Journal of Plant Nutrition

ISSN: 0190-4167 (Print) 1532-4087 (Online) Journal homepage: http://www.tandfonline.com/loi/lpla20

Optimizing Fertilizer Nitrogen for Winter Wheat Production in Yangtze River Region in China

Q. Yi, P. He, X. Z. Zhang, L. Yang & G. Y. Xiong

To cite this article: Q. Yi, P. He, X. Z. Zhang, L. Yang & G. Y. Xiong (2015) Optimizing Fertilizer Nitrogen for Winter Wheat Production in Yangtze River Region in China, Journal of Plant Nutrition, 38:11, 1639-1655, DOI: 10.1080/01904167.2015.1061547

To link to this article: http://dx.doi.org/10.1080/01904167.2015.1061547

Accepted online: 06 Jul 2015.

Journal of Plant Nutrition, 38:1639–1655, 2015

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904167.2015.1061547

OPTIMIZING FERTILIZER NITROGEN FOR WINTER WHEAT PRODUCTION IN YANGTZE RIVER REGION IN CHINA

Q. Yi,[1,2] P. He,[1] X. Z. Zhang,[1] L. Yang,[3] and G. Y. Xiong[3]
[1]*Ministry of Agriculture Key Laboratory of Crop Nutrition and Fertilization, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China*
[2]*Guangdong Key Laboratory of Recycling of Nutrient Resources and Land Conservation, Institute of Agricultural Resources and Environment, Guangdong Academy of Agricultural Sciences, Guangzhou, China*
[3]*Institute of Plant Protection and Soil Fertilization, Hubei Academy of Agricultural Sciences, Wuhan, China*

□ *Excessive nitrogen (N) application has been considered as one of the reasons for restricting yield increases in rice-wheat rotation system in the Yangtze River area. From 2007 to 2009, field experiments were conducted to evaluate the effects of optimized N management on grain yield, nitrogen use efficiency (NUE) and N surplus of winter wheat in Jianghan Plain (Hubei province, China). Results indicated that grain yield and crop N uptake of treatments with reducing fertilizer N ($N_{135(2)}$ for the first year and $N_{120(3)}$ for the second season) did not significantly reduce yield compared to farmers' practice (FP). Under the same amount of N application, three-time splitting improved grain yield and enhanced NUE as compared with two-time splitting. The optimized N treatment of $N_{135(2)}$ and $N_{120(3)}$ was observed with higher NUE parameters, i.e. recovery efficiency (RE_N), agronomic efficiency (AE_N) and partial factor productivity (PFP_N). Positive correlation between SPAD value and leaf N concentration provided the effective tool to evaluate N status during the growth season. The optimized N rate and top dressing frequency could reduce the residual N retained in the 0–20 cm soil layer after harvest, which could reduce the possibility of soil N loss to the environment. This paper provides insights into N management strategy based on farmers' practices, which could be regarded as a guideline to improve agricultural management for wheat growth season.*

Keywords: nitrogen, winter wheat, SPAD, optimizing fertilization, Yangtze River region.

Received 28 December 2011; accepted 3 April 2015.
Address correspondence to P. He, Ministry of Agriculture Key Laboratory of Crop Nutrition and Fertilization, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing100081, China. E-mail: phe@caas.ac.cn

INTRODUCTION

Winter wheat (*Triticum aestivum* L.), as a major staple crop, is widely planted in China and about 23% of wheat production is distributed in the middle and lower Yangtze valleys and southwestern China (Wang et al., 2009). As the increase of population and the decline of cropping area in China, increasing wheat yield become more urgent (Zhu and Chen, 2002). Local farmers often apply excessive nitrogen (N) fertilizers as an "insurance" against low yields. A recent investigation on N application in Yangtze River region has shown that farmer's N application rate ranged from 36 to 345 kg N ha^{-1}, and 23% of farmers' N application rate was much higher than the government recommendation. Excessive and imbalanced N application resulted in not only yield stagnant, but also low nutrient use efficiency and high environmental risk (Alam et al., 2006; Yi et al., 2010). Zhang et al. (2008) reported that nitrogen use efficiency (NUE) of wheat ranged from 8.9% to 78.9% (averaged in 28.7%) and the wheat NUE varied from 10.8% to 40.5% (averaged in 27.5%) in different regions. The possible reason for low NUE in this region was caused by imbalanced fertilizer N application. Firstly, the total N application rate was excessive and unbalanced that could result in plant lodging and decrease of wheat yield. In consequence, the lower yield led to profit losses and higher soil residual N to increase environment pollution. Secondly, the ratio of basal and top dressing in fertilizer N application was unreasonable. Large proportion of fertilizer N was applied at early growth stage when little N was required by plant and small amount of N was applied not adequate to feed crop N uptake at late growth stage (i.e. panicle initiation). During last decades, many efforts have been taken on wheat N management strategies to improve NUE. The site-specific N management method has been used in wheat and it has been proved to be less input, higher grain yield and more profitability (Khurana et al., 2008a; 2008b). A method based on soil plant analyzer development (SPAD), that is chlorophyll meter, which can be used to monitor N status of crops and determine the timing of topdressing, was also considered to be functional to guide N application in winter wheat (Shuakla et al., 2004; Arregui et al., 2006; Alam et al., 2006). The critical N concentrations and soil mineral N (N_{min}) level test methods could be regarded as good indicators for evaluating and improving wheat production in North China Plain (NCP) (Cui et al., 2008, 2009; Chen et al., 2006). Several studies on N managements, such as crop-residue management, mulching cultivation and the incorporation of organic fertilizer application (Sharma and Prasad, 2008; Yadvinder-Singh et al., 2009a, 2009b; Liu et al., 2003), were well advocated in the rice-wheat rotation system. Apparently, all of these methods have made some progresses on improving grain yield and NUE. However, attempts to fertilizer N saving and NUE improvement in winter wheat, particularly for N in-season management, have not been well carried out in Yangtze River region.

The present study was conducted in farmer's fields in Qianjiang of Jianghan Plain, Hubei Province from 2007 to 2009. The goals of this study were: to determine the optimum fertilizer N rate and basal-top dressing frequency to synchronize N supply with crop requirement, to improve NUE with high yield of winter wheat and to reduce soil N surplus.

