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RESEARCH ARTICLE

Nitrogen input, ^{15}N balance and mineral N dynamics in a rice–wheat rotation in southwest China

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Abstract A field experiment and farm survey were conducted to test nitrogen (N) inputs, ^{15}N-labelled fertilizer balance and mineral N dynamics of a rice–wheat rotation in southwest China. Total N input in one rice–wheat cycle averaged about 448 kg N ha^{-1}, of which inorganic fertilizer accounted for 63% of the total. The effects of good N management strategies on N cycling were clear: an optimized N treatment with a 27% reduction in total N fertilizer input over the rotation decreased apparent N loss by 52% and increased production (sum of grain yield of rice and wheat) compared with farmers' traditional practice. In the ^{15}N-labelled fertilizer experiment, an optimized N treatment led to significantly lower ^{15}N losses than farmers' traditional practice; N loss mainly occurred in the rice growing season, which accounted for 82% and 67% of the total loss from the rotation in farmers' fields and the optimized N treatment, respectively. After the wheat harvest, accumulated soil mineral N ranged from 42 to 115 kg ha^{-1} in farmers' fields, of which the extractable soil NO_3^-–N accounted for 63%. However, flooding soil for rice production significantly reduced accumulated mineral N after the wheat harvest: in the ^{15}N experiment, farmers' practice led to considerable accumulation of mineral N after the wheat harvest (125 kg ha^{-1}), of which 69% was subsequently lost after 13 days of flooding. Results from this study indicate the importance of N management in the wheat-growing season, which affects N dynamics and N losses significantly in the following rice season. Integrated N management should be adopted for rice–wheat rotations in order to achieve a better N recovery efficiency and lower N loss.

Keywords Alternate soil wetting and drying · Integrated nutrient management · ^{15}N labelled Urea · Nitrogen budget · Nitrogen cycling · Rice–wheat cropping system

Abbreviations

N	Nitrogen
R–W	Rice–wheat
TRF	Farmers' traditional nitrogen practice
OPT	Optimized nitrogen treatment

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BNF	Biological N_2 fixation
N_{min}	Mineral nitrogen

Introduction

Nitrogen (N) cycles in intensified agricultural ecosystems have received much attention because of the often very large N inputs, especially from chemical fertilizer (Richter and Roelcke 2000). As a nation with the largest agricultural production in the world, China consumed 25.4 Mt of fertilizer N in 2002, accounting for about 30% of total world N consumption (FAO 2004). Thus an understanding of the N budget and the fate of fertilizer N in Chinese agricultural ecosystems has become increasingly important and has received attention from both agricultural and environmental scientists (Zhu 1997; Zheng et al. 2002).

Rice–wheat (R–W) rotations are important cropping systems practiced widely along the Yangtze River Basin in China, where they occupy a total area of about 13 million ha and contribute 72% of total cereal production and 56% of the total national calorie intake of China (Timsina and Connor 2001). These systems include the complete range from flooded rice to strategically irrigated or rainfed wheat. However, the sustainability of R–W rotations is threatened by decreasing crop yields (Ladha et al. 2003), low N fertilizer use efficiencies (Ladha et al. 2000; Bijay-Singh et al. 2001; Liu et al. 2005) and environmental degradation, e.g., groundwater pollution by NO_3^-–N (Shrestha and Ladha 1998; Xing et al. 2001; Lu et al. 2002). This may be partly ascribed to inappropriate nutrient management, especially of N, by farmers using R–W rotations (Dawe et al. 2000; Peng et al. 2002; Ladha et al. 2003). In the quest to achieve high yields of rice and wheat, farmers tend to apply excess N fertilizer in the rotation. For example, China's national average fertilizer N application rate for rice was 145 kg N ha^{-1} in 1997 (IFA 2002) but rates of 150–250 kg N ha^{-1} are common (Peng et al. 2006) and reached 500–600 kg N ha^{-1} $year^{-1}$ in a R–W rotation in the Tai Lake region of eastern China (Xing et al. 2001). However, studies in China have also shown that both wheat and rice may attain higher yields when optimum applications of fertilizer N (from 120 to 150 kg N ha^{-1}) are combined with suitable P and/or K applications (Zhu 1999; Fan et al. 2005).

Fertilizer applications are often not based on real-time nutrient requirements of the crop and/or site-specific knowledge of soil nutrient status. This is especially true in R–W rotations of southwest China, where most of farmers usually apply N in two splits (as basal and top-dressings) within the first 10 days of the rice season, and all of the fertilizer N to wheat (>120 kg N ha^{-1}) as a basal application (Fan 2005). This large amount of fertilizer-N is prone to loss over an extensive period because the rice and wheat take time to develop a sufficient root system and a significant demand for N. Therefore, integrated N management, which emphasizes splitting N fertilizer applications to match crop requirements at different growth stages, based on the difference between total N requirement and the soil and environment N supply, should be adopted in R–W systems in order to achieve high N recovery efficiency and low N loss.

