The difference in yield between RTNM and FTNM was statistically insignificant at the Chinese sites. There was no difference between RTNM and FTNM in RE_N, but RTNM had higher IE_N, AE_N, and PFP_N than FTNM. The variation in total N rate across sites was smaller in FTNM than in RTNM. The overall performance of FTNM was better than that of RTNM at the Chinese sites because the total N rate of FTNM was closer to the optimal level than that of RTNM. The lower N rate of RTNM at the Chinese sites was due to the low critical SPAD value for determining the need of N application. The critical SPAD value of 35 was more suitable for indica rice varieties in the tropics than in the subtropics. Consequently, RTNM had a tendency to slightly reduce yield compared with the maximum yield at the Chinese sites. These results suggest that the critical SPAD value for maximum grain yield could be one to two units higher at the Chinese sites than at IRRI for the same variety. Both RTNM and FTNM are equally effective in improving AE_N when appropriately implemented.

Indigenous N supply capacity can be estimated by measuring aboveground plant N uptake in an N-omission plot at crop maturity under well-managed field conditions, that is, when all other nutrients except N are amply supplied and other constraints to growth such as water stress or pests are absent (Janssen et al., 1990). The biggest differences between the Chinese sites and IRRI were the yield level and total N uptake of the zero-N control. The yield level of the zero-N control at IRRI was similar to the reported values for farmers' fields in the Philippines and in other rice-growing countries in the tropics (Dobermann et al., 2003). The total N uptake of the zero-N control at the Chinese sites was higher than that at IRRI. This suggests a higher indigenous N supply capacity in the intensive rice-growing areas of China than in rice-growing countries in the tropics. The high indigenous N supply capacity at the Chinese sites may be associated with the high residual N from the previous crop because of the high amount of N applied and contaminated irrigation water that contains a high amount of N. However, Chinese rice farmers do not consider the high indigenous N supply capacity of the soil when they determine the total N rate for their rice crop, and the N rate of irrigated rice in China is much higher than in many other rice-growing countries.

The low yield level and total N uptake of the zero-N control at IRRI cannot be explained by soil chemical properties. This is because (1) the IRRI site had lower soil organic carbon and total N than the Jiangsu site, (2) the IRRI site had soil organic carbon and total N similar to those of the Zhejiang site, (3) all five sites had ample available soil P, and (4) IRRI soil contained 12 times more extractable K than the Chinese sites. Furthermore, soil testing could not explain the higher yield at Jiangsu than at the other sites because the Jiangsu site had the lowest soil organic carbon and total N among the five sites. The difference in the yield of the zero-N control between the Chinese sites and IRRI was associated with indigenous N supply capacity, not with yield potential. The greater yield in Jiangsu was probably due to the higher climatic yield potential caused by lower air temperature and/or higher solar radiation compared with the other sites.

5. Summary

The high input rate of fertilizer N and improper timing of N application in farmers' N-fertilizer management resulted in low AE_N of irrigated rice in China. The low AE_N of farmers' N-fertilizer practices at the Chinese sites was associated with poor IE_N and not with RE_N. There was a higher indigenous N supply capacity at the Chinese sites than at IRRI, but this was not considered by the rice farmers in determining total N rate for their rice crop. At the optimal total N rate, IE_N, RE_N, and AE_N at the Chinese sites were comparable with those of the IRRI site. Therefore, there is no intrinsic barrier to achieving high AE_N in irrigated rice in China. Overall, FTNM outperformed RTNM at the Chinese sites because the total N rate of FTNM was closer to the optimal level than that of RTNM. A quantum leap in AE_N is possible in irrigated rice at the study sites in China by simply reducing the current N rate and by allocating less N at the early vegetative stage. Government policy intervention is necessary to reduce the total N rate of irrigated rice in China. The extension service will be crucial to help farmers improve the timing of N application. Further improvement in AE_N will be possible at the Chinese sites by adopting knowledge-intensive technologies of fertilizer management such as RTNM and FTNM.

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