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Crop production, nitrogen recovery and water use efficiency in rice–wheat rotation as affected by non-flooded mulching cultivation (NFMC)

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Abstract

Non-flooded mulching cultivation (NFMC) for lowland rice, as a novel water-saving technique, has been practiced in many areas of China since the 1990s. However, the information on NFMC effects on crop production, nitrogen and water use in rice–wheat rotations is still limited. A field experiment using ^{15}N-labeled urea was conducted to evaluate the impacts of NFMC on crop yield, fertilizer N recovery and water use efficiency in rice–wheat rotations. Plastic film mulching (PM), and wheat straw and plastic film double mulching (SPM) resulted in the same rice grain yield (7.2 t ha^{-1}) while wheat straw mulching (SM) and no mulching (NM) led to 5 and 10% yield reduction, compared with rice under traditional flooding (TF). In the rice–wheat rotation, crop productivity in PM, SM or SPM was comparable to that in TF but greater than in NM. Weed growth and its competition with rice for nitrogen were considered the main reason that led to yield decline in NM. Compared with TF, NFMC treatments did not obviously affect fertilizer N recoveries in plant and soil in both rice and wheat seasons. The total fertilizer N recoveries in crop, weed and soil in all treatments were only 39–44% in R–W rotations, suggesting that large N losses occurred following one basal N application for each growing season. Water use efficiency, however, was 56–75% greater in NFMC treatments than in TF treatment in the R–W rotation. The results revealed that NFMC (except NM) can produce comparable rice and wheat yields and obtain similar fertilizer N recovery as TF with much less water consumption.

Introduction

Rice–wheat (R–W) rotations are the main cropping systems along the Yangze River Basin in China. A total area of 13 million hectares is currently under this cropping system (Timsina and Connor 2001). Seasonal water shortage (both rainfall and irrigation water) has become a critical factor that limits the productivity and sustainability in such cropping systems. Non-flooded mulching cultivation (NFMC) was introduced to R–W rotations in China in the late 1990s, as a novel water-saving technique for lowland rice (Liu et al. 2003). The main mulching materials include plastic film and crop straw (Liang et al. 1999; Peng et al. 1999). NFMC is employed under non-flooded conditions with limited irrigation (to ensure 70–90% soil saturated water content) compared with traditional flooding cultivation. The plastic film mulching proved its potential to increase soil temperature and water use efficiency and to inhibit weed growth at comparable or even higher yields compared to traditional flooded rice (Liang et al. 1999; Wang 2001). Other mulching materials, such as wheat or rice straw, produced some negative effects on rice yield and nutrient uptake (Fan et al. 2002; Liu et al. 2003), presumably due to low soil temperature at the early rice growth stage (Liu et al. 2003). There is, however, some yield compensation on wheat in plots that received SM from previous rice, especially under lower N rates (Liu et al. 2003; Fan et al. 2005). The open question is whether rice productivity can be improved by solving the low soil temperature problem using double mulching of straw with plastic film.

Straw management is an important concern in most regions with R–W rotations, due to the short turn-around time between wheat harvest and rice transplanting or between rice harvest and wheat sowing (Prasad et al. 1999). The burning of wheat straw is common in Chinese R–W systems, particularly in the Chengdu Plain of southwest China. This leads to large losses of organic C and N as well as significant air pollution. Therefore, utilization of wheat straw (e.g. as mulching material) is not only a nutrient recycling issue but an important environmental issue in southwest China. The weed problem is another concern under non-flooded straw mulching cultivation (Wang 2001). Usually, weeds can be well controlled by the stable water layer on the soil surface in flooded rice. However, the weed growth and its detrimental effect on crops cultivated under NFMC condition are still not clear.

Traditional R–W rotation leads to periodic changes of soil water status from anaerobic condition to aerobic condition then to anaerobic condition again, which greatly affects nutrient (e.g. Fe and Mn) availability in rhizosphere (Zhang et al. 2004). The cycle of soil water condition inevitably leads to lower N recovery because of greater N losses by ammonia volatilization, denitrification and/or leaching compared to upland cropping systems (Ladha et al. 2000; Cai et al. 2002). That is the main reason why fertilizer N is not utilized efficiently in rice-based cropping systems (De Datta 1986; Eagle et al. 2000). Under NFMC, the soil is kept aerobic during most of the R–W rotation period. A change from traditional flooding (anaerobic) to non-flooded mulching (aerobic) may have large effects on the forms and availability of N in the soil. It is therefore important to test for interactions between N inputs and non-flooded mulching cultivation as they affect productivity and N cycling. Furthermore, the effect of NFMC on fertilizer N recovery is poorly understood in R–W rotations.