A unique feature of R–W rotations is the annual conversion of soil from aerobic to anaerobic and then back to aerobic. The alternate wetting and drying between rice and wheat creates particular difficulties for N conservation (Kundu and Ladha 1999). Flooding and puddling of soil for rice production rapidly depletes the soil of O_2, resulting in nitrate present in the soil being lost by denitrification (Ponnamperuma 1985) and leaching. Thus, mineral N dynamics have been the focus of many studies in these systems. Tripathi et al. (1997) reported an extreme case in which N losses, when the soil became aerobic after being submerged for rice, ranged from 240 kg ha^{-1} $year^{-1}$ with tobacco (*Nicotiana* spp., L.) to 575 kg ha^{-1} $year^{-1}$ with sweetpepper (*Capsicum annuum* L.). Much of this N leached into groundwater in the rice–sweetpepper cropping areas; some 50% of the wells sampled had NO_3^-–N concentrations exceeding WHO limits (Shrestha and Ladha 1998). Fan et al. (2005) recorded mineral N (N_{min}, sum of ammonium and nitrate N) accumulation in soil of 84 kg N ha^{-1} after wheat in a three-year R–W rotation experiment of southwest China. However, research is still needed to determine the N_{min} accumulation and loss, both the magnitude and rapidity, in farmers' fields in response to flooding for rice production. Furthermore, we hypothesize that the N management strategy in the wheat-growing season will significantly affect N cycling of the whole

R–W rotation, especially N loss when aerobic soil is flooded for rice production.

The experiments described in this study were conducted in Chengdu Plain, a typical R–W rotation area of southwest China, and had the following objectives: (1) determine the N input and the amount of N_{min} accumulated in farmers fields during or after both wheat and rice seasons, (2) test the effects of soil submergence for rice production on N_{min} accumulated at the end of the wheat season under different N treatments, and (3) compare ^{15}N fertilizer balances and apparent N losses between the optimized N treatment and the farmers' traditional practice for the wheat season, rice season and whole rotation.

Materials and methods

Field experiment

Wheat and rice main plot

The experimental site (30°42′ N, 103°50′ E and 539 m elevation) is located at Wenjiang County near the center of Chengdu Plain. The region is classified as humid sub-tropical with a monsoon climate. Average annual rainfall is 947 mm. The soil is classified as a sandy loam Stagnic Anthrosol (Fluvaquent) developed from alluvial deposits of the Minjiang river (containing free $CaCO_3$). The top 20 cm of the soil contained 22.1 g kg^{-1} soil organic Matter (SOM), 1.36 g kg^{-1} total N (TN), 3.3 mg kg^{-1} Olsen-P (OP), and 30.4 mg kg^{-1} exchangeable K (EK) and had a pH value (in water) of 6.6 at the start of the experiment in October 2003.

The field experiment comprised three treatments in a randomized block design with three replicates and a plot size of 11 × 3.5 m. The plots were separated by a 40-cm-wide alley using plastic film inserted into the soil to a depth of 40 cm. The farmers' traditional practice (TRA) was based on a survey of farmers' nutrient management practices. Optimized treatments (OPT) were established according to an Integrated Nutrient Management (INM) strategy. Details of the INM approach were described by Zhang et al. (2006). Briefly, the N fertilizer was split to match crop requirements at different growth stages, based on the difference between the estimated total N requirement and the soil and environment N supply. Fine-tuning of applications was achieved using leaf greenness measurements for rice (SPAD meter; Peng et al. 1996; Dobermann et al. 2002). The maintenance P and K applications were calculated from measurements of soil nutrient supply (Wang et al. 1995). In the wheat season, the P and K fertilizers on all plots (72 kg P_2O_5 ha^{-1} as calcium superphosphate, 67.5 kg K_2O ha^{-1} as potassium Chloride), N fertilizer in the TRA treatment (180 kg N ha^{-1} as urea) and 50% of N fertilizer in the OPT treatment (60 kg N ha^{-1} as urea) were applied to the seedbed just before sowing. The remaining half of the N fertilizer (60 kg N ha^{-1} as urea) for the OPT treatment was broadcast in early February (at the booting stage of wheat). Wheat (*Triticum aestivum* L.) was planted using zero tillage on 1 November, 2003. The variety 'SW3243' supplied by the Institute of Crop Science, SAAS, was sown directly into the soil at spacings of 10 × 15 cm and 10 × 25 cm as bunch planting. The wheat was harvested on 17 May 2004.