MATERIALS AND METHODS

Experimental Site

Field experiments were conducted from November 2007 to May 2009 at Liuzhou village, Qianjiang county, Hubei province, China (30°22′ 54.5″ N, 112°37′ 21.5″E), which were located at the Jianghan Plain in Yangtze River region. The region belongs to humid sub-tropical region with a monsoon climate, and the average annual temperature and precipitation are 15–17°C and 1150 mm, respectively. Monthly averages of maximum and minimum temperature revealed the relative year-to-year consistency during the whole wheat growth season (Figure 1). In contrast, total precipitation fluctuated from October to next March, and then was relatively higher from March to June in 2008/09 compared with 2007/08 season. The two sites were located in the same village, and there are only about 10–20 meters far away from each other, so the soil fertility and soil type were extremely similar; and the chemical properties of tested soil in the 0-20 cm soil layer in two experiment sites were as follows: pH 7.1, organic matter (OM) 20.62 g kg^{-1}, total N 1.53 g kg^{-1}, Olsen P 19.2 mg kg^{-1}, ammonium acetate-extractable (NH_4OAc-K) 72.5 mg kg^{-1} (site 1) and pH 7.2, OM 19.27 g kg^{-1}, total N 1.12 g kg^{-1}, Olsen P 16.4 mg kg^{-1}, NH_4OAc-K 184.4 mg kg^{-1} (site 2), respectively.

Experimental Design and Treatment

In 2007/08, field experiment was carried out using a complete randomized block design with three replications and plot sizes of 5×8 m^2. The experiment consisted of six N treatments : N_0, zero N application; $N_{225(2)}$, farmers' practice (FP), 225 kg N ha^{-1}, 1/2 as basal and 1/2 as topdressing at tillering stage; $N_{180(2)}$, 20% N reduction of FP (180 kg N ha^{-1}, 1/2 as basal and 1/2 as topdressing at tillering stage); $N_{158(2)}$, 30% N reduction of FP (158 kg N ha^{-1}, 1/2 as basal and 1/2 as topdressing at tillering stage); $N_{135(2)}$, 40% N reduction of FP (135 kg N ha^{-1}, 1/2 as basal and 1/2 as topdressing at tillering stage); $N_{158(3)}$, 30% N reduction of FP (158 kg N ha^{-1}, 1/3 of N equally applied as basal before sowing, topdressing at tillering and at booting, respectively). In 2008/09, the plot size and replications were the same as 2007/08, but N treatments were adjusted according to the results of previous year. Five N treatments were arranged as below: N_0 (0 kg N ha^{-1}), $N_{60(3)}$ (60 kg N ha^{-1}), $N_{120(3)}$ (120 kg N ha^{-1}), $N_{180(3)}$ (180 kg N ha^{-1}), and

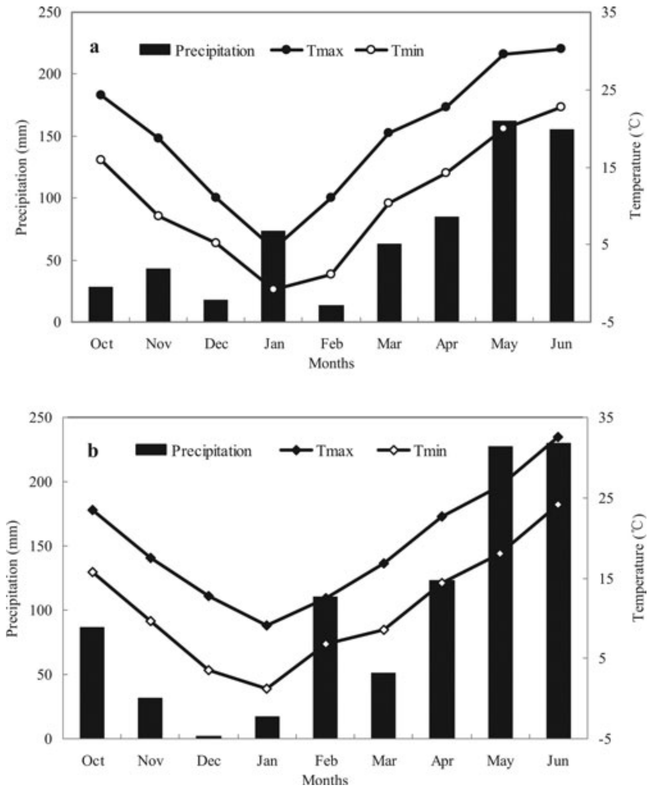

FIGURE 1 Total precipitation and averages of the maximum and minimum temperature for winter-wheat growing periods in A) 2007/08 and B) 2008/09.

$N_{240(3)}$ (FP with 240 kg N ha^{-1}). N fertilizer was applied in three frequencies; i.e., 1/3 of basal dressing before sowing, 1/3 of topdressing at tillering and 1/3 of top dressing at booting.

All plots across two years received 90 kg phosphorus pentoxide (P_2O_5) ha^{-1} (superphosphate) as basal dressing and 120 kg K_2O ha^{-1} (Potassium oxide) with half as basal and half as topdressing at tillering. The tested cultivar of winter wheat for two years was Zhengmai 9023, a dominant variety widely planted in this region. Farmers' normal crop management practices were used for all treatments through two years.

Sampling and Data Analysis

Soil samples were collected from a depth of 100 cm with 20 cm increments at the critical growth stages. Six to ten soil cores were sampled and then mixed thoroughly and quickly. Fresh subsoil samples were carried to laboratory in an ice box and analyzed in a timely fashion. The ammonia-N (NH_4^+-N) and nitrate-N (NO_3^--N) of the soil samples were extracted with 1:5 ratio (g: ml) of soil sample to potassium chloride (KCl) solution

($1\ mol\ L^{-1}$) and oscillated for 45 min, analyzed with Continuous Flow Analysis (FIASTAR 5000, Foss Tecator, Hillerød, Denmark). Soil moisture content was measured by oven drying at 105 °C for eight hours. Five to ten plant samples were collected per plot at the same time during the growing stages. Samples of straw and grain were dried at 70 °C to a constant weight, and then analyzed for total N concentration with Kjeldahl method (Bremner, 1996). Grain yield was obtained on harvested areas of 3.5 m^2 and adjusted to 13.5% moisture content.