The main objectives of this study are to determine: (1) the impact of NFMC in R–W rotation on crop production and water saving potential, and (2) fertilizer N recovery and possible major pathways for N loss. We used ^{15}N labeled urea to trace the fate of N in the plant–soil systems.

Materials and methods

The experimental site is located at the center of Chengdu flood plain, in southwest China. The soil is a loam paddy soil (Fluvaquent) with relatively high fertility (pH 6.5, organic carbon 23 g kg^{-1}, total N 1.8 g kg^{-1}, available (Olsen) P 23 mg kg^{-1} and exchangeable K 60 mg kg^{-1}). The air temperature, relative humidity, precipitation and sunshine hours in this region during the experiment (May 2001 to May 2002) are listed in Table 1, which are similar to the average weather conditions as described by Liu et al. (2003).

The field experiment was composed of five treatments in the rice season: traditional flooding (TF) as control, plastic film mulching (PM), wheat straw mulching (SM), and wheat straw (lower layer) and plastic film (upper layer) double mulching (SPM) and no mulching (NM) as non-flooded mulching cultivation (NFMC) systems. The same conventional management practice was used for all treatments in the wheat season. The water, mulching, cultivation and nutrient management in the experiment was described in detail by Ai (2003). Briefly, in the TF treatment, a stable water level (about 3 cm) was maintained until two weeks before rice harvest; in NFMC treatments, no permanent water layers were kept during whole rice season. In the rice growing period, the amounts of irrigation for TF and NFMC treatments were recorded by a flow meter. In the wheat growing season, no irrigation was used for all treatments.

Table 1. Average maximum and minimum temperatures, relative humidity, monthly rainfall and sunshine hours during the experiment (May 2001 to May 2002).

Month	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)	Rainfall (mm)	Sunshine hours (h)
May	28	18	65	32	162
June	28	21	82	105	129
July	32	24	82	242	149
August	26	20	87	244	106
September	23	13	90	201	4
October	22	17	83	15	44
November	17	11	83	12	57
December	10	5	81	4	48
January	8	4	88	16	15
February	14	8	80	2	58
March	19	11	76	24	90
April	22	14	75	83	110
May	25	18	78	90	64
Total				1070	1036

Nitrogen, P and K fertilizers were broadcast to the soil surface as basal dressing prior to rice transplanting or wheat sowing in the two crop seasons. The rates of N, P and K were 150 kg N ha^{-1} as urea, 24 kg P ha^{-1} as single superphosphate and 93 kg K ha^{-1} as potassium sulfate for rice, and 120 kg N ha^{-1} as urea, 28 kg P ha^{-1} as single superphosphate and 62 kg K ha^{-1} as potassium sulfate for wheat, respectively.

The rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) varieties used were the hybrid 'II-527' and conventional '9023', respectively. Rice seedlings were transplanted at a spacing of 0.25×0.25 m with two seedlings per hill while wheat was sown at a spacing of 0.2×0.1 m. Rice was transplanted on 26 May, 2001, and harvested on 23 September, 2001. After the rice harvest, wheat was planted on the same plots on 3 November, 2001, with conventional tillage and the removal of rice straw. The wheat was harvested on 15 May, 2002. Most residual plastic film was removed from the field before sowing of wheat in the PM and SPM treatments to avoid any negative effects on soil properties. However, the wheat straw left over from the mulching of the rice crop remained in the field in the SM and SPM treatments. In order to evaluate the effect of NFMC on weed growth and N uptake, no herbicides or hand weeding were used during the R–W rotation.

All plots were 6×5 m and there were three replicates of each treatment in a randomized block design, giving a total of 15 plots. A microplot (1×1 m) was established in the northeastern side of each plot. Using 0.25×0.25 m and 0.2×0.1 m spacings, 16 and 50 hills were included in the 1 m^2 microplots in rice and wheat seasons, respectively. Metal squares 0.45 m high were driven 0.30 m deep into the soil to prevent surface runoff and lateral contamination. Urea enriched with 5.26% atom % ^{15}N (provided by Shanghai Chem-Industry Institute) was applied to soil as the same N rate (150 kg N ha^{-1}) as the remainder of the large plot on 25 May, 2001. In the wheat season, the microplots were moved to the southeastern side of the plots. Urea with the same ^{15}N enrichment as in the rice season was applied to microplots as the same N rate (120 kg N ha^{-1}) as the remainder of the plots on 2 November, 2001. All of the P and K applications and field management practices in microplots were kept the same as the corresponding large plots in both rice and wheat seasons.