Rice (*Oryza sativa* L., variety Xiangyou 1) was transplanted as 44-day-old seedlings on 23 May 2004 at a 30 × 18.5 cm spacing on both the TRA and control plots. In the OPT plots, cultivation involved planting three seedlings per hill in a triangular pattern with 10–12 cm spacing between the plants. The hills were planted in a staggered 30 × 40 cm grid. As before, no N fertilizer was applied to the control treatment. The P (42 kg P_2O_5 ha^{-1} as calcium superphosphate in TRA and control, 96 kg P_2O_5 ha^{-1} in OPT, respectively) and K fertilizer (67.5 kg K_2O ha^{-1} as potassium chloride of all plots) were broadcast and incorporated into the seedbed of all three treatments prior to transplanting. N fertilizer as urea was split-applied, with 73 kg N ha^{-1} before transplanting and 73 kg ha^{-1} after 12 days of transplanting in TRA; and 42 kg N ha^{-1} before transplanting, 40 kg N ha^{-1} at flowering and 38 kg N ha^{-1} at panicle initiation in OPT. All N fertilizers were uniformly broadcast by hand and followed irrigation. The rice was harvested on 17 September 2004.

^{15}N fertilizer microplot

A microplot (1 × 1 m) was established in the northeastern side of each experimental plot. Using the same plant spacing as the corresponding main plots, the study covered 36 and 20 hills in the 1 m^2

microplots in the wheat and rice seasons, respectively. The microplots were bordered by metal retainers 0.45 m high, pressed to 0.30 m deep into the soil to prevent surface runoff and lateral contamination. In the rice season, the microplots were moved to the southeastern side of the plots. Urea enriched with 5.26% atom % ^{15}N (provided by Shanghai Chem-Industry Institute) was applied in both the wheat and rice season. All of the ^{15}N fertilizer, P and K fertilizers and field management practices in the microplots were the same as the corresponding large plots in both the wheat and rice seasons.

On-farm survey

The surveys were conducted to understand the nutrient management practices of farmers using R–W rotations, and to determine the residual soil N_{min} after both rice and wheat harvests in southwest China in 2003–2004. A random sample of 200 farmers in 10 villages, which belong to five counties in Chengdu plain, was interviewed. The survey questions addressed farmers' social-economic backgrounds and farming practices, and focused on fertilizer (inorganic and organic) application. From the 200 farms, 40 fields were selected to measure N_{min} at 0–80 cm after the wheat (13–16 May in 2004) and rice (7–9 September 2004) harvests.

Soil and plant sampling and analyses

Soil samples from 0–80 cm were collected from the experimental plots with a 3-cm i.d. tube auger and separated into 20-cm depth increments. Soil samples were collected at the beginning of each experiment (1 Nov., 2003), wheat seedling (16 Nov., 2003), wheat heading (4 Mar., 2004), wheat harvest (17 May, 2004), 12 days after rice transplanting (4 June, 2004) and rice harvest (17 Sep., 2004) from all plots; and at wheat harvest, 12 days after rice transplanting (only for those microplots established in the wheat season), and at rice harvest from the microplots. The soil samples from the 40 farmers' fields were only collected at wheat and rice harvests, as explained above. Soil samples were immediately frozen or refrigerated. Within 12 h a 12-g moist subsample was extracted with 100 ml 0.01 M $CaCl_2$. The extracts were analyzed for NO_3^-–N and NH_4^+–N by continuous flow analysis (Bran and Luebbe TRAACS Model 2000 Analyzer). Simultaneously, another subsample was weighed in a pre-weighed aluminium can for determination of soil water content. Ammonium and nitrate values (mg kg^{-1}) were converted to kg N ha^{-1} using soil bulk density concurrently determined using soil cores from each depth. Soil samples from microplots were air-dried, ground to pass a 150-μm (100-mesh) screen, and analysed for total N and ^{15}N as described below.

Grain and straw yields (on a dry matter basis) were determined by harvesting 15 m^2 from each plot. Every season the entire above-ground biomass was removed from microplots at harvest and separated into grain and straw. Grain and straw samples were subsequently dried at 60°C in a forced air oven and ground to pass a 150-μm (100 mesh) screen. Grain, straw and soil samples were analyzed for total N and ^{15}N abundance by the micro-Kjeldahl procedure and isotope ratio mass spectrometry on a Finnigan Mat-251 mass spectrometer.

Data analyses

From all microplots, the percentage of fertilizer N recovered in above-ground crops at harvest, and in the soil on the 12th day after rice transplanting and at harvest of each crop was determined using the following Eqs. 1 and 2, where all ^{15}N was expressed as the atom % excess corrected for background abundance (0.3663%).

$$\text{N derived from fertilizer } (N_{dff}) \text{ in plant } (\text{kg N ha}^{-1}) = \text{N uptake by plant} * {}^{15}\text{N atom \% excess in plant}/{}^{15}\text{N atom\% excess in fertilizer} \quad (1)$$

$$N_{dff} \text{ in soil } (\text{kg N ha}^{-1}) = \text{Total N in soil} * {}^{15}\text{N atom\% excess in soil}/{}^{15}\text{N atom\% excess in fertilizer} \quad (2)$$