Meanwhile, the chlorophyll meter value was measured using a SPAD-502 meter [SPAD-502; Soil-Plant Analysis Development (SPAD) Section, Minolta Camera Co., Osaka, Japan] on ten topmost fully expanded leaves per plot at the critical growth stages (Peng et al., 1993).

Calculations and Statistical Analysis

Nitrogen harvest index (NHI) and three NUE parameters (apparent recovery efficiency (RE_N), agronomic efficiency (AE_N) and partial factor productivity of N (PFP_N)) were calculated based on formulas from Fageria et al. (2008) and Dobermann (2007):

$$\text{NHI}\ (\%) = U_0/U_F \times 100$$

$$RE_N(\%) = (U_F - U_0)/N_a \times 100$$

$$AE_N(\text{kg grain , yield increased per kg N applied}) = (Y_F - Y_0)/N_a$$

$$PFP_N(\text{kg yield per kg N applied}) = Y_F/N_a$$

Where Y_F and Y_0 are grain yields in N_a plots (kg) and N_0 plot (kg), N_a is the amount of N applied (kg), U_F and U_0 are the above-ground crop N uptake in N_a plots (kg) and N_0 plot (kg), respectively.

Analysis of variance (ANOVA) was performed on grain yield and N concentration data to test for significance of treatments and multiple comparisons of the treatment means were compared by SSR at the 5% level using SAS (SAS 8.0).

The surplus N was calculated with the following equation:

$$\text{Surplus N} = \text{N input} - \text{N output}$$

Where N inputs included fertilizer N application and indigenous nitrogen supply (INS) which was defined as the sum of other N sources from seed, initial soil mineral N, dry and wet air deposition, biological N fixation and N mineralization (Jassen et al., 1990). N outputs only considered the N removal by grain and straw at harvest.

TABLE 1 Grain yield and N use efficiency of the winter-wheat in 2007/08 and 2008/09

Year	Treatment	Yield	N uptake	NHI	RE_N	AE_N*	PFP_N
		kg ha^{-1}	kg N ha^{-1}	%		kg kg^{-1}	
2007/08	N_0	3493 b†	80.3d	80.7a			
	$N_{225(2)}$ ‡	4246 a	203.6a	53.9c	54.8a	3.3c	18.9d
	$N_{180(2)}$	4327 a	189.4ab	59.1bc	60.6a	4.6bc	24.0c
	$N_{158(2)}$	4268 a	161.2c	64.1b	53.6a	4.9bc	27.1b
	$N_{135(2)}$	4577 a	170.3c	66.8b	66.6a	8.0a	33.9a
	$N_{158(3)}$	4393 a	165.3c	64.5b	53.9a	5.7b	27.9b
2008/09	N_0	1529 e	39.0d	64.7a			
	$N_{60(3)}$	2683 b	80.1c	64.9a	68.5a	19.3a	44.7a
	$N_{120(3)}$	2932 a	94.0bc	64.2a	45.8b	11.7b	24.4b
	$N_{180(3)}$	2367 c	114.9ab	49.2b	38.5bc	4.7c	13.2c
	$N_{240(3)}$	1778 d	118.2ab	38.0bc	33.0c	1.0d	7.4d

† Within each column, means followed by different letters are significantly different ($P < 0.05$).
‡ Treatment $N_{225\ (2)}$ in 2007/08 and treatment N_{240} in 2008/09 was considered as the farmers' fertilizer practice respectively.
* AE_N, Agronomic efficiency of nitrogen; NHI, Nitrogen harvest index; PFP_N, Partial factor productivity of nitrogen; RE_N, Recovery efficiency of nitrogen.

RESULTS

Grain Yields and N Use Efficiency

N application significantly increased grain yields in both years (Table 1). Compared with FP (225 kg N ha^{-1} for 2007/08 and 240 kg N ha^{-1} for 2008/09), there was no significant yield decrease with reducing N application rate, suggesting that fertilizer N can be saved without sacrificing grain yield. Additionally, it was noted that the highest grain yield was recorded with $N_{135(2)}$ treatment in 2007/08, which was partly due to spike length and grain numbers per ear (data not shown). For the second year, yield increased with N application when N application rate was below 120 kg N ha^{-1}, however, N application rate beyond 120 kg N ha^{-1} gave no significantly further yield increase. As compared with FP treatment over two years, the optimum N application rates for maintaining higher yield were 135 kg N ha^{-1} for 2007/08 and 120 kg N ha^{-1} for 2008/09, indicating that excess N application was proved to be happened in this area.

In addition, the grain yield of 2007/08 (ranged from 3494 to 4577 kg ha^{-1}) was almost doubled as compared with that of 2008/09 (ranged from 1529 to 2932 kg ha^{-1}). The results mostly attributed to the continuous heavy rainfall and crop lodging at harvest in 2008/09.

N uptake increased with N application rate and FP treatment achieved the highest N uptake for two years. However, the N harvest index (NHI) of FP treatment was observed to be lower than other N treatments, indicating that

TABLE 2 Total N uptake at maturity in biomass and grain, N uptake, N translocation after heading and translocation efficiency of winter wheat in both years

Year	Treatment	N uptake at maturity			
		Straw	Grain	N translocation†	N translocation efficiency‡
		kg N ha^{-1}			%
2007/08	N_0	13.0	67.3	24.5	65.4
	$N_{225(2)}$	84.9	118.7	11.9	12.3
	$N_{180(2)}$	83.3	106.1	31.8	27.6
	$N_{158(2)}$	64.0	105.6	27.0	29.6
	$N_{135(2)}$	56.1	114.2	23.6	29.6
	$N_{158(3)}$	57.4	107.8	48.2	45.6
	$LSD^{*}_{(0.05)}$	13.0	32.2	16.4	16.8
2008/09	N_0	13.8	25.2	34.9	71.7
	$N_{60(3)}$	28.1	52.0	57.3	67.1
	$N_{120(3)}$	33.7	60.4	59.0	63.7
	$N_{180(3)}$	61.9	53.0	89.0	59.0
	$N_{240(3)}$	73.3	44.9	80.1	52.2
	$LSD_{(0.05)}$	6.3	6.7	26.2	12.7

† Translocated N (kg N ha^{-1}) = Total whole plant N at heading −N content in straw at maturity.
‡ Translocation efficiency (%) = Translocated N / total whole plant N at heading.
*LSD: Least significant difference.

although more N application resulted more N absorption to some extent, while, the absorbed N could not translocated into grain efficiently. The treatments of $N_{135(2)}$ in 2007/08 and $N_{120(3)}$ in 2008/09 obtained higher NHI, demonstrating that the absorbed N could translocate into grain better. The check treatments got the highest NHI from over translocation from vegetative parts due to early senescence (Tables 1 and 2).