Soil samples were collected from 0 to 100 cm depths from all plots and microplots with a 3-cm inner diameter tube auger and separated into 20-cm depth increments at the beginning of experiment, and after harvest of rice and wheat crops. Soil samples were stored in an ice-box immediately after sampling and were then transported to laboratory for analysis. Within 12 h all the fresh soil samples were extracted with 0.01 M $CaCl_2$ solution (ratio of soil to solution 1:10). The extracts were analyzed for NO_3^-–N and NH_4^+–N as mineral N (N_{min}) by a continuous flow analysis (Bran and Luebbe TRAACS 2000). Soil samples from microplots were air-dried and were ground to pass a 150-μm (100-mesh) screen for total N and ^{15}N isotope analysis as described below.

Grain and straw yields and weed biomass (dry matter basis) were determined by harvesting half (15 m^2) of each plot. Every season the entire aboveground biomass was removed from microplots at harvest and separated into grain, straw and weed. Grain, straw and weed samples were subsequently dried at 60 °C in a forced air oven and were ground to pass a 150-μm screen. Grain, straw, weed and soil samples were analyzed for total N and ^{15}N abundance by the micro-Kjeldahl procedure and isotope ratio mass spectrometry (Finnigin Mat-251). From all microplots, percentage of fertilizer N recovery in grain and straw of crops, weed and soil at harvest of each crop was determined using the following Equations (1) to (3), where all ^{15}N was expressed as the atom % excess corrected for background abundance (0.366%).

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

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

$$\text{Fertilizer N recovery(\%)} = \text{Ndff/N rate} \times 100 \quad (3)$$

Apparent N balances were estimated after rice, wheat and one cycle of R–W rotation under traditional flooding and non-flooded mulching cultivation using the method proposed by Tripathi et al. (1997). The N balances or apparent N losses were calculated by differences between the inputs (from fertilizer, initial soil N_{min}, rainfall and crop straw) and outputs (from uptake by crops and weeds, and residual soil N_{min}).

Statistical analysis using SAS software (SAS 1996) on the measured data (biomass yield, N uptake, fertilizer N recovery and soil mineral N) from crop, weed and soil were performed by standard procedures on a randomized plot design for rice, wheat and the whole cropping system. Wherever treatment differences were found, significance was calculated based on results of *F*-tests and least significant differences (LSD) at the 0.05 probability level.

Results

Crop yield and nitrogen accumulation

NFMC effects on grain yield and N uptake by rice and wheat in R–W rotations are shown in Table 2. PM and SPM led to almost the same rice grain yield as TF (7.2 t ha^{-1}) while SM and NM led to 5% and 10% lower rice grain yield compared with TF. Double mulching of straw and plastic (SPM) improved rice yield by about 6% in comparison to SM. Wheat grain yield was the highest in TF (5.8 t ha^{-1}). SM and SPM showed a residual effect on grain yield (5.2–5.3 t ha^{-1}) of wheat compared with PM and NM (4.6–4.9 t ha^{-1}). In the whole R–W system, the productivity was highest in TF (13 t ha^{-1}); SPM, PM and SM yields were 12.1–12.4 t ha^{-1} and lowest yield was in NM (11.1 t ha^{-1}) (Table 2).

Shoot N uptake was not always consistent with grain yield especially in the rice season (Table 2). PM and SPM led to the highest N uptake by rice. This suggests that the plastic film mulching material promotes the N uptake by rice, but the increased N accumulation was mainly distributed in straw under NFMC (data not shown). Trends in wheat shoot N uptake were similar to grain yield with TF, SM and SPM > NM and PM. This trend could be mainly explained by more N being available in the soil following wheat due to less N removal by rice and weeds (TF) or more N inputs (SM and SPM, see below) in the previous rice season. It should be stressed that total N uptake by rice and wheat (256–296 kg ha^{-1}) was almost the same as the total fertilizer N application (270 kg ha^{-1}).