Apparent N losses were estimated after rice, wheat and one cycle of the R–W rotation using the method proposed by Liu et al. (2003). The apparent N losses were calculated by difference between the inputs (fertilizer, initial soil mineral N, rainfall, irrigation, seed/seedling, biological N_2 fixation (BNF) and N mineralization) and outputs (uptake by crops and residual soil N_{min}). N mineralization was estimated from the balance of inputs and outputs in the control (N0) treatment according to the following formula:

$$\begin{aligned}\text{N mineralization} = {} & \text{N uptake from the control} \\ & + \text{residual soil } N_{min} \text{ of 0–80 cm} \\ & \quad \text{depths in the control} \\ & - \text{N from irrigation, rainfall,} \\ & \quad \text{seed/seedling and BNF} \\ & - \text{initial 0–80 cm soil } N_{min} \\ & \text{in the control (units: kg N ha}^{-1}\text{).}\end{aligned} \tag{3}$$

Analysis of variance (ANOVA) was performed on a fully randomized plot design to test for significance of treatments and means were compared by least significance difference (LSD) at the 5% level (SAS, 1996).

Results

N inputs

Table 1 lists the N input of the R–W rotation on the sampled farmers' fields in Chengdu Plain, southwest China. The average N input in the wheat season was 169 kg ha^{-1}, ranging from 77 to 286 kg ha^{-1}. Fertilizer N (average 125 kg ha^{-1}) was the main source, accounting for 74% of the total average N input. N inputs from organic manure, rain, seeds and biological N fixation (BNF) were 7, 13, 8 and 15 kg ha^{-1}, respectively. The average N input was 279 kg ha^{-1} in the rice season, ranging from 144–445 kg ha^{-1}. N input from inorganic fertilizer (average 156 kg ha^{-1}) and BNF (58 kg ha^{-1}) accounted for 56% and 21% of total N input, respectively. N input in the rice reason accounted for 63% of the total input in the whole rotation (average 449 kg ha^{-1}). N input from organic fertilizers in R–W rotations accounted for only 11% of the total N input in the present study. However, national average contributions of organic manure to total nutrient inputs are approximately 35% (Ju et al. 2005). Variance in N inputs for both crops suggests that under- and over-fertilization might coexist in farmers' fields.

Mineral N accumulation after crop harvest

The average amounts of residual N_{min} in the 0–80 cm layer of soil after the wheat and rice harvests in farmers' fields are shown in Fig. 1. The residual N_{min} after the wheat harvest ranged from 42 to 115 kg ha^{-1} (average 84 kg ha^{-1}). The extractable soil NO_3^{-}–N

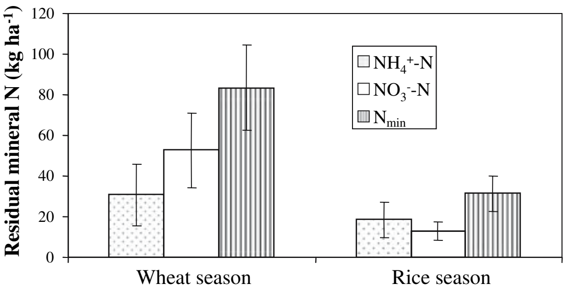

Fig. 1 Residual mineral nitrogen from 0–80 cm soil depths after crops harvest in farmer's fields in southwest China. The bars denote standard errors of mean, n = 40

Table 1 N input (kg N ha^{-1}) in one Rice–Wheat rotation on farmers' fields in southwest China (2003–2004)

	Wheat season	Rice season	System (wheat + rice)
N fertilizer[a]	40.0–230.0 (125[b])	50.0–280.0 (156)	102.0–483.0[e] (281)
Organic manure[a]	1.0–20.0 (7.2)	10.1–81.1(37.5)	19.1–90.5.1[e] (47.7)
N from rain[c]	13.4	15.6	29
N from Irrigation[c]	0	6.0	6.0
N from seeds/seedling[c]	7.9	4.5	12.4
Biological N fixation[d]	15.0	57.5	72.5
Total input	77.3–286.3 (168.5)	143.7–444.7 (279.1)	251.0–688.3 [e] (448.6)

[a] Data from on-farm survey (n = 200), [b] average of input, [c] data from analyse to rain, irrigation water and wheat seeds/rice seedling, [d] data from Shi et al. (2003), and [e] the range of applications to R + W observed in farmers' fields