For NUE parameters in 2007/08, no significant differences among N treatments were found for RE_N, but the treatment $N_{135(2)}$ achieved significant higher AE_N and PFP_N than those of FP treatment and other N treatments. The values of RE_N, AE_N and PFP_N obtained by treatment $N_{135(2)}$ were 66.6%, 8.0 kg kg^{-1} and 33.9 kg kg^{-1}, which were 1.21, 2.42, and 1.79 times of the FP treatment. For the year 2008/09, NUE parameters reduced with increment of N application, and the treatment $N_{120(3)}$ with highest grain yield obtained relatively higher RE_N, AE_N and PFP_N, which were 1.39, 11.7 and 3.30 times of the FP treatment.

It was also deserved mentioning that under the same N level in 2007/08, grain yield and NUE parameters followed the trends: $N_{158(2)} < N_{158(3)}$, indicating that splitting fertilization for three times could improve yield and NUE than splitting fertilization for twice. Therefore, fertilizer N was adjusted to be applied by three times split applications in 2008/09.

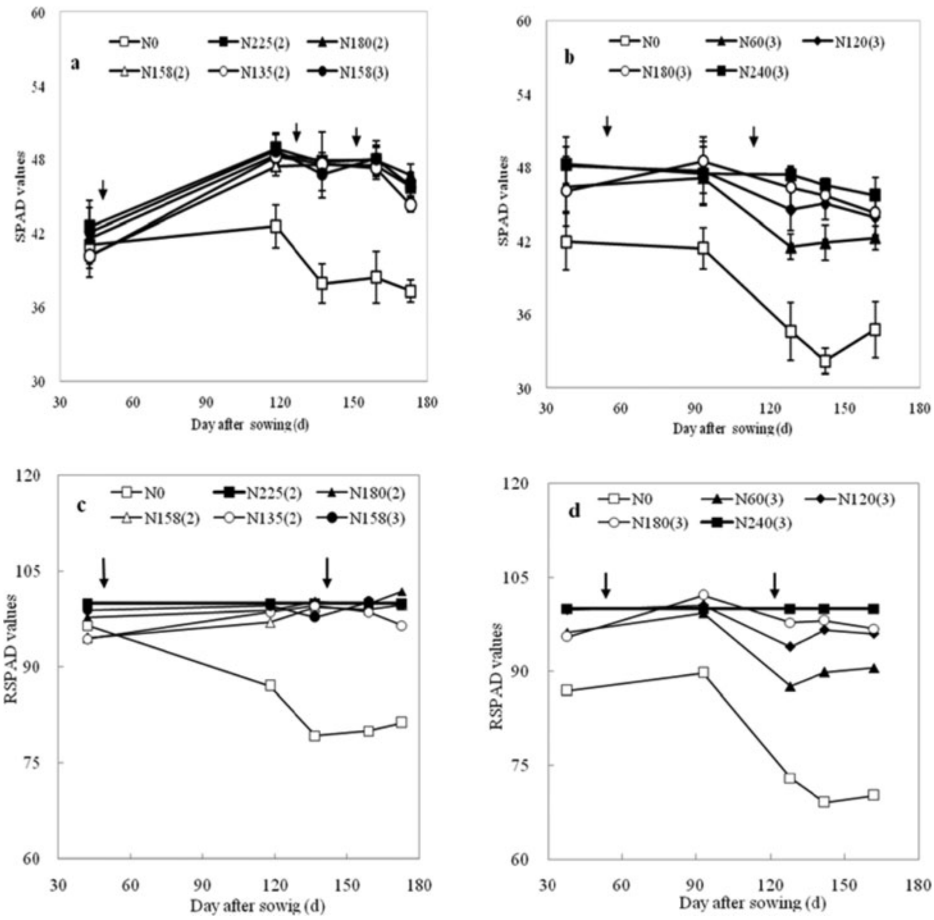

FIGURE 2 Chlorophyll meter (SPAD) values and relative SPAD (RSPAD) values of winter-wheat during the growing season in A, C) 2007/08 and B, D). 2008/09 growing seasons.

Leaf Chlorophyll Meter Values

It was well known that chlorophyll meter values of leaves during the growth stages of wheat could well reflect the status of soil N supply (Bijay-Singh et al., 2002). The SPAD values of wheat leaves increased with N application rates during the growth season across two years (Figure 2), and N_0 treatment had the lowest SPAD value compared with N treatments. In 2007/08 growing season, little differences existed for SPAD values among different N treatments, and the trend was similar to grain yield. In 2008/09 growing season, the SPAD values increased significantly with N application rates, and the variation trend of SPAD was followed $N_{240(3)} > N_{180(3)} > N_{120(3)} > N_{60(3)} > N_0$ (Figure 2).

The relative SPAD (RSPAD) values can be used clearly to indicate the adequate or lack of N status (Varvel et al., 1997). For example, in 2007/08

TABLE 3 Coefficient of determination (r^2-value) among yield, N uptake and N concentration with SPAD values in wheat

Year	Growth stage	Items	Equation	r^2
2007/08	Jointing	SPAD-Yield	$y‡ = -12.79x^2 + 1213† - 24366$	0.92
		SPAD-Total N uptake	$y = -0.002x^2 + 0.444x + 27.28$	0.91
		SPAD-N concentration in leaves	$y = 6.094x + 31.38$	0.92
	Heading	SPAD-Yield	$y = -32.73x^2 + 2913x - 60125$	0.93
		SPAD-Total N uptake	$y = -0.002x^2 + 0.481x + 23.69$	1.00
		SPAD-N concentration in leaves	$y = 10.15x + 31.09$	0.96
2008/09	Jointing	SPAD-Yield	$y = -28.28x^2 + 2355x - 46145$	0.89
		SPAD-Total N uptake	$y = -0.002x^2 + 0.546x + 15.02$	0.97
		SPAD-N concentration in leaves	$y = 8.300x + 26.59$	0.98
	Heading	SPAD-Yield	$y = -21.82x^2 + 1759x - 32515$	0.74
		SPAD-Total N uptake	$y = -0.002x^2 + 0.599x + 8.382$	0.98
		SPAD-N concentration in leaves	$y = 7.192x + 29.65$	0.69

† x = SPAD value.
‡ y = Yield, Total N uptake, N concentration in leaves.

growing season, the RSPAD value of N_0 treatment was just 85% of $N_{225(2)}$ treatment, while the RSPAD values of all other N treatments were higher than 95% of $N_{225(2)}$ treatment, suggesting that N application rates (> = $N_{135(2)}$ treatment) had enough N supply for high yield in 2007/08. Similarly, it could be found that N supply of treatment $N_{60(3)}$ was insufficient for the higher yield because the RSPAD value was much lower than the higher N treatments (> = $N_{120(3)}$), which was adequate for the second year since little drop of RSPAD value as compared with ample N supply of $N_{240(3)}$ treatment (Figure 2).