Weed biomass and nitrogen accumulation

To evaluate the effects of NFMC on weeds, we examined the weed biomass and N accumulation during both rice and wheat seasons. Weed biomass was greatly enhanced by NFMC in the rice season

Table 2. Grain yield and shoot N uptake of rice and wheat crops in rice–wheat rotations as affected by non-flooded mulching cultivation.

Treatment	Grain yield (t ha^{-1})			Shoot N uptake (kg ha^{-1})		
	Rice	Wheat	System	Rice	Wheat	System
TF	7.20 a	5.77 a	13.0 a	153 b	129 a	282 ab
PM	7.24 a	4.90 bc	12.1 b	179 a	99 b	278 ab
SPM	7.23 a	5.21 ab	12.4 ab	182 a	114 ab	296 a
SM	6.84 ab	5.29 ab	12.1 b	161 ab	119 ab	280 ab
NM	6.45 b	4.62 c	11.1 c	153 b	103 b	256 b

Values without the same letters in a column were significantly different.

Table 3. Shoot biomass and N uptake of weeds in rice and wheat seasons in rice–wheat rotations as affected by non-flooded mulching cultivation.

Treatment	Weed biomass (t ha^{-1})			Shoot N uptake (kg ha^{-1})		
	Rice	Wheat	System	Rice	Wheat	System
TF	0.01 c	0.15 b	0.16 c	0.4 c	2.5 b	2.9 c
PM	0.09 c	0.41 a	0.50 c	1.9 c	4.5 ab	5.4 c
SPM	0.09 c	0.42 a	0.51 c	1.5 c	5.7 ab	7.2 c
SM	1.29 b	0.42 a	1.71 b	16.5 b	8.3 a	24.8 b
NM	3.91 a	0.47 a	4.38 a	46.0 a	8.6 a	54.6 a

Values without the same letters in a column were significantly different.

compared to that in the wheat season (Table 3). In the rice season, the highest weed biomass (3.9 t ha^{-1}) was found in the NM treatment. Weed production was lower in SM (1.3 t ha^{-1}) and much lower in PM, SPM and TF (less than 0.1 t ha^{-1}). In the wheat season, weed biomass in TF was still the lowest, while weed biomass in other treatments (NFMC) was greater but comparable (0.4–0.5 t ha^{-1}).

The trends in weed N uptake were similar to weed biomass (Table 3). In the rice season, the greatest N uptake by weeds was observed in NM (46 kg ha^{-1}), and followed by SM (17 kg ha^{-1}) then by PM and SPM (about 2 kg ha^{-1}) and by TF (less than 1 kg ha^{-1}). In the wheat season, much smaller differences among all treatments were found although there were some residual effects of NFMC from the previous rice crop on weed N uptake in wheat. In the whole system, total N removal by weed was relatively large in NM (55 kg ha^{-1}) and SM (25 kg ha^{-1}) while it could be neglected in SPM, PM and TF (less than 8 kg ha^{-1}). These results indicated that double mulching of straw with plastic (SPM) significantly inhibits weed growth and its nitrogen uptake compared with straw mulching alone (SM) in R–W rotations.

The recovery of labeled fertilizer N

Differences in fertilizer N recovery in grain and straw and weed were not consistent from rice to wheat (Table 4). In the rice season, fertilizer N recovery in grain and straw was greater in PM and NM (about 21%) than in SPM, SM and TF (13.4–16.5%). In the wheat season, however, fertilizer N recovery in the grain and straw was greater in TF, SPM and SM (19.6–23.6%) than in PM and NM (17.8–18.3%). As a result, in the whole system, there were no significant differences in fertilizer N recovery in both grain and straw among all traditional flooded and non-flooded treatments.

In the rice season, fertilizer N recovery in weeds was highest in NM, next highest in SM, then lowest in SPM, PM and TF, suggesting that in NM and SM treatments weeds compete with rice for N. In the wheat season, fertilizer N recovery in weeds was much smaller than that in the rice season but the trends across treatments were similar. In the whole system, fertilizer N recovery by weeds (0.1–1.6%) increased according to the sequence TF, PM and SPM $<$ SM $<$ NM.

Fertilizer N recovery in the soil (0–100 cm) was not significantly different among TF and NFMC treatments in both rice (18.9–21.4%) and wheat

Table 4. Recoveries of fertilizer ^{15}N in rice–wheat rotations as affected by non-flooded mulching cultivation.