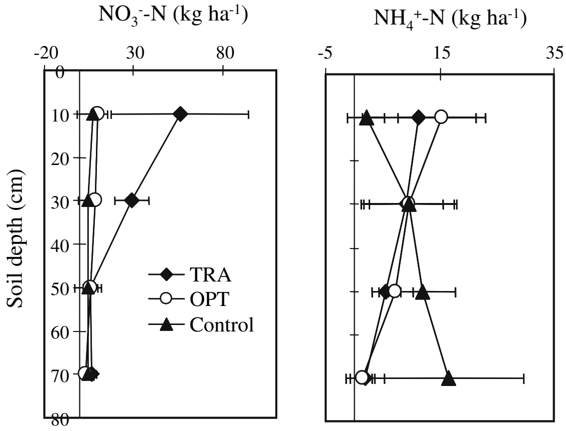

Fig. 2 Distribution of NO_3^-–N and NH_4^+–N in soil after wheat harvest in the field plot experiment in southwest China. The bars denote standard errors of mean, $n = 3$. TRA, farmers' traditional practice; OPT, optimized nitrogen treatment

after wheat harvest averaged 53 kg ha^{-1} and accounted for 63% of the average residual N_{min}. This was probably because well-aerated soils in the wheat season favour aerobic N transformations, resulting in nitrification of NH_4^+–N to NO_3^-N. However, residual soil N_{min} after rice harvest was lower (13 kg ha^{-1} for NO_3^-–N, 18 kg ha^{-1} for NH_4^-–N, and 31 kg ha^{-1} for N_{min}) than that after wheat harvest. It is usually difficult to accumulate mineral N in flooded soils in the rice season.

Residual soil NO_3^-–N and NH_4^+–N in the top 80 cm of the soil after wheat harvest under the different N treatments of the field experiments are presented in Fig. 2. TRA led to higher residual soil NO_3^-–N (97 kg ha^{-1}) after wheat harvest, which was located mainly in the 0–20 cm (51 kg ha^{-1}) and 20–40 cm (29 kg ha^{-1}) layers, than those in the OPT (28 kg ha^{-1}) and control (21 kg ha^{-1}) treatments. There were no statistically significant differences in the distribution of NO_3^-–N and NH_4^+–N between the OPT and control treatments. This indicated that the optimized N treatment of INM decreased residual soil N_{min} after wheat. However, there was little difference in NH_4^+–N and NO_3^-–N in the soil of the three treatments after rice harvest (Fig. 3).

Mineral N dynamics

Soil N_{min} dynamics as affected by N treatment are presented in Fig. 4. During the wheat season, NO_3^-–N and N_{min} values in the 0–80 cm of soil in the TRA

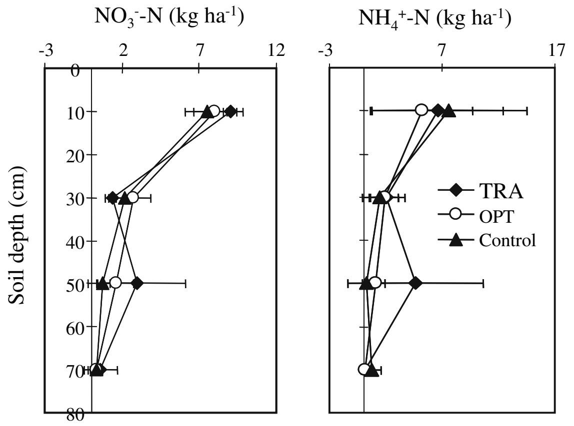

Fig. 3 Distribution of NO_3^-–N and NH_4^+–N in soils from the field experiments after rice harvest in southwest China. The bars denote standard errors of mean, $n = 3$. TRA, farmers' traditional practice; OPT, optimized nitrogen treatment

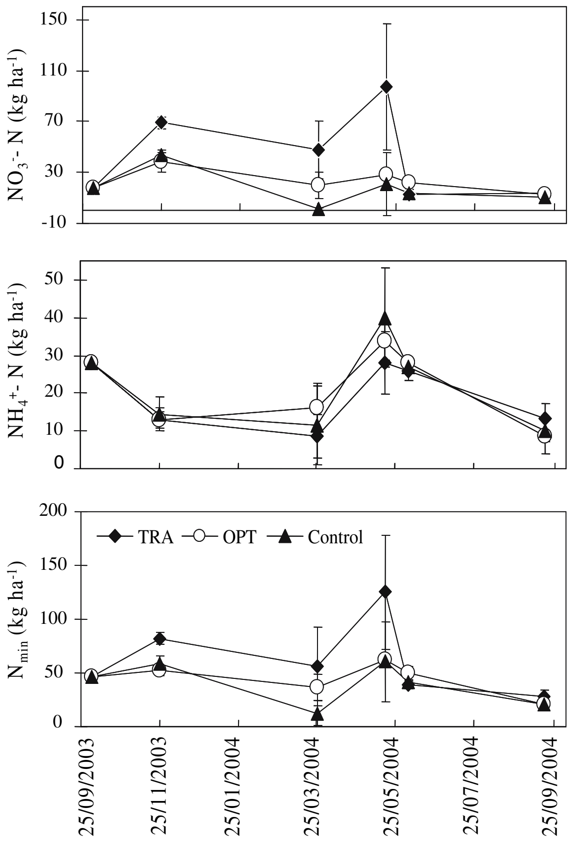

Fig. 4 Mineral nitrogen dynamics in the 0–80 cm soil layer of the field experiment over one rice–wheat rotation in southwest China. The bars denote standard errors of mean, $n = 3$. TRA, farmers' traditional practice; OPT, optimized nitrogen treatment