Regression analyses between SPAD values and yield, total N uptake and N concentration in leaves at jointing and at heading were carried out. And the results indicated that positive correlation existed between SPAD values and yield, N uptake and N concentration in leaves in both years (Table 3). N concentration in tested leaves responded to SPAD values at jointing and heading stages could be well fitted by a linear model. The regression between grain yield and total N uptake and SPAD values at jointing and heading stage could be best fitted by a quadratic model. It was demonstrated that the SPAD values could be regarded as a practical indicator for monitoring N status at critical growth stages in in-season N management.

Treatment $N_{135(2)}$ in 2007/08 and N_{120} in 2008/09 obtained the highest yield in each season, and their SPAD values showed no significant differences to FP treatment with highest SPAD values, indicating that efficient N application could supply N timely and sufficiently with crop requirement for maintaining high yield without losing N.

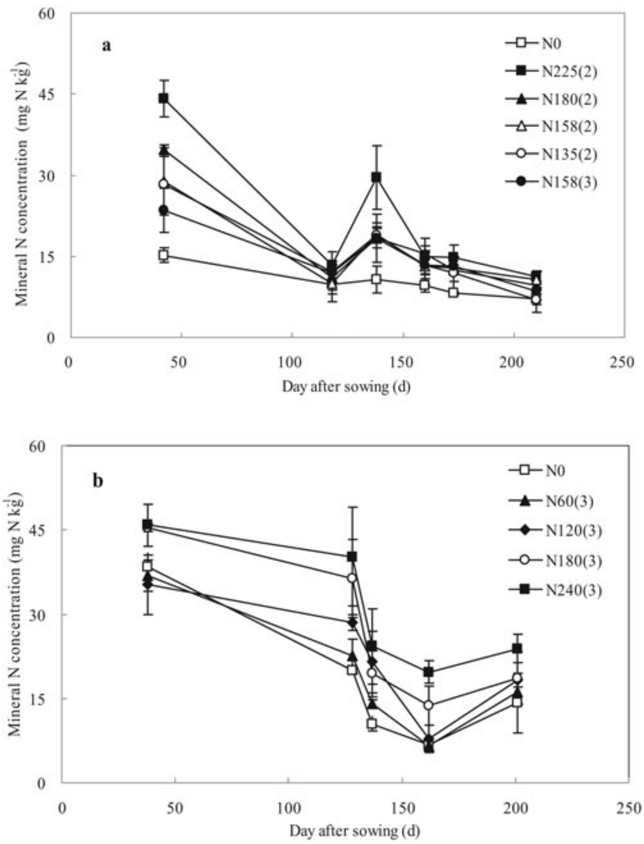

FIGURE 3 Dynamics of soil mineral N concentration in the 0–20 cm soil layer during the growing seasons of winter-wheat in A) 2007/08 and B) 2008/09.

Soil Mineral N

Soil Mineral N Dynamic

Soil N_{min} (i.e. NO_3-N plus NH_4-N) in the 0–20 cm layer varied greatly during the growth season and increased with fertilizer N levels (Figure 3). At the seedling stage, the N_{min} of all treatments in 2007/08 and 2008/09 experiments exhibited the highest levels, ranging from 15.2 to 44.2 mg N kg^{-1} in 2007/08 and 35.2 to 45.9 mg N kg^{-1} in 2008/09. During the earlier stage in 2007/08 growing season, the N_{min} decreased gradually as a result of plant uptakes of soil N, but the soil N_{min} increased sharply for treatment $N_{225(2)}$ after topdressing at jointing stage [130 days after sowing (DAS)]. After that, the soil mineral N decreased gradually and from 130 DAS to harvest. At harvest time, it was clear that the soil mineral N in FP treatment was relatively higher than those of other treatments while soil mineral N in $N_{135(2)}$ plot had the relative lower level during entire growing

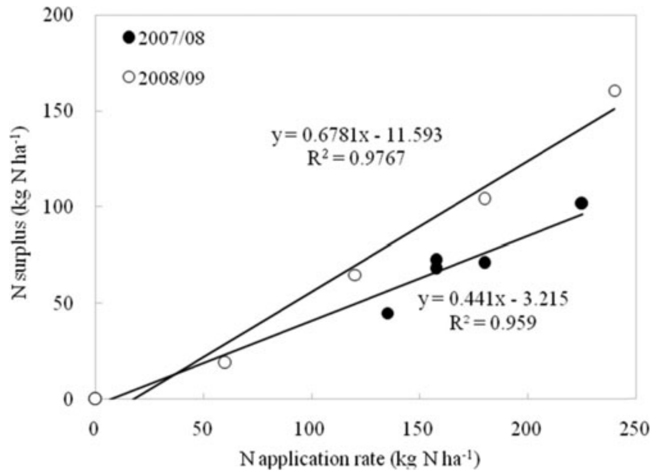

FIGURE 4 The relationship between N application rate and N surplus in 2007/08 and 2008/09 winter-wheat growing seasons.

season excepting N_0 treatment. Compared with $N_{158(2)}$, $N_{158(3)}$ plot had the lower level N_{min}, and this result demonstrated that $N_{158(3)}$ treatments with three splitting N applications were able to reduce the soil mineral N, and then decrease the risk of soil mineral N loss, especially with high precipitation before harvest (Figure 3a). In 2008/09 season, soil N_{min} in 0–20 cm layer declined from sowing to the 4th soil sampling stage (i.e., 160DAS), and then it increased at harvest due to loading in 2008/09 season. The N_{min} trend also revealed that higher fertilizer N levels resulted in a higher soil N_{min} during the growing seasons, especially in 2008/09 season (Figure 3b).

