Journal of Agricultural Science (2009), **147**, 303–312. © 2009 *Cambridge University Press*
doi:10.1017/S0021859609008466 *Printed in the United Kingdom*

Quantifying N response and N use efficiency in rice–wheat (RW) cropping systems under different water management

Q. JING[1,2,3]*, H. VAN KEULEN[2,3], H. HENGSDIJK[2], W. CAO[1], P. S. BINDRABAN[2], T. DAI[1] AND D. JIANG[1]

[1] *Key Laboratory of Crop Growth Regulation, Ministry of Agriculture, Nanjing Agricultural University, Nanjing 210095, China*
[2] *Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA, Wageningen, The Netherlands*
[3] *Group Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands*

(*Revised MS received 7 December 2008; First published online 26 February 2009*)

SUMMARY

About 0·10 of the food supply in China is produced in rice–wheat (RW) cropping systems. In recent decades, nitrogen (N) input associated with intensification has increased much more rapidly than N use in these systems. The resulting nitrogen surplus increases the risk of environmental pollution as well as production costs. Limited information on N dynamics in RW systems in relation to water management hampers development of management practices leading to more efficient use of nitrogen and water. The present work studied the effects of N and water management on yields of rice and wheat, and nitrogen use efficiencies (NUEs) in RW systems. A RW field experiment with nitrogen rates from 0 to 300 kg N/ha with continuously flooded and intermittently irrigated rice crops was carried out at the Jiangpu experimental station of Nanjing Agricultural University of China from 2002 to 2004 to identify improved nitrogen management practices in terms of land productivity and NUE.

Nitrogen uptake by rice and wheat increased with increasing N rates, while agronomic NUE (kg grain/kg N applied) declined at rates exceeding 150 kg N/ha. The highest combined grain yields of rice and wheat were obtained at 150 and 300 kg N/ha per season in rice and wheat, respectively. Carry-over of residual N from rice to the subsequent wheat crop was limited, consistent with low soil nitrate after rice harvest. Total soil N hardly changed during the experiment, while soil nitrate was much lower after wheat than after rice harvest. Water management did not affect yield and N uptake by rice, but apparent N recovery was higher under intermittent irrigation (II). In one season, II management in rice resulted in higher yield and N uptake in the subsequent wheat season. Uptake of indigenous soil N was much higher in rice than in wheat, while in rice it was much higher than values reported in the literature, which may have consequences for nitrogen fertilizer recommendations based on indigenous N supply.

INTRODUCTION

In China, as in many other parts of Asia, rice and wheat are grown frequently in rotation. Rice–wheat (RW) systems occupy 0·10 of the arable area in China, mainly along the Yangtze River (Huke & Huke 1992). These systems are of major importance for ensuring China's food security. The population of China is expected to increase by nearly half a billion people by 2030 (FAO 2003), requiring large additional quantities of rice and wheat. Since suitable agricultural land is scarce in China, RW systems are managed very intensively, i.e. with high inputs to

* To whom all correspondence should be addressed. Email: jingq@njau.edu.cn and jingq58@yahoo.com

maximize yields per unit of land. Extremely high annual doses of 500–650 kg N/ha are common in RW systems (Zhu *et al.* 2000), with low nitrogen use efficiency (NUE) (Xu & Wu 1999; Cui *et al.* 2000; Peng *et al.* 2002), particularly in southern Jiangsu Province. Applying N beyond crop needs results in undesirable emissions to the environment, such as gaseous and leaching losses and runoff to surface water, and in unnecessary production costs for farmers (Li & Zhang 1999; Xing & Zhu 2000).

Commonly, the rice crop in RW systems is grown by keeping a permanent layer of water on the field, resulting in higher seepage and percolation losses than in the wheat crop. Competing claims for fresh water sources call for more efficient use of irrigation water in rice production (Bouman & Tuong 2001; Bouman *et al.* 2006). To reduce water use in irrigated rice, water-saving techniques are being developed. These include the introduction of periods with saturated, but non-flooded, soil conditions during part of the growing period, also known as intermittent irrigation (II) (Mao 1993), direct seeding of rice under non-flooded conditions (Xie *et al.* 1995) and the introduction of ground cover, reducing evaporation losses (Lin *et al.* 2002). II can reduce water input without affecting yields (Belder *et al.* 2004, 2005). Water-saving techniques in rice may also improve soil physical and biological properties for the associated wheat crop (Timsina & Connor 2001), resulting in increased NUEs in the wheat (Zheng 2000).

There has been considerable research on N dynamics in rice and wheat separately, but few studies have described those dynamics in RW systems (Timsina *et al.* 2001). Information on N dynamics in RW systems in relation to II is especially scarce, which constrains the development of RW systems with improved water and NUEs. The present study examines N response and NUE in a RW system based on a 2-year field experiment with two seasons of rice and wheat, different nitrogen regimes and different water management in the rice crop, including conventional flooding and II.