treatment were consistently higher than those in the OPT and control treatments. There were no significant differences in the NO_3^-–N contents of the OPT and control treatments with the exception of 6 March 2004 (heading stage), when that in OPT was larger than that in control. Soil N_{min} values in the three treatments sharply increased after 6 March 2004. This might be because increasing temperatures resulted in enhanced mineralization of soil organic matter (Wilson and Jefferies 1996; Bernhard-Reversat 1988). However, compared with control and OPT, TRA maintained a higher rate of increase of NO_3^-–N and total N_{min}. Perhaps the presence of more NO_3^-–N in the TRA soil increased microbial activity and enhanced the turnover soil organic C.

The residual N_{min} in the top 0–80 cm of soil after wheat harvest decreased significantly upon flooding the aerobic soil for rice production, especially in the TRA treatment. The observed NO_3^-–N values after 13 days of flooding (12 days after rice transplanting) were 13 kg ha^{-1} in TRA, 22 kg ha^{-1} in OPT, and 14 kg ha^{-1} in control, respectively. Thus NO_3^-–N accumulated during the wheat season in TRA decreased by 87% in 13 days in the flooded soil. This is most likely the result of denitrification of N that could not be taken up by rice seedlings recovering from transplanting shock. The observed value of soil N_{min} from that at 13 days after flooding to rice harvested was consistently lower and no significant differences were found among the treatments.

^{15}N fertilizer balance

^{15}N fertilizer recoveries as influenced by N managements are shown in Table 2. In the wheat season compared with TRA, OPT decreased significantly the residues of ^{15}N-labelled fertilizer and losses (as unaccounted for N): ^{15}N-labelled fertilizer residues and losses after wheat harvest were 53 kg ha^{-1} and 60 kg ha^{-1} in TRA, and 32 kg ha^{-1} and 19 kg ha^{-1} in OPT, respectively, accounting for 29% and 33% of total ^{15}N-labelled fertilizer application in TRA, and 26% and 16% in OPT, respectively. No significant differences in ^{15}N-labelled fertilizer removal by the wheat crop were found between TRA and OPT because the above-ground biomass of wheat was similar in the two treatments (Table 2). However, the proportion of ^{15}N-labelled fertilizer removal by wheat to the total application rate in OPT (58%) was significantly larger than that in TRA (38%). This suggests that OPT increased ^{15}N fertilizer use efficiency in the wheat season.

In the rice season, OPT led to a significantly higher grain yield/above-ground biomass and consequently higher uptake of ^{15}N fertilizer than TRA, and so decreased the losses. The amount of ^{15}N-labelled fertilizer removed by rice and the amount lost were 12 kg ha^{-1} and 121 kg ha^{-1} in TRA, and 22 kg ha^{-1} and 85 kg ha^{-1} in OPT, accounting for 8% and 83% of total ^{15}N fertilizer application in TRA, and 18% and 73% in OPT. No significant differences in ^{15}N-labelled fertilizer residue after rice harvest were

Table 2 The fate of ^{15}N fertilizer in rice–wheat rotation system in southwest China

Treatment[a]	N rate	Yield (kg/ha)		Crop uptake		Soil residual		Loss[b]	
		Grain	Straw	kg ^{15}N ha^{-1}	%	kg ^{15}N ha^{-1}	%	kg ^{15}N ha^{-1}	%
Wheat season									
CK	0	3592 b	3462 b	/	/	/	/	/	/
OPT	120	5918 a	6192 a	69.3a	57.7a	32.0b	26.6a	18.7b	15.6b
TRA	180	5764 a	5758 a	67.8a	37.7b	52.6a	29.2a	59.6a	33.1a
Rice season									
CK	0	5036 c	3562 c	/	/	/	/	/	/
OPT	119	8560 a	7419 a	21.7a	18.2a	12.7 a	10.7a	84.6b	73.1b
TRA	146	6622 b	5765 b	11.5b	7.8b	13.2a	9.0a	121.4a	83.1a

Within each column, values with the same letter are not significantly different by LSD at the 0.05 level across soil depth

[a] OPT, optimized nitrogen treatment; TRA, farmers' traditional practice

[b] As the part of unaccounted for

found between TRA and OPT. The very large loss of ^{15}N-labelled fertilizer is probably due to soil conditions and management practices and is not atypical: Liu et al (2005) reported that 65% of ^{15}N-labelled fertilizer was lost in the rice season in an adjacent field.