Treatment	Grain (%)	Straw (%)	Weed (%)	Soil (%)	Total (%)
Rice season					
TF	8.4 b	5.0 b	0.01 c	21.4 a	34.8 a
PM	12.1 a	8.9 a	0.06 c	18.9 a	40.0 a
SPM	9.2 ab	6.9 ab	0.04 c	19.3 a	35.4 a
SM	8.9 b	7.6 ab	0.4 b	19.1 a	36.1 a
NM	12.0 a	8.9 a	2.1 a	20.4 a	43.4 a
Wheat season					
TF	20.6 a	3.0 a	0.3 b	24.0 a	47.8 a
PM	16.0 b	2.3 a	0.5 b	24.2 a	42.9 a
SPM	18.3 ab	2.9 a	0.7 ab	22.5 a	44.4 a
SM	17.6 ab	2.0 a	1.1 a	28.9 a	49.5 a
NM	15.9 b	1.9 a	1.1 a	25.4 a	44.3 a
Rice–wheat rotation					
TF	13.8 a	4.1 a	0.1 b	22.5 a	40.6 a
PM	13.8 a	5.9 a	0.3 b	21.3 a	41.3 a
SPM	13.2 a	5.1 a	0.3 b	20.7 a	39.4 a
SM	12.7 a	5.1 a	0.7 a	23.5 a	42.0 a
NM	13.8 a	5.8 a	1.6 a	22.6 a	43.8 a

Values without the same letters in a column of each crop were significantly different.

(22.5–28.9%) seasons. In the whole system, fertilizer N recovery in the soil was relatively lower than the value from other field experiment under similar condition (personal communication, Zeng X.Z. and Pan J.R., 2003).

Total fertilizer N recovery was estimated by summing the amounts found in the grain, straw and weed in both rice and wheat seasons, and those found in the soils after harvest of rice and wheat. Obviously, this estimate does not account for the N via leaching, denitrification, or volatilization through soil and/or plants. Estimated total fertilizer N recoveries amounted to 34.8% in TF and 35.4–43.4% in NFMC in the rice season; and 47.8% in TF and 42.9–49.5% in NFMC in the wheat season. There were no statistically significant differences between TF and NFMC treatments. In the whole system, total fertilizer N recoveries (39.4–43.8%) showed little variation among all treatments. These results demonstrated that NFMC did not significantly change the fertilizer N recovery in the whole rice–wheat cropping systems.

One interesting N loss mechanism is leaching below 20 cm in the soil. We found that most of the remaining fertilizer N was distributed in the soil surface layer (0–20 cm) after harvest of rice or wheat (Figure 1). In the rice season, the distribution of fertilizer N in the soil profile showed the same tendency in all treatments, e.g. that more than 55% of fertilizer N that remained in soil was in 0–20 cm layer and the rest was almost uniformly distributed in the other four layers below 20 cm (Figure 1a). In the wheat season, however, distribution of fertilizer N in the soil profile was distinctly different between TF and various NFMC treatments particularly in 0–20 cm and 80–100 cm layers (Figure 1b). In 0–20 cm layer, fertilizer N in the soil was greater in TF than in PM, SPM and SM, which were greater than in NM. In contrast, more fertilizer N in the 80–100 cm layer was found in SM and SPM compared to that in TF, PM and NM. The distribution of fertilizer N in the soil profile agreed well with nitrate N in the soil profile (data not shown), suggesting that N leaching loss should be negligible especially in rice season. But N leaching below 20 cm depth particularly in SM and SPM treatments probably occurred in the wheat season. Zhu et al. (2000) found that fertilizer N leaching loss (3.4%) in the wheat season was double that found in the rice season (1.8%) during R–W rotations. This is mainly due to greater soil nitrate N in the wheat season under aerobic condition. In contrast, ammonium N is the major mineral N in the soil cultivated with flooded rice because the anaerobic condition inhibits the nitrification process in the soil.