MATERIALS AND METHODS

Experimental design

The experiments were carried out at the Jiangpu experimental station of Nanjing Agricultural University at Nanjing (32°04′N, 118°48′E) from 2002 to 2004, covering two sequences of rice and wheat crops. The soil is a clayey loam (Anthrosol; FAO 2006) with pH 7·1, soil organic matter content 16·3 g/kg, total N content 1·6 g/kg, available phosphorus 23·9 mg/kg and available potassium 95·7 mg/kg in the 0–400 mm soil layer. The japonica rice cultivar Wuxiangjing9 and wheat cultivar Yangmai10 were grown.

Management and treatments in the rice season

The experiment was a two-factor split plot design with three replicates. The main factor, water management, consisted of two treatments, i.e. conventional irrigation (CI) and II. The sub-factor nitrogen management consisted of five application rates, i.e. 0, 75, 150, 225 and 300 kg N/ha. Plot size was 10×3 m^2. Plots were separated by plastic film to 300 mm below soil surface to reduce water and nitrogen flows between adjacent plots. In 2002, rice was sown on 11 May and transplanted as six-leaf seedlings on 15 June at one seedling per hill, spaced at 250 and 150 mm between and within the rows, respectively. Because of differences in maturity, the 0 kg N/ha plots were harvested on 5 October, the remaining II-plots on 15 October and the remaining CI-plots on 21 October. After transplanting, the CI treatment was flooded with a water layer of 20–50 mm, except during mid-season drainage for 2 days, starting on 31 July, and for 5 days, starting on 25 August. Relative soil water content (defined as soil water content divided by field capacity) in II was maintained throughout the growth period between *c.* 0·85 (when the soil started to form cracks) and saturation, through drainage or irrigation. Before transplanting, 0·60 of the total nitrogen was applied as basal fertilizer, another 0·20 at 15 days after jointing, and the remaining 0·20 at 25 days after jointing (5–10 days before heading). In addition to nitrogen, 135 kg P_2O_5 and 210 kg K_2O/ha were applied as basal fertilizer.

In 2003, rice was sown on 15 May and transplanted on 15 June in a 300×150 mm pattern. All plots were harvested on 23 October. Crop management was identical to that in 2002.

Management and treatments in the wheat season

In 2002, after the rice harvest, the land was ploughed and seed was drilled on 9 November at 180 grains/m^2. Each rice plot was sub-divided into three to apply three N rates to wheat, i.e. 0, 150 and 300 kg N/ha. Before sowing, 0·60 of the N was applied, and the remainder was top-dressed at the jointing stage. In addition, 135 kg P_2O_5 and 210 kg K_2O/ha were applied as basal fertilizer. Wheat was harvested on 3 June.

In 2003, an alternative layout was selected, based on the results of the previous year: the rice plots of each N treatment were split into two, with half receiving the same N-doses as in the rice season, while the other half did not receive any N. Before sowing of the wheat crop, the soil was prepared with a rotating plough and 0·60 of the fertilizer was applied, the remainder being applied in equal splits at jointing and booting. All plots received 135 kg P_2O_5 and 210 kg K_2O/ha as basal fertilizer. Wheat was sown on 6 November at a density of 150 grains/m^2 and was harvested on 26 May.

Measurements

Dry weight and nitrogen content

During the entire experiment, dates of key growth stages of crops were recorded. Rice and wheat plants were harvested from 1 m^2 subplots to determine panicle and spike number, grain number/panicle, grain number/spike and grain weight. The proportion of filled grains was determined from the number of filled grains/panicle. Filled grains were selected in a NaCl solution with a specific gravity of 1·03. Plant samples, separated in grain and straw, were oven-dried at 80 °C for 2 days. The yields were measured from the samples and expressed on the basis of 0·86 g dry matter (DM)/g fresh weight moisture content for both crops. Concentrations of N in grain and straw were determined by micro-Kjeldahl (AOAC 1984), following digestion in a H_2SO_4–H_2O_2 solution.

Soil nitrogen

Total and nitrate nitrogen in the 0–400 and 400–800 mm soil layers were periodically monitored, both before and after crop growth in the plots of 0, 150 and 300 kg N/ha and under both water management treatments. Nitrate (NO_3-N) was extracted from fresh soil samples using an equilibrium extraction with 2·0 N KCl solution and analysed using a flow analyser. Total soil N was determined after air-drying of soil samples, using micro-Kjeldahl, following digestion in a H_2SO_4–H_2O_2 solution. Nitrate and total N were expressed in kg/ha using the bulk density of each soil layer.

NUE indicators and analysis

Apparent nitrogen recovery (ANR) is the ratio of the difference in N uptake between the treated and the zero-fertilizer plot to the application rate. Physiological NUE (kg grain DM/kg N) is defined as grain production per unit N uptake by the crop, while agronomic efficiency (AE, in kg grain DM/kg N) is defined as grain production per unit N applied. These characteristics are presented in three-quadrant graphs (De Wit 1953; Van Keulen 1982): one quadrant presents grain yield against N application (fertilizer response curve, AE), the second, yield against N uptake (yield–uptake curve, NUE), and the third relates N application to N uptake (application–uptake curve, ANR). Only two out of these three relations are mutually independent, the third relation always follows from the other two.

