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Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice–wheat cropping systems

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Abstract

A field experiment on a sandy loam was conducted to evaluate the effects of non-flooded mulching cultivation on the productivity, nutrient uptake and nutrient balance in rice–wheat (R–W) cropping systems in Chengdu flood plain, southwest China over a 3-year period. Plastic film mulching (PM) resulted in 12% higher average yield of rice while wheat straw mulching (SM) led to 14% lower average yield of rice compared with lowland rice under traditional flooding (TF). Biomass accumulation and nutrient uptake followed similar trends to grain yield. Changes in soil temperature in relation to root growth and nutrient uptake were likely to be the major factor responsible for the changes in rice yields under non-flooded mulching cultivation. Compared with TF, PM of preceding rice did not affect the grain yield of wheat, whereas SM of preceding rice resulted in comparable grain yields of wheat at a lower N rate (60 kg N ha^{-1}) in the wheat season. The system productivity (total yield of rice + wheat) in PM was similar to that of TF and higher than that of SM. The yield decline in rice, however, could be partly compensated by the yield increase in wheat following rice, particularly at lower N rates. Apparent nutrient budgets showed positive nitrogen (N) and phosphorus (P) balances but negative potassium (K) balance in the TF and non-flooded mulching R–W systems. Compared with TF, PM led to lower NPK balance due to more nutrient removal by crops while SM led to greater NPK balance due to more nutrient inputs from straw but less nutrient removal by crops. After 3 years soil organic carbon (OC) and total nitrogen (TN) were not significantly altered by PM and SM but soil Olsen-P (AP) and exchangeable K (EK) were significantly increased by SM compared with TF. The changes in soil properties under non-flooded mulching cultivation initially reflected the nutrient balances in R–W systems. In conclusion, non-flooded mulching cultivation as PM and SM could be applied to R–W systems in southwest China but nutrient (especially N) management should be optimized in the two systems.

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Keywords: Rice–wheat cropping system; Non-flooded mulching cultivation; System productivity; Nutrient uptake and balance

Abbreviations: TF, traditional flooding; PM, plastic film mulching; SM, wheat straw mulching; R–W, rice–wheat; N, nitrogen; P, phosphorus