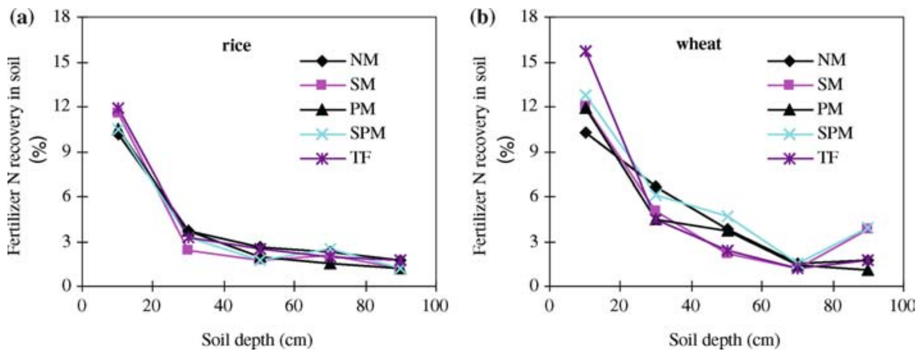

Figure 1. Fertilizer N recoveries in 0–100 cm soil profile after harvest of rice (a) and wheat (b) as affected by non-flooded mulching cultivation. Significant differences of fertilizer N recovery are found between TF and NM in 0–20 cm soil layer and between SM or SPM and the other three treatments in 80–100 cm soil layer in the wheat season.

Table 5. Apparent N balance in rice–wheat rotations as affected by non-flooded mulching cultivation.

Treatment	N rate (kg N ha^{-1})	Initial N_{min} (kg N ha^{-1})	N from rain and straw (kg N ha^{-1})	N removal (kg N ha^{-1})		Residual N_{min} (kg N ha^{-1})	Apparent N loss (kg N ha^{-1})
				Crop	Weed		
Rice season							
TF	150	117	13	153	< 1	76 a	51 a
PM	150	117	13	179	2	72 a	27 ab
SPM	150	117	39	182	2	71 a	51 a
SM	150	117	39	161	17	79 a	49 a
NM	150	117	13	153	46	86 a	−5 b
Wheat season							
TF	120	76	12	129	3	47 ab	29 a
PM	120	72	12	99	5	75 a	29 a
SPM	120	71	12	114	6	31 b	52 a
SM	120	79	12	119	8	49 ab	35 a
NM	120	86	12	103	9	70 a	36 a
Rice–wheat rotation							
TF	270	117	25	282	3	47 ab	80 ab
PM	270	117	25	278	7	75 a	52 bc
SPM	270	117	51	296	8	31 b	103 a
SM	270	117	51	280	25	49 ab	84 ab
NM	270	117	25	256	55	70 a	31 c

Values without the same letters in a column of each crop were significantly different.

Apparent N balance and N use efficiency in R–W rotations

Apparent N balances in rice, wheat and the whole rotation systems that accounted for all N inputs and outputs measured in this study were calculated (Table 5). In the rice season, considerable N (130–156 kg ha^{-1}) from initial mineral N (N_{min}, sum of ammonium N and nitrate N), rainfall, and wheat straw in addition to fertilizer addition were found in all treatments. Total N inputs were 280–306 kg ha^{-1} while total N removal by rice (grain + straw) and weeds was only 153–199 kg ha^{-1}. As a consequence, N surplus (residual N_{min} plus apparent N loss) were relatively high (81–127 kg ha^{-1}) after harvest of rice regardless of TF or NFMC. Apparent N loss was greater in TF, SPM and SM than in PM and NM, which was mainly due to the lower N removal (TF) and/or higher N input (SPM, SM) in the former treatments.

In the wheat season, total N inputs from fertilizer, soil N_{min} and rainfall dropped to 203–218 kg ha^{-1} in TF and NFMC. At the same time,

Table 6. Water-saving percentage and water use efficiency (WUE) in R–W rotation as affected by non-flooded mulching cultivation (26 May, 2001 to 15 May, 2002).

Treatment	TF	PM	SPM	SM	NM
Rice season					
Rainfall (mm)	742	742	742	742	742
Irrigation (mm)	945	90	90	90	90
Sum (mm)	1687	832	832	832	832
Water saving (%)	–	50.7	50.7	50.7	50.7
WUE(g grain kg^{-1} water)	0.43 b	0.87 a	0.87 a	0.82 a	0.78 a
Wheat season					
Rainfall (mm)	211	211	211	211	211
Irrigation (mm)	0	0	0	0	0
Sum (mm)	211	211	211	211	211
Water saving (%)	–	0	0	0	0
WUE(g grain kg^{-1} water)	2.73 a	2.32 a	2.47 a	2.51 a	2.19 a
Rice–wheat rotation					
Rainfall (mm)	953	953	953	953	953
Irrigation (mm)	945	90	90	90	90
Sum (mm)	1898	1043	1043	1043	1043
Water saving (%)	–	45.0	45.0	45.0	45.0
WUE (g grain kg^{-1} water)	0.68 b	1.16 a	1.19 a	1.16 a	1.06 a

Values without the same letters in a line of each crop were significantly different.