N Surplus

N surplus, calculated by the difference between N inputs and N outputs, is another NUE indicator, which could indicate how much annual inputs of N left in soil after harvest. The more soil N surplus, the higher N lost during non-growing season (De Jong et al., 2009). Our results showed that N surplus values ranged from 45.0 to 101.7 kg N ha^{-1} (averaged 59.1 kg N ha^{-1}) in 2007/08 season among all N treatments, accounting for 33.4 to 46.1% of N application rates. While, N surplus values ranged from 18.9 to 160.8 kg N ha^{-1} (averaged 69.8 kg N ha^{-1}) in 2008/09 season, accounting for 31.5% –67.0% of N application rates. Correlation analyses showed that N surplus was linearly related to N application rates in both years (i.e., $R^2 = 0.94$ and 0.98, respectively). The results indicated that 43.7% and 67.8% of fertilizer N were left in soil after harvest in 2007/08 and 2008/09 seasons, respectively (Figure 4).

These results concluded that excessive amounts of fertilizer N were not uptaken by wheat crop, and the N surplus were not only a manifestation of N resource waste, but also a potential risk to environment pollution. Thus, it is necessary to improve NUE and reduce N loss by optimizing N application rates and adjusting the timing of N fertilization.

DISCUSSION

Relationship of N Application and N Use Efficiency

Many studies reported that NUE of wheat in China was lower than that of world average level due to unbalanced and excessive use of N fertilizer in last two decades (Cassman et al., 2002, Dobermann et al., 2002; Ladha et al., 2005; Ma et al., 2009; Ju et al., 2009). Wang et al. (2004) showed that the appropriate N application rate for wheat was 180 to 225 kg N ha^{-1}, while, some other researchers reported that the current N application rate of single season winter wheat has reached to 270 kg N ha^{-1}, and even more than 300 kg N ha^{-1} in some high yielding areas. Zhang et al. (2008) confirmed that low N efficiency was mainly ascribed to excessive N fertilization, and their results also showed that RE_N decreased with N application when N application was over 240 kg N ha^{-1}. Meng et al. (2007) indicated that under the high fertility soil conditions, the recommended N application rate should be about 150 kg N ha^{-1}. Since the soil nitrate-N accumulation was mitigated when the N fertilizer amount was between 0–180 kg N ha^{-1}, while over this level, soil nitrate accumulation would substantially increase. Timsina et al. (2001) reported that more than half of the applied N was lost because N supply could not synchronize with the crop N demand. In this situation, high N inputs would increase the concentration of soil residual N and negatively impact to the environment. Thus, more attention has been paid to improve NUE, optimize N application and minimize environment effects in recent years (Cui et al., 2010). Liu et al. (2004) demonstrated that reduction of fertilizer N could significantly enhance NUE and decrease the accumulation of nitrate-N and N loss in high fertility soils. Further analysis demonstrated that negative correlation existed between RE_N, $AE_{N,}$ PFP_N and N application rate (Figure 5), which was consistent with previous observation (He et al., 2009). It was suggested that the higher RE_N, $AE_{N,}$ PFP_N could be reached either by lowered N application rate in the N overuse areas, or by improved N management to improve NUE. In this study, the optimum N application rate of 135 kg N/ha in 2007/08 and 120 kg N/ha in 2008/09 achieved both high grain yield and NUE parameters. The FP treatment with excessive N application could not increase wheat grain yield further, great potential for N saving and efficiency improvement existed for winter wheat in Yangtze River region.

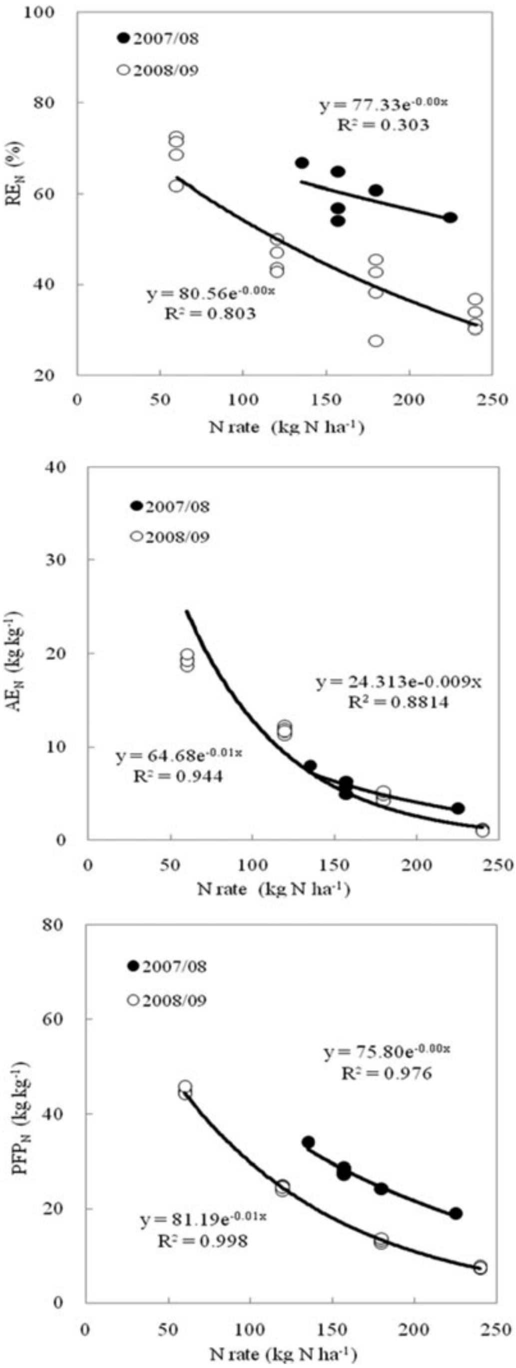

FIGURE 5 Effect of N treatments on nitrogen utilization parameters in 2007/08 and in 2008/09.