Weather data

Daily radiation, precipitation, maximum and minimum temperature data were collected from a meteorological station located 1 km from the experiments.

Data analysis

GenStat for Windows, 8th edition (http://www.vsn-intl.com/genstat/) was used for the data analysis, i.e. establishing effects of management and N rates, and their interactions on yield, yield components and soil N. Statistical differences were determined using Wald statistics.

RESULTS

Weather

Average daily solar radiation during the first rice-growing season was 14·9 MJ/m^2 compared to 13·2 MJ/m^2 during the second season (Fig. 1). Rainfall in the second rice season was more frequent and much higher than in the first rice season (1054 *v.* 421 mm). Average temperature was 25·7 °C in the first *v.* 25·1 °C in the second season. Frequency of rainfall in the first wheat season was higher than in the second, although total rainfall was similar (511 *v.* 435 mm). However, the higher rainfall frequency and the associated cloudiness resulted in lower average daily solar radiation during the first wheat season: 13·0 MJ/m^2 compared to 14·4 MJ/m^2 during the second season. Consistent with the radiation levels, average temperature during the first wheat season was 10·1 *v.* 11·4 °C in the second season.

Rice

Grain yield

In both seasons, yields increased with N rates except for the highest N rate (Table 1). Neither water management nor the interaction of water and nitrogen had an effect on yields. The lower yield at the highest N rate was associated with the lowest proportion of filled grains. The number of spikelets was 26% higher in the first year than in the second year, and associated with a 20% higher grain yield. There was no interaction between years and treatments, indicating consistent yield responses across years.

Aboveground N uptake

N uptake was similar for both water management treatments (Table 1), but uptake increased with increasing N rates. Below 150 kg N/ha, total crop N uptake exceeded N fertilizer input, while at the higher rates it was reversed. There was no interaction between N and water management on N uptake. Consistent with the yield difference between both years, crop N uptake in 2002 was clearly higher than in 2003 (194 *v.* 149 kg N/ha), associated with N uptake in the control (0 kg N/ha) plots, i.e. 130 kg N/ha in 2002 and 91 kg N/ha in 2003. Interactions between

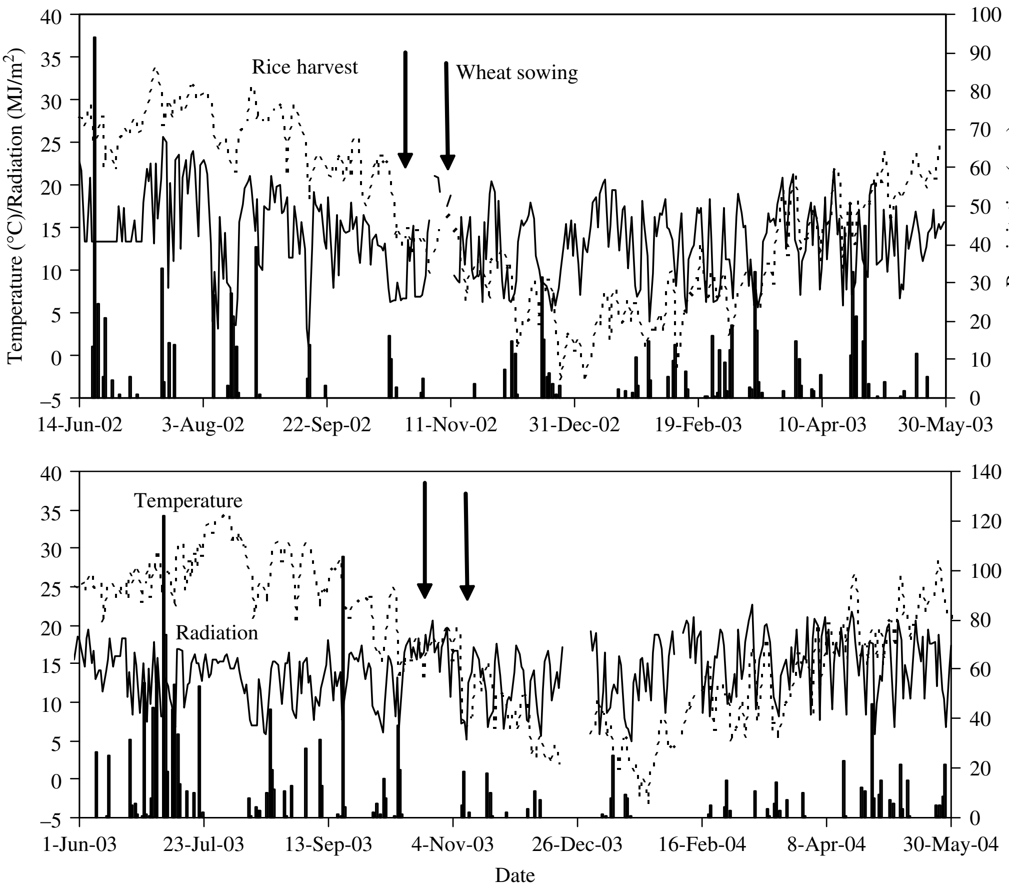

Fig. 1. Daily mean temperature, radiation and precipitation at Nanjing in two seasons with RW rotations. Solid lines are radiation, dotted lines are temperature and columns are precipitation.

years and treatments were not significant, indicating that the variation in N uptake was consistent under different N and water management in both years.