After both wheat and rice harvests, most of the residual ^{15}N-labelled fertilizer was in the 0–20 cm layer of soil irrespective of treatment (Table 3). The amount of residual ^{15}N-labelled fertilizer in the 20–40, 40–60 and 60–80 cm soil layers ranged from 3–8 kg N ha^{-1} after wheat and from 1–3 kg N ha^{-1} after rice. Thus ^{15}N-labelled fertilizer was leached or denitrified in both the wheat and rice seasons.

Table 3 Distribution of ^{15}N fertilizer in the soil profile after rice and wheat harvests (kg N ha^{-1})

Treatment[a]	Wheat season		Rice season	
	OPT	TRA	OPT	TRA
0–20	21.3 a	36.7 a	6.4 a	7.2 a
20–40	3.8 b	7.5 b	2.1 bc	1.3 b
40–60	4.1 b	3.4 c	1.2 c	2.3 b
60–80	2.8 b	4.9 bc	3.0 b	2.3 b

Within each column, values with the same letter are not significantly different by LSD at the 0.05 level across soil depth

[a] OPT, optimized nitrogen treatment; TRA, farmers' traditional practice

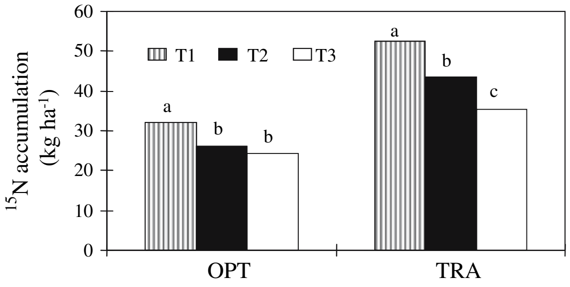

Fig. 5 Effect of soil flooding on residual ^{15}N-labelled fertilizer: T1, at the end of the wheat season; T2, at the 13th day after flooding/12th day after rice transplanting; T3, after rice harvest. OPT, optimized nitrogen treatment; TRA, farmers' traditional practice. Within each treatment, values with the same letter are not significantly different by LSD at the 0.05 levels across soil depth

Figure 5 shows the dynamics of residual ^{15}N fertilizer in the soil to 80 cm after wheat harvest and in response to flooding for rice production. After 13 days of soil flooding/12 days of rice transplanting, the amounts of residual ^{15}N-labelled fertilizer in both the TRA and OPT treatments significantly decreased. Compared with those after wheat harvest, the residual ^{15}N-labelled fertilizer after 13 days of flooding decreased by 17% in TRA, and 18% in OPT, respectively. ^{15}N-labelled fertilizer remaining in the 0–80 cm soil layers after rice harvest accounted for 78% of the residual ^{15}N-labelled fertilizer at the end of wheat harvest in OPT and 68% in TRA. These results suggest that the loss of residual ^{15}N fertilizer after wheat harvest occurred mainly within 13 days of flooding, probably because the rice seedlings were recovering from transplanting shock and required less N.

Apparent N loss

Apparent N losses from rice, wheat and the whole rotation, accounting for all N inputs and outputs measured in this study, are in Table 4. In the wheat season, the total N input was 314 kg ha^{-1} in TRA and 254 kg ha^{-1} in OPT. N removal by wheat in TRA was similar to that in OPT, while residual soil Nmin was higher in TRA (125 kg ha^{-1}) than that in OPT (61 kg ha^{-1}). In the rice season, TRA led to a higher apparent N loss (180 kg ha^{-1}) in comparison to OPT (62 kg ha^{-1}). This was mainly due to the larger initial mineral N (125 kg ha^{-1}) and fertilizer (149 kg ha^{-1}), and the lower N removal (85 kg ha^{-1}) in the former treatment. The loss of 86 kg ha^{-1} mineral N accumulated during the wheat season within 13 days of flooding for rice production, accounted for 48% of the total apparent N loss during the rice season in TRA. In the whole system, total N inputs were 394–454 kg ha^{-1} over the treatments, but the removal by crops and residual soil N_{min} amounted to only 272–304 kg ha^{-1}. Thereby large N surpluses occurred after one R–W rotation cycle. The apparent N losses were higher in TRA (209 kg ha^{-1}) than that in OPT (90 kg ha^{-1}); that in the rice season accounted for 86% of total apparent loss in TRA, and 69% in OPT. However, as the N losses have been estimated relative to the control treatment, in which losses were set zero, the N losses in the fertilizer treatments may have been underestimated.