Optimized N in Season Management by Splitting Application

Another major reason for low NUE would be attributed to the incongruous between N supply and crop N demand for time scale. The farmers' current N fertilization in wheat was that all fertilizer N was applied as basal fertilizer in one time or in two splits as basal and topdressing with imbalanced ratio (Wang et al., 2002, Chen, 2009). As the N requirement at early stage was relatively low, too much fertilizer N could not completely absorbed by crops but lose through volatilization, nitrification, leaching or leakage. Moreover, soil N supply with less N fertilizer application at later stage could not meet crop requirement for growth, which would affect grain yield. Thus, it was important to optimize both N application rates and application times. The results of this study suggested that splitting N could improve grain yield and enhance NUE efficiently under the same amount of N fertilizer, which was in agreement with many other researches (Anderson et al., 1985). Arregui and Quemada (2008) proposed that it was a great strategy to coordinate the input and output of N harmoniously by splitting of N fertilizer application. Research also showed that postponing N application from basal to re-greening stage could improve wheat grain yield and NUE (Chen et al., 2008). In addition, Shukla et al. (2004) reported that INS could be a simple and convenient indicator to determine whether basal N fertilization was necessary or not. They also demonstrated that NUE could be increased without any basal application at planting for wheat crops since the INS was sufficiently high (35–45 kg N/ha). In this study, the INS was 80.3 kg N ha^{-1} in 2007/08 and 39 kg N ha^{-1} in 2008/09, respectively, and both were at high level of N supply. In this case, basal N fertilizer may not necessary in present condition and part of N fertilizer could be saved, and N loss for asynchrony of N supply and N demand at early growth stage also can be reduced, and therefore N application can be optimized and NUE could be improved. Therefore, it could be interpreted that INS could be a supplemental tool used for optimized nutrient recommendation. However, the INS value in different ecological regions may be varied to some extent, and how to integrate INS into N management strategy is still need further study.

As the positive relationships between SPAD value and leaf N concentration, SPAD value has been considered as an effective tool to evaluate N status of crop in different growing periods and help define the appropriate timing and quantity of N topdressing in winter (Varinderpal-Singh et al., 2010). The most typical example was site-specific N management, which not only increased NUE but also reduced the risk of environmental pollution by spreading N application rationally and timely. Additionally, Bijay-Singh et al. (2002) also recorded that wheat yield could increase by 20% with need-based N management according to SPAD meter. However, SPAD value was affected by many factors, such as cultivars, growth stages and agro-climatic conditions, improvement on reliability and universality of SPAD threshold value still needs more studies.

CONCLUSIONS

From the current study, it was concluded that N application under the rate of 135 kg/ha in 2007/08 and 120 kg/ha in 2008/09 could maintain the same yield level as the FP treatment with 225-240 kg N ha^{-1}. Moreover, NUE parameters improved and N loss decreased by optimized N management. The optimized N management improved the grain yield and NUE in two ways. First, the optimized N application rate could feed the N requirement of winter wheat growth for high grain yield and NUE. Secondly, the proper N in season management strategy could synchronize crop N need with N supply, such as splitting fertilizer N application in three times (one basal dressing and two top dressings) other than in two times (on basal dressing and one top dressing), which was a valid way to increase grain yield, enhance NUE and reduce apparent N loss. The SPAD value could help optimize fertilizer N application rate at the critical growth stage, and INS could also help decide the amounts of basal fertilizer N application rate in further study.

ACKNOWLEDGMENTS

We thank the field experiment assistants from the Institution of Plant Protection and Soil Fertilization, Hubei Academy of Agricultural Sciences.

FUNDING

This study was sponsored by National Basic Research Program of China (973 Program) (2007CB109306).

REFERENCES

Alam, M. M., J. K. Ladha, Foyjunnessa, Z. Rahman, S. R. Khan, Harun-ur-Rashid, A. H. Khan, and R. J. Buresh. 2006. Nutrient management for increased productivity of rice-wheat cropping system in Bangladesh. *Field Crops Research* 96: 374–386.

Anderson, W. K. 1985. Grain yield responses of barley and durum wheat to split nitrogen applications under rainfed conditions in a Mediterranean environment. *Field Crops Research* 12: 191–202.

Arregui, L. M., B. Lasa, A. Lafarga, I. Irãneta, E. Baroja, and M. Quemada. 2006. Evaluation of chlorophyll meters as tools for N fertilization in winter wheat under humid Mediterranean conditions. *European Journal of Agronomy* 24: 140–148.

Arregui, L. M., and M. Quemada. 2008. Strategies to improve nitrogen use efficiency in winter cereal crops under rainfed conditions. *Agronomy Journal* 100: 277–284.

Bijay-Singh, Yadvinder-Singh, J. K. Ladha, K. F. Bronson, V. Balasubramanian, J. Singh, and C. S. Khind. 2002. Chlorophyll meter-and leaf color chart-based nitrogen management for rice and wheat in northwestern India. *Agronomy Journal* 94: 821–829.

Bremner, J. M. 1996. Nitrogen-total. In: *Methods of Soil Analysis, Part 3: Chemical Methods*, eds. D. L. Sparks, pp. 1085–1121. Madison, WI: SSSA.

Cassman, K. G., A. Dobermann, and D. T. Walters. 2002. Agro-ecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31: 132–140.

Chen, D. 2009. The technical measures of "postponing N" in high yield of wheat in Yudong. *China Agricultural Technology Extension* 25(11): 36–38 (in Chinese).

Chen, X., Y. Tong, H. Kang, J. Yu, Z. Wang, and J. Yang. 2008. Effect of postponing N application on the yield, apparent N recovery and N absorption of winter wheat. *Plant Nutrition and Fertilizer Science* 14(3): 450–455 (in Chinese).

Chen, X., F. Zhang, V. Römheld, D. Horlacher, R. Schulz, M. B. Zilkens, P. Wang, and W. Claupein. 2006. Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved N_{min} method. *Nutrient Cycling in Agroecosystems* 74: 91–98.

Cui, Z., F. Zhang, X. Chen, Z. Dou, and J. Li. 2010. In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context. *Field Crops Research* 116: 140–146.

Cui, Z., F. Zhang, X. Chen, Y. Miao, J. Li, and D. Bao. 2008. On-farm evaluation of an in-season nitrogen management strategy based on soil N_{min} test. *Field Crops Research* 105: 48–55.

Cui, Z., F. Zhang, Z. Dou, Y. Miao, Q. Sun, and X. Chen. 2009. Regional evaluation of critical nitrogen concentrations in winter wheat production of the North China Plain. *Agronomy Journal* 101: 159–166.