N removal by wheat and weeds was also lower in the wheat season than in the rice season. Residual N_{min} ranged from 31 to 75 kg ha^{-1} and showed a distinct variation among all treatments after harvest of wheat. TF, SM and SPM led to greater N uptake by crop and weed but caused smaller residual soil N_{min} in the wheat season in comparison to NM and PM. Therefore, apparent N loss (29–52 kg ha^{-1}) did not show significant difference between TF and NFMC treatments in the wheat season.

In the whole system, total N inputs were 412–438 kg ha^{-1} but the removal by crops and weeds was only 285–311 kg ha^{-1} . Thereby large N surpluses occurred after one rice–wheat rotation cycle. The apparent N losses were comparable in TF, SM and SPM (80–103 kg N ha^{-1}) but were higher than those in NM and PM (31–52 kg N ha^{-1}). This can be mainly explained by the greater residual N_{min} in NM and PM treatments (Table 5).

In addition, N use efficiency (NUE) in the study (data not shown) was also evaluated according to the method proposed by Moll et al. (1982). The NUE (Gw/Ns) was not significantly affected by NFMC compared with TF in the rice season while significantly lower NUE was observed only in NM in the wheat season. This phenomenon can be mainly explained by different crop responses under NFMC to the two NUE components – N uptake efficiency (Nt/Ns) and N utilization efficiency (Gw/Nt). In the rice season, NFMC especially PM and SPM led to relatively higher uptake efficiency but lower utilization efficiency compared with TF. In the wheat season, the situation was reversed with the exception of NM. Therefore, the NUE in PM, SPM and SM was similar to that in TF in both rice season and wheat season.

Water-saving advantage and water use efficiency

Plastic film and straw mulching cultivation could save irrigation water by reducing water consumption during land preparation and during the rice growing season. In the rice season, the total water consumption (832 mm) in NFMC was much lower than that in TF (1687 mm, Table 6). This resulted in a water saving percentage of up to 51% compared with the TF treatment. Water use efficiency (WUE) was increased by 81–102% for NFMC treatments with no (PM and SPM) or small (SM and NM) yield loss as mentioned before. Water consumption was the same (211 mm) for TF and NFMC treatments in the wheat season due to no irrigation input, but the average WUE was 2.3 times higher than that in the rice season (Table 6). In the whole R–W rotation, SPM, SM and PM showed significant water-saving advantage and significantly higher WUE compared with TF (Table 6). These results support the hypothesis that suitable mulching methods can greatly increase water saving potential and water use efficiency in rice.

Discussion

The results given here demonstrated that NFMC can maintain similar productivity as traditional flooded cultivation with much less irrigation water. This finding is strongly supported by other studies done in the same region (Liu et al. 2003; Fan et al. 2005) and other regions of China (Liang et al. 1999; Shi et al. 2001; Fan et al. 2002). On the other hand, non-flooded NM cultivation led to a decline in crop productivity in the rice–wheat system. Compared with TF, the vigorous growth and N accumulation of weeds in NM, particularly during the rice season, were presumably the major reason of less rice grain yield. But the yield loss of rice (10%) due to weeds in NM in the present study was much less than the results from Johnsona et al. (2004), who reported 47–49% yield loss of rice when weeds were not controlled. Similarly, SM also led to the problem of weeds in the rice season and slightly decreased rice yield as well. However, the weed growth and its N uptake could be significantly reduced to that found in PM and TF in the rice season if both wheat straw and plastic film (SPM) were used. Grain yield and N uptake by rice were improved by SPM, suggesting that the yield loss by weed growth and nitrogen competition can be avoided through double mulching of straw and plastic film. In a previous study, Liu et al. (2003) observed the negative effect of lower soil temperature by straw mulching on rice yield and nutrient uptake. In the present study, we also found that soil temperature in SPM was similar to PM but higher than in SM (data not shown). Therefore, it seems that both soil temperature and weed competition play major roles in rice yield and nitrogen utilization in the SM treatment.

From the present study, the fertilizer N recoveries in grain and straw were less than 20–25% in all TF and NFCM treatments both in rice and wheat seasons, and/or the whole R–W systems. Compared with TF, NFMC increased fertilizer N recovery by 3.1–6.6% in the rice season but decreased fertilizer N recovery by 2.4–5.8% in the wheat season. Thus fertilizer N recovery (18–20%) did not show any difference among TF and NFMC treatments in the whole R–W rotation. Such low fertilizer N recovery is thought partly to be caused by the basal N application, which probably led to large fertilizer N loss as NH_3 volatilization, denitrification and/or nitrate leaching (Buresh and De Datta 1990; Liu et al. 2002). Phongpan and Mosier (2003) also found that large N loss (47–54% of applied N) occurred in a rice–soil system and the combined use of organic residues with urea did not improve N use efficiency, reduce N losses nor produce higher yields compared to urea alone. However, we could not judge which pathway is the main one for N loss. From the distribution of fertilizer N recovery in the 0–100 cm soil profile (Figure 1), we found that the amount of fertilizer N remaining in the soil was small (less than 25%) and that 55–60% of this fertilizer N was concentrated on 0–20 cm layer. This suggests that N leaching loss is probably small, particularly in rice season and gaseous N loss is likely the main pathway for fertilizer N loss. In the North China Plain, Cai et al. (2002) showed that NH_3 volatilization is an important pathway for N loss from N fertilizer applied to rice (30–39%) but less so for wheat (1–20%). Their results reflected the situation of traditional lowland rice and wheat. We suspect that nitrification–denitrification and plant NH_3 volatilization are extremely important in NFMC because soil NH_3 volatilization is likely inhibited by plastic or straw mulching. In addition, N leaching loss probably occurred for SM and SPM in the wheat season according to fertilizer N accumulation in 80–100 cm layer. Wheat straw could provide soluble C for microorganisms during straw degradation. Therefore, N immobilization may have occurred in the rice season and N mobilization (including nitrification) followed during the wheat season in SM and SPM treatments, causing the leaching of nitrate N in the soil. Zhu et al. (2000) and Shi (2003) also found that N leaching mainly occurred in the wheat season in a traditional rice–wheat rotation. Further studies on N transformation in soil and major pathway for N loss are needed to better evaluate the sustainability and environmental risks of NFMC in R–W rotations (Yadav et al. 2000; Liu et al. 2003).

Another reason for the lower fertilizer N recovery in this study was due to the large N inputs (soil mineral N, rainfall and/or straw) in addition to fertilizer N. We found that N inputs from soil and environment contributed 46–51% and 41–45% of total N inputs across various treatments in rice and wheat seasons, respectively. If we consider the contribution of soil organic N mineralization and biological N fixation (e.g. in rice season) to N inputs, we believe that ratio of fertilizer N to total N input would be much lower than 50%. In short, there is great potential to improve the fertilizer N recovery in both TF and NFMC practices in the R–W rotations. For example, we can split fertilizer N for several times as smaller doses to each crop for matching N needs during rice or wheat growing season. In addition, the application of controlled-release N fertilizer, urease or nitrification inhibitor and deep placement of N fertilizer (Zhu and Chen 2002) are also potential ways to improve fertilizer N recovery or NUE in R–W rotations under NFMC.

In contrast to fertilizer N recovery and NUE, PM, SM and SPM showed great advantage in conserving irrigation water and in improving WUE in R–W rotations, which confirms other studies in China (Liang et al. 1999; Liu et al. 2003). The main objective of NFMC in rice production is to save irrigation water without decreasing grain yield compared with traditional flooded cultivation. From this viewpoint, PM and SM cultivation achieved this goal because these treatments produced similar grain yields compared to TF with much less water consumption (Tables 2 and 6). Furthermore, rice yield can be further improved by double mulching of straw and plastic film (SPM) due to higher soil temperature and less weed biomass (Table 3). As a result, we believe that PM and SM cultivation will become the practice of choice in R–W rotations with the increasing water shortage worldwide.

Conclusions

From this study, we conclude that NFMC has the potential to produce grain yields that are comparable to TF cultivation while consuming only 55% as much water supply in R–W rotations. Attaining these yields is predicated upon controlling weeds.

Fertilizer N recoveries in grain and straw were greater in NFMC treatments in the rice season but were lower in those treatments in the wheat season than those in TF. From the whole rotation systems, fertilizer N recoveries were not affected by NFMC treatments. Total fertilizer N recovery in crop, weed and soil only accounted for 39–44% in the whole R–W rotations, suggesting that a large amount of fertilizer N loss occurred during both rice and wheat growth seasons. Further analysis on apparent N loss or NUE in the two crop seasons supported the results of ^{15}N balance data.

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