NUE

Data on rice yields and N uptake for the 2 years were pooled, as trends were similar. The fertilizer response (AE) curve in quadrant (*a*) of Fig. 2 shows maximum yields at N doses of 150 kg N/ha. Under CI, AE varied between 18·8 and 4·3 kg grain/kg N applied and under II between 10·4 and 3·5 kg grain/kg N applied.

NUE is the slope of the linear part of the curve relating grain yield and N uptake (Fig. 2, quadrant (*b*)). In the present experiment, the relation between yield and N uptake started to deviate from the linear at uptake values exceeding 145 (CI) and 169 kg N/ha (II), indicating that at higher N-availability, other growth factors became limiting (Van Keulen 1982). Comparison of the CI and II curves shows that in two of the three cases, NUE of II is lower than that of CI, which could hint at some water stress during at least part of the growing season.

Indigenous soil N supply was about 110 kg N/ha and not significantly different between II and CI (Fig. 2, quadrant (*c*)). At N rates below 225 kg N/ha, average ANR was lower under CI (0·43) than under II (0·49). At 300 kg N/ha, ANR dropped to 0·32 and 0·39 for CI and II, respectively.

When comparing both rice seasons, NUEs were much higher in 2002 than in 2003 (not shown), i.e. the crop produced more grain yield per unit N uptake in 2002, suggesting that factors other than N reduced yield in 2003, such as unfavourable weather conditions.

Table 1. *Average (two seasons, 2002 and 2003) yield components, grain yield and aboveground N uptake at maturity of rice at different N rates and for two irrigation methods, and their variation source*

Treatment	Spikelet no. ($10^3/m^2$)	Grain weight (mg)	Proportion of filled grains	Grain yield (t/ha)	N uptake (kg/ha)
Irrigation (I)					
CI	40	24·3	0·68	9·0	171
II	37	24·4	0·69	8·7	173
N rate (kg/ha)					
0	27	24·4	0·74	6·9	111
75	34	24·3	0·75	8·5	150
150	40	25·0	0·70	9·7	176
225	47	24·1	0·63	9·9	207
300	45	24·0	0·61	9·2	214
S.E.D. (D.F. = 50)	6·1	0·23	0·057	0·47	13·0
Year					
2002	43	24·4	0·63	9·6	194
2003	34	24·3	0·75	8·1	149
S.E.D. (D.F. = 50)	2·3	0·18	0·020	0·47	13·3
Variation source					
I	NS	NS	NS	NS	NS
Y × I	NS	NS	NS	NS	NS
Y × N	< 0·001	NS	< 0·001	NS	NS
I × N	NS	0·014	NS	NS	NS

NS, not significant.

Wheat

Grain yield

Grain yields ranged from 1·3 to 3·6 t/ha on average for the control (0/0 kg N/ha) and the 300/300 kg N/ha treatment, respectively. Wheat yields in the II plots were 10 % higher than in the CI plots (Table 2). Hence, water management affected grain yields and yield components in the first wheat season. In the second season, yields ranged from 1·4 to 5·7 t/ha. Grain yield increased almost linearly with increasing N rates and was closely related to grain number per unit area (R^2 = 0·9618, n = 15), which ranged from 4000 to 15 800 per m², suggesting a strong N limitation to grain formation in the 0/0 plots. In both seasons, grain number increased with increasing N rate, though effects were more pronounced in the second season. On average, yields at the N rates of 150 and 300 kg/ha were lower in the first season, associated with lower grain numbers per unit area. In both seasons, effects of N rates in the preceding rice crop on wheat yield and yield components were not significant, suggesting no carry-over of residual N between seasons. This even holds for the wheat control plots in the second year, following high N applications in rice season.

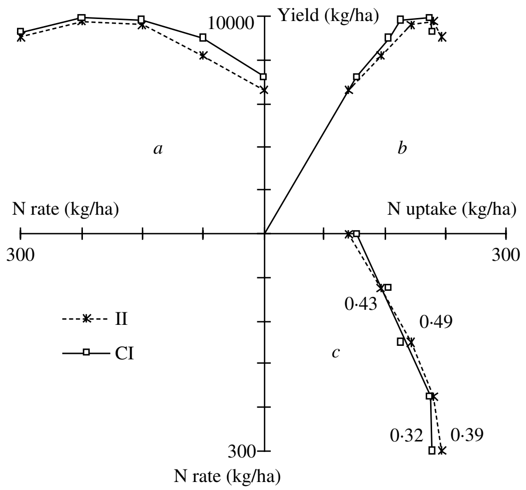

Fig. 2. Relations between N application and yield (quadrant *a*), N uptake and yield (quadrant *b*) and N application and N uptake (quadrant *c*) for the rice seasons in 2002 and 2003 (pooled data from two seasons). The numbers in quadrant *c* represent mean ANRs (see text for details) under different water management practices, II = intermittent irrigation, CI = conventional flood irrigation (see text for details), below and above 150 kg N/ha.