De Jong, R., C. F. Drury, J. Yang, and C. A. Campbell. 2009. Risk of water contamination by nitrogen in Canada as estimated by the IROWC-N model. *Journal of Environmental Management* 90: 3169–3181.

Dobermann, A. 2007. Nutrient use efficiency – measurement and management. In: *FA International Workshop on Fertilizer Best Management Practices*, pp. 1–22. Paris: IFA.

Dobermann, A., C. Witt, D. Dawe, S. Abdulrachman, and H. C. Gines. 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* 74: 37–66.

Fageria, N. K., V. C. Baligar, and Y. C. Li. 2008. The role of nutrient efficient plants in improving crop yield in the twenty first century. *Journal of Plant Nutrition* 31: 1127–1157.

He, P., S. Li, J. Jin, H. Wang, C. Li, Y. Wang, and R. Cui. 2009. Performance of an optimized nutrient management system for double-cropped wheat-maize rotations in North-Central China. *Agronomy Journal* 101: 1489–1496.

Janssen, B. H., F. C. T. Guiking, and der Eijk D. Van. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46: 299–318.

Ju, X., G. Xing, X. Chen, P. Christie, Z. Zhu, and F. Zhang. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America* 106: 3041–3046.

Khurana, H. S., S. B. Phillips, B. Singh, M. M. Alley, A. Dobermann, A. S. Sidhu, Y. Singh, and S. Peng. 2008. Agronomic and economic evaluation of site-specific nutrient management for irrigated wheat in northwest India. *Nutrient Cycling in Agroecosystems* 82: 15–31.

Khurana, H. S., B. Singh, A. Dobermann, S. B. Phillips, A. S. Sidhu, and Y. Singh. 2008. Site-specific nutrient management performance in a rice-wheat cropping system. *Better Crops* 92: 26–28.

Ladha, J. K., H. Pathak, T. J. Krupnik, J. Six, and C. van. Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy* 87: 85–156.

Liu, X., X. Ju, and F. Zhang. 2004. Effect of reduced N application on N utilization and balance in winter wheat-summer maize cropping system. *Chinese Journal of Applied Ecology* 15: 458–462 (in Chinese).

Liu X., J. Wang, S. Lu, F. Zhang, X. Zeng, Y. Ai, S. Peng, P. Christie. 2003. Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice-wheat cropping systems. *Field Crops Research* 83: 297–311.

Ma, W., J. Li, L. Ma, F. Wang, I. Sisak, G. Cushman, and F. Zhang. 2009. Nitrogen flow and use efficiency in production and utilization of wheat, rice, and maize in China. *Agricultural Systems* 99: 53–63.

Meng, J., Y. Li, and H. Dang. 2007. Effect of nitrogen application rate on nitrogen absorption, NO_3-N accumulation in soil and grain yield of winter wheat. *Journal of Agricultural University of Hebei* 30(2): 1–5 (in Chinese).

Peng, S., F. V. Garcia, R. C. Laza, and K. G. Cassman. 1993. Adjustment for specific leaf weight improves chlorophyll meters estimation of rice leaf nitrogen concentration. *Agronomy Journal* 85: 987–990.

Sharma, S. N., and R. Prasad. 2008. Effect of crop-residue management on the production and agronomic nitrogen efficiency in a rice-wheat cropping system. *Journal of Plant Nutrition and Soil Science* 171: 295–302.

Shukla, A. K., J. K. Ladha, V. K. Singh, B. S. Dwivedi, V. Balasubramanian, and S. K. Gupta. 2004. Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. *Agronomy Journal* 96: 1606–1621.

Timsina J., U. Singh, M. Badaruddin, C. Meisner, and M. R. Amin. 2001. Cultivar, nitrogen, and water effects on productivity, and nitrogen-use efficiency and balance for rice-wheat sequences of Bangladesh. *Field Crops Research* 72: 143–161.

Varinderpal-Singh, Bijay-Singh, Yadvinder-Singh, H. S. Thind, and R. K. Gupta. 2010. Need based nitrogen management using the chlorophyll meter and leaf colour chart in rice and wheat in South Asia: A review. *Nutrient Cycling in Agroecosystems* 88: 361–380.

Varvel, G. E., J. S. Schepers, and D. D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. *Soil Science Society of America* 61: 1233–1239.

Wang, W., W. Guo, C. Feng, X. Zhu, M. Fang, and Y. Peng. 2002. Effects of nitrogen application methods on flag leaf senescence after anthesis and grain development in wheat. *Journal of Yangzhou University* 23: 61–65 (in Chinese).

Wang, F., Z. He, K. Sayre, S. Li, J. Si, B. Feng, and L. Kong. 2009. Wheat cropping systems and technologies in China. *Field Crops Research* 111: 181–188.

Wang, D., Q. Liu, J. Lin, and R. J. Sun. 2004. Optimum nitrogen use and reduced nitrogen loss for production of rice and wheat in the Yangtse Delta region. *Environmental Geochemistry and Health* 26: 221–227.

Yadvinder-Singh, R. K. Gupta, Gurpreet-Singh, Jagmohan-Singh, H. S. Sidhu, and Bijay-Singh. 2009a. Nitrogen and residue management effects on agronomic productivity and nitrogen use efficiency in rice–wheat system in Indian Punjab. *Nutrient Cycling in Agroecosystems* 84: 141–154.

Yadvinder-Singh, R. K. Gupta, H. S. Thind, Bijay-Singh, Varinderpal-Singh, Gurpreet-Singh, Jagmohan-Singh, and J. K. Ladha. 2009b. Poultry litter as a nitrogen and phosphorous source for the rice-wheat cropping system. *Biology and Fertility of Soils* 45: 701–710.

Yi, Q., X. Zhang, P. He, L. Yang, and G. Xiong. 2010. Effects of reducing N application on crop N uptake, utilization, and soil N balance in rice-wheat rotation system. *Plant Nutrition and Fertilizer Science* 16: 1069–1077 (in Chinese).

Zhang, F. S., J. Wang, W. Zhang, Z. Cui, W. Ma, X. Chen, and R. Jiang. 2008. Nutrient use efficiencies of major cereal crops in China and measures for improvement. *Acta Pedologica Sinica* 45: 916–923 (in Chinese).

Zhu, Z. L., and D. Chen. 2002. Nitrogen fertilizer use in China – Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems* 63: 117–127.