Table 4 Apparent N balances of rice–wheat rotation systems under different N management strategy (all data kg ha^{-1})

Treatment[a]	N input			N output			Apparent N loss
	N Rate (1)	Initial N_{min} (2)	Environment N (3)[b]	Mineralization (4)[c]	Crop uptake (5)	Residual N_{min} (6)	(1) + (2) + (3) + (4) − (5) − (6)
Wheat season							
Control	0	51.0	28.4	54.1	73	60.5	0
OPT	120	51.0	28.4	54.1	164	61.7	27.8
TRA	180	51.0	28.4	54.1	159	125.3	29.2
Rice season							
Control	0	60.5	79.1	−57.8	61	20.8	0
OPT	119	61.7	79.1	−57.8	119	21.2	61.8
TRA	146	125.3	79.1	−57.8	85	27.4	180.2
System							
Control	0	51.0	107.5	−3.7	134	20.8	0
OPT	239	51.0	107.5	−3.7	283	21.2	89.6
TRA	326	51.0	107.5	−3.7	244	27.4	209.4

[a] OPT, optimized nitrogen treatment; TRA, farmers' traditional practice

[b] N from irrigation, raining, seeds/seedlng and biological N fixation (see Table 1)

[c] Net N mineralization = Plant N uptake in control + N_{min} residual in control − Initial N_{min} in control − N input from environment

Discussion

Nitrogen input and ^{15}N fertilizer loss of R–W rotation

Inorganic fertilizer inputs (total average input 281 kg ha^{-1}, Table 1) accounted for 63% of entire N inputs in this R–W rotation systems for southwest China. Large losses of N fertilizer inevitably occur on farmers' fields where large amounts of N fertilizers are applied. This is shown clearly by the ^{15}N-labelled fertilizer experiment in which TRA, with its large N fertilizer application, led to significantly higher N losses than OPT (Table 2) without a corresponding increase in grain yield. However, the losses of ^{15}N-labelled fertilizer during the rice season accounted for 81% and 67% of the loss over the whole system in OPT and in TRA, respectively. This finding, that ^{15}N-labelled fertilizer is lost mainly during the rice-growing season under a R–W rotation, is strongly supported by other studies made in the same region of China (Liu et al. 2005) and in other regions of India (Bijay-Singh et al. 2001).

The losses of ^{15}N fertilizer were calculated by difference between the total application and the amount recovered in the grain and straw in both rice and wheat, and residual N in the soils after harvest of both crops. Obviously, this estimate does not apportion N lost between leaching, denitrification, or volatilization. Past research ascribes most losses to denitrification during the wheat-growing season (Xiong 2002) and ammonia volatilization during the rice-growing season (Fillery and De Datta 1986; Zhu 1997). However, losses due to leaching cannot be ruled out (Table 3) because of the high infiltration rate of this soil. Irrigation was applied almost daily for much of the rice-growing season because the floodwater typically remained on the surface less than a day, making both leaching and denitrification highly likely (Xing et al. 2002; Aulakh et al. 1996; Cai et al. 1999).

Effect of flooding of soil for rice production on N dynamic of R–W rotation

Significant effects of flooding for rice production on N dynamics in R–W rotations were observed in our study. After wheat harvest, N_{min} accumulation in the 0–80 cm layer of soil on observed farmers' fields was approximately 84 kg N ha^{-1}, of which the NO_3^-–N content accounted for 63%. Buresh et al. (1989) reported NO_3^-–N levels of 39–91 kg ha^{-1} in the top

60 cm soil at onset of the wet season in a mungbean-lowland rice system in the Philippines. However, this accumulated NO_3^-–N is lost when the aerobic soil is flooded for rice production. In the present plot experiment, excessive amounts of N fertilizer applied when wheat was sown led to considerable accumulated N_{min} after the wheat harvest, which was subsequently lost within 13 days of flooding of the soil/12 days of rice transplanting (Fig. 4). Tripathi et al. (1997) recorded an almost halving of NO_3^-–N accumulated in 0–100 cm soil during the pepper season (112 kg ha^{-1}) after 40 days of flooding for rice production. The rapidity and extent of the decrease of residual NO_3^-–N in response to flooding an aerobic soil for rice production may be related to the soil fertility and/or soil type/texture.

Effect of management strategy on N cycling of R–W rotation

Management strategies have a significant effect on N cycling in R–W rotations. The plot experiments show that OPT, with its 27% reduction in total N fertilizer input over the rotation, decreased the apparent N loss from the rotation by 52% and increased productivity by 17%. Management during the wheat season is especially important, given the losses of accumulated soil mineral N at the end of the wheat season when soil is submerged for rice production. The efficient use of N by the whole system requires that the wheat crop leaves as little mineral N as possible at the end of the season. This is especially important for R–W rotations in the southwest of China, because the short turnaround time between the wheat harvest and rice transplanting makes it impossible to use catch crops as in southern Asia. Strategies presented in this study propose a holistic and practicable, but simple means to manage nutrients. Nevertheless, there is still a need to simplify and more effectively promote the current nutrient management technology to make farmers more enthusiastic about adopting it.

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