Aboveground N uptake

Average N uptake in wheat following II was 9 kg/ha higher than following CI in the first season (Table 2). In the control plots, wheat in particular absorbed more N following rice under II. Nitrogen uptake ranged from 31 to 109 kg N/ha in the first season, and from 30 to 184 kg N/ha in the second and was

Table 2. *Yield components, yield and aboveground N uptake at maturity of wheat under different treatments in the 2002/03 and 2003/04 seasons, and their variation source*

Treatment	Grain density (no./m²)	Kernel weight (mg)	Grain yield (t/ha)	N uptake (kg/ha)
2002/03				
N rates (kg/ha)				
0	3639	36	1·33	31
150	7987	35	2·79	78
300	9084	40	3·60	109
S.E.D. (D.F. = 75)	293·2	0·8	0·091	3·6
Irrigation in rice season				
CI	6633	37	2·46	68
II	7201	37	2·68	77
S.E.D. (D.F. = 84)	238·7	0·7	0·074	3·0
Variation source				
N rates in rice season	NS	NS	NS	NS
2003/04				
N rates (kg/ha)				
0	4094	35	1·4	30
75	6363	40	2·6	57
150	11 019	41	4·5	111
225	11 507	37	4·2	122
300	15 779	36	5·7	184
S.E.D. (D.F. = 10)	1500·0	1·8	0·64	16·9
Variation source				
N rates in rice season	NS	NS	NS	NS

NS, not significant.

significantly affected by N rates, but not by the N rates on the preceding rice crop, indicating no carry-over of residual N in either year.

NUE

Grain yields increased with N rates in both wheat seasons (Fig. 3, quadrant (*a*)). In the first season, agronomic NUE (AE) of the 150 and 300 kg N/ha treatments was 9 kg grain/kg N applied and was not affected by water management in the preceding rice season. AE was on average 16 kg grain/kg N applied in the second season. ANRs in the first season were identical following CI and II in rice: 0·34 and 0·27 below and above 150 kg N/ha, respectively (Fig. 3, quadrant (*c*)), average ANR was 0·45 in the second season. Grain yield increased with increasing N uptake (Fig. 3, quadrant (*b*)), and NUE was not different for the water management treatments in the rice season, with an average value of 42 kg/kg in the first season.

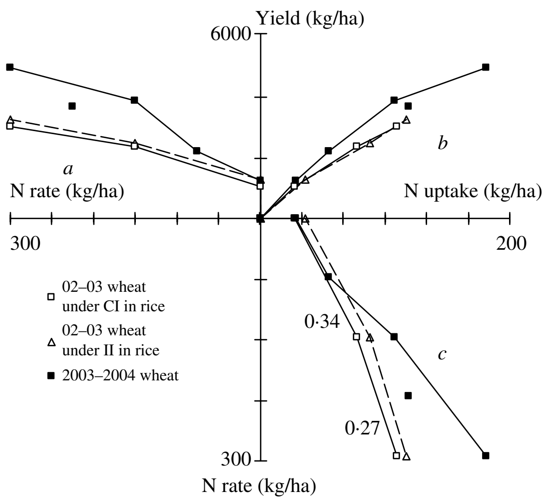

Fig. 3. Relations between N application and yield (quadrant *a*), N uptake and yield (quadrant *b*) and N application and N uptake (quadrant *c*) for the wheat seasons. Numbers in quadrant *c* represent ANRs (see text for details).

Soil nitrogen content

Total soil N

Total N in the 0–800 mm soil layer was variable during the experiment (Table 3), but the effects of irrigation and nitrogen management were not significant, while the distribution over the 0–400 and 400–800 mm soil layers hardly changed. In all treatments, total soil N decreased with soil depth.

Table 3. *Total nitrogen (kg/ha) in the 0–400 mm and 400–800 mm soil depths during the experiment*

Soil layer	After first rice harvest	Before first wheat sowing	After first wheat harvest	After second rice harvest	After second wheat harvest
0–400 mm	10 340 ± 509	10 509 ± 791	9690 ± 509	9690 ± 452	9577 ± 565
400–800 mm	6664 ± 560	7168 ± 672	6412 ± 896	6636 ± 448	6104 ± 896
Source of variation					
Irrigation	NS	NS	NS	NS	NS
N rates	NS	NS	NS	NS	NS

NS, not significant.

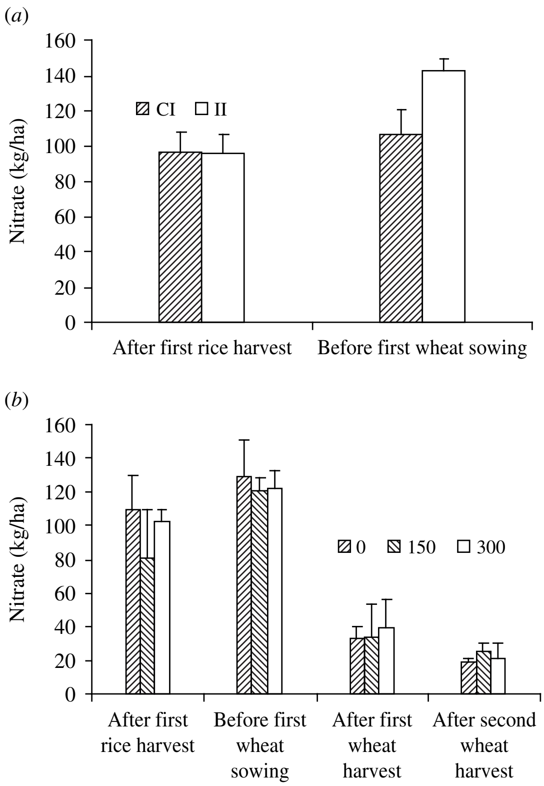

Fig. 4. Effects of different water management (*a*) and nitrogen application rates (*b*) on nitrate in the 0–400 mm soil profile during the experiment.

Soil nitrate

Soil nitrate varied significantly during the experiment (Fig. 4). Directly following harvest of the first rice crop, nitrate in the surface 400 mm layer was not different between CI and II, while after a fallow period of 17 days, it was higher under II than under CI. Nitrate was low and not different among N rates after rice harvest, confirming that carry-over of mineral N was limited. Nitrate following wheat harvest was much lower than after the first rice season, but not different among the N treatments.

DISCUSSION

II of rice did not result in significantly lower yields than continuous flooding in the two experimental seasons, confirming previous experiences (Cao *et al.* 2002; Belder *et al.* 2004, 2005). In the present study, the soil water content in II was kept between 0·85 of soil water content at field capacity and saturation, which is not low enough (soil water tension <-10 kPa) to cause severe water stress for rice (Belder *et al.* 2004). II, however, increased nitrogen uptake and yield of the subsequent wheat crop in the first season, associated with higher soil nitrate before the wheat season (Fig. 4). One possible reason is the higher residual root biomass of rice under II (Yang *et al.* 2004), resulting in higher N mineralization from residues, which resulted in higher indigenous N supply (Fig. 3 *c*). Further research is required to investigate this hypothesis.

Nitrogen had significant effects on grain yield and yield components of both rice and wheat. In rice, yield responded no further at N rates exceeding 150 kg/ha, in contrast to wheat, which responded up to rates of 300 kg N/ha, especially in the first season. In general, wheat yields were much lower than those of rice at the same N fertilizer rates. The period between panicle and spike initiation and maturity for both rice and wheat lasted 65 days. However, leaf area duration (the integral of green leaf area over time) in wheat was smaller than in rice, as wheat leaves senesced well before maturity in contrast to those of rice, which resulted in smaller average crop biomass (5 *v.* 15 t/ha).

The lower yields of rice in the second season are a consequence of high rainfall and associated low solar radiation, resulting in lower spikelet densities. Two weeks after rice transplanting, in the tillering phase, a 3-week heavy rainfall period started. Rainfall on 4 and 5 July, totalled 200 mm (Fig. 1), resulting in

Table 4. *The PTQ and radiation (R) from 20 days prior to panicle initiation (PI-20) to PI and from PI to anthesis (A) in rice and from 20 days prior to anthesis (A-20) to A in wheat in two seasons*

	Rice				Wheat	
	PTQ MJ/($m^2 \times d \times$ °C)		R MJ/($m^2 \times d$)		PTQ MJ/($m^2 \times d \times$ °C)	R MJ/($m^2 \times d$)
Season	PI-20 to PI	PI to A	PI-20 to PI	PI to A	A-20 to A	A-20 to A
First season	0·89	0·74	19·5	14·6	1·27	13·8
Second season	0·58	0·53	11·6	12·4	1·42	16·9

PTQ is defined as the ratio of the mean daily total incident solar radiation for an interval to the mean temperature less the base temperature (Nix 1976). The base temperature for japonica rice is 8 °C and for wheat 4·5 °C.

complete submergence of the crop for 2 days. Radiation before anthesis was lower in 2003 than in 2002 (Table 4), resulting in lower growth rates and thus lower spikelet densities (Kropff *et al.* 1994). The difference in yield between the 2 years was also consistent with the difference in photothermal quotient (PTQ), defined by Nix (1976) as the ratio of mean daily radiation for an interval to mean temperature minus a base temperature. PTQ prior to anthesis showed a positive linear relationship to grain yield (Nix 1976; Islam & Morison 1992; Ortiz-Monasterio *et al.* 1994).

N rates in the preceding rice season did not affect wheat yields, suggesting that there was little N carryover from the rice season to wheat, which is supported by low total soil nitrogen and nitrate after rice harvest. This is consistent with results from Ladha *et al.* (2000), showing no residual effect on rice grain yield and N uptake after 8 years of urea–N application. Fan *et al.* (2005) also observed no differences in soil mineral N after rice harvest following different N rates in rice. In contrast to the present results, however, Fan *et al.* (2005) observed differences in residual mineral N following differential N rates on wheat. These divergent results may reflect differences in experimental conditions (soil and climate).

In the 2002/03 season, wheat yields were lower than in 2003/04 and the yields (4·5–6·0 t/ha) commonly realized at application rates of 135–315 kg N/ha after rice in South Jiangsu (Xu & Wu 1999; Wang *et al.* 2003). The lower radiation and PTQ during the 20 days prior to anthesis in the first wheat season (Table 4) resulted in much lower grain numbers (Nix 1976; Fischer 1985; Bindraban *et al.* 1998), which may have created sink limitations during grain filling.

The pooled rice data showed higher ANRs under II than under CI, in line with other reports (Belder *et al.* 2005). Low ANRs may have been caused by higher N losses under CI due to de-nitrification and ammonia volatilization (Cai *et al.* 1986; Zhu *et al.* 1989). Water management treatments in the previous rice season had no effect on ANR of wheat.

Dobermann *et al.* (2003) reported strong variations in indigenous N supply in different areas of Asia, with a maximum value of 80 kg/ha in irrigated rice in Jinhua, Zhejiang Province in Southeast China. In the present experiment, indigenous soil N supply was 130 kg/ha in the first rice season and 91 kg/ha in the second, which was fully reflected in differences in rice yields of the control plots between the two years, i.e. 7·2 t/ha in 2002 and 6·7 t/ha in 2003. Potential indigenous N supply in rice in Southeast China may thus be substantially higher than the widely accepted rate of 80 kg N/ha, which should have consequences for nitrogen recommendations in rice (Witt & Dobermann 2004). Indigenous N supply was much lower in the wheat season, i.e. about 30 kg/ha (Table 2). This difference in indigenous soil N supply should be accounted for in nutrient management of RW systems.

REFERENCES

AOAC (1984). *Official Methods of Analysis*, 14th edn. Arlington, VA: Association of Official Analytical Chemists.

Belder, P., Bouman, B. A. M., Cabangon, R., Lu, G., Quilang, E. J. P., Li, Y., Spiertz, J. H. J. & Tuong, T. P. (2004). Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agricultural Water Management* **65**, 193–210.

Belder, P., Spiertz, J. H. J., Bouman, B. A. M., Lu, G. & Tuong, T. P. (2005). Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crops Research* **93**, 169–185.

Bindraban, P. S., Sayre, K. D. & Solis-Moya, E. (1998). Identifying factors that determine kernel number in wheat. *Field Crops Research* **58**, 223–234.

Bouman, B. A. M. & Tuong, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* **49**, 11–30.

Bouman, B. A. M., Humphreys, E., Tuong, T. P. & Barker, R. (2006). Rice and water. *Advances in Agronomy* **92**, 187–237.

Cai, G., Zhu, Z., Trevitt, A. C. F., Freney, J. R. & Simpson, J. R. (1986). Nitrogen loss from ammonium bicarbonate and urea fertilizers applied to flooded rice. *Fertilizer Research* **10**, 203–215.

Cao, W., Jiang, D., Wang, S. & Tian, Y. (2002). Physiological characterization of rice grown under different water management systems. In *Water-wise Rice Production. Proceedings of the International Workshop on Water-wise Rice Production* (Eds B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong & J. K. Ladha), pp. 249–257, Los Baños, Philippines: International Rice Research Institute (IRRI).

Cui, Y. T., Cheng, X., Han, C. R. & Li, R. G. (2000). The economic and ecological satisfactory amount of nitrogen fertilizer using on rice in Tai Lake Watershed. *Acta Ecologica Sinica* **20**, 659–662.

De Wit, C. T. (1953). *A Physical Theory on Placement of Fertilizers*. Verslagen Landbouwkundig Onderzoek (Agricultural Research Reports) 59.4, s'Gravenhage, The Netherlands: Staatsdrukkerij.

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H. C., Nagarajan, R., Son, T. T., Tan, P. S., Wang, G. H., Chien, N. V., Thoa, V. T. K., Phung, C. V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Simbahan, G. C. & Adviento, M. A. A. (2003). Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia. *Agronomy Journal* **95**, 913–923.

Fan, M. S., Jiang, R. F., Liu, X. J., Zhang, F. S., Lu, S. H., Zeng, X. Z. & Christie, P. (2005). Interactions between non-flooded mulching cultivation and varying nitrogen inputs in rice-wheat rotations. *Field Crops Research* **91**, 307–318.

FAO (2003). *Water Management: Towards 2030*. Rome: FAO.

FAO (2006). *Guidelines for Soil Description*. Rome: FAO.

Fischer, R. A. (1985). Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agricultural Science, Cambridge* **105**, 447–461.

Huke, R. & Huke, E. (1992). *Rice/Wheat Atlas of South Asia*. Los Baños, Philippines: IRRI.

Islam, M. S. & Morison, J. I. L. (1992). Influence of solar-radiation and temperature on irrigated rice grain-yield in Bangladesh. *Field Crops Research* **30**, 13–28.

Kropff, M. J., Cassman, K. G., Peng, S., Matthews, R. B. & Setter, T. L. (1994). Quantitative understanding of yield potential. In *Breaking the Yield Barrier* (Ed. K. G. Cassman), pp. 21–38. Los Baños, Philippines: IRRI.

Ladha, J. K., Dawe, D., Ventura, T. S., Singh, U., Ventura, W. & Watanabe, I. (2000). Long-term effects of urea and green manure on rice yields and nitrogen balance. *Soil Science Society of America Journal* **64**, 1993–2001.

Li, Y. & Zhang, J. (1999). Agricultural diffuse pollution from fertilisers and pesticides in China. *Water Science and Technology* **39**, 25–32.

Lin, S., Dittert, K., Tao, H., Kreye, C., Xu, Y., Shen, Q., Fan, X. & Sattelmacher, B. (2002). The ground-cover rice production system (GCRPS): a successful new approach to save water and increase nitrogen fertilizer efficiency? In *Water-wise Rice Production. Proceedings of the International Workshop on Water-wise Rice Production* (Eds B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong & J. K. Ladha), pp. 187–195. Los Baños, Philippines: IRRI.

Mao, Z. (1993). Study on evaluation of irrigation performance in China. In *Proceedings of Asian Regional Symposium on Maintenance and Operation of Irrigation/Drainage Scheme and Improved Performance*, pp. 6–35. Beijing.

Nix, H. A. (1976). Climate and crop productivity in Australia. In *Climate and Rice* (Ed. S. Yoshida), pp. 495–507. Los Baños, Philippines: IRRI.

Ortiz-Monasterio, J. I., Dhillon, S. S. & Fischer, R. A. (1994). Date of sowing effects on grain yield and yield components of irrigated spring wheat genotypes and relationships with radiation and temperature in Ludhiana, India. *Field Crops Research* **37**, 169–184.

Peng, S., Huang, J., Zhong, X., Yang, J., Wang, G. & Zou, Y. (2002). Research strategy in improving fertilizer-nitrogen use efficiency of irrigated rice in China. *Scientia Agricultura Sinica* **35**, 1095–1103.

Timsina, J. & Connor, D. (2001). Productivity and management of rice-wheat cropping systems: issues and challenges. *Field Crops Research* **69**, 93–132.

Timsina, J., Singh, U., Badaruddin, M., Meisner, C. & Amin, M. R. (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.

Van Keulen, H. (1982). Graphical analysis of annual crop response to fertilizer application. *Agricultural Systems* **9**, 113–126.

Wang, D. J., Lin, J. H., Sun, R. J., Xia, L. Z. & Lian, G. (2003). Optimum nitrogen rate for a high productive rice-wheat system and its impact on the groundwater in the Taihu Lake area. *Acta Pedologica Sinica* **40**, 426–432.

Witt, C. & Dobermann, A. (2004). Towards a decision support system for site-specific nutrient management. In *Increasing Productivity of Intensive Rice Systems Through Site-specific Nutrient Management* (Eds A. Dobermann, C. Witt & D. Dawe), pp. 359–396. Enfield, NH, USA/Los Baños, Philippines: Science Publishers Inc./IRRI.

Xie, C., Cheng, G. & Feng, Z. (1995). Managing techniques for high-yield cultivation in mechanical direct seeding rice fields and line seeding wheat fields under mechanised minimum tillage. *Acta Agriculturae Shanghai* **11**, 57–62.

Xing, G. X. & Zhu, Z. L. (2000). An assessment of N loss from agricultural fields to the environment in China. *Nutrient Cycling in Agroecosystems* **57**, 67–73.

Xu, X. & Wu, J. (1999). Effective utilization of N fertilizers by wheat and the effects of N fertilizer application on pollution of water body environment. *Chinese Journal of Soil Science* **30**, 268–270.

Yang, C. M., Yang, L. Z., Yang, Y. X. & Zhu, O. Y. (2004). Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. *Agricultural Water Management* **70**, 67–81.

Zheng, J. (2000). Rice–wheat cropping system in China. In *Soil and Crop Management Practices for Enhanced*

Productivity of the Rice–Wheat Cropping System in the Sichuan Province of China (Eds P. R. Hobbs & R. K. Gupta), pp. 1–10. Rice–Wheat Consortium Paper Series 9. New Delhi, India: Rice–Wheat Consortium for the Indo-Gangetic Plains.

Zhu, J. G., Han, Y., Liu, G., Zhang, Y. L. & Shao, X. H. (2000). Nitrogen in percolation water in paddy fields with a rice/wheat rotation. *Nutrient Cycling in Agroecosystems* **57**, 75–82.

Zhu, Z. L., Cai, G. X., Simpson, J. R., Zhang, S. L., Chen, D. L., Jackson, A. V. & Freney, J. R. (1989). Processes of nitrogen loss from fertilizers applied to flooded rice fields on a calcareous soil in North-central China. *Fertilizer Research* **18**, 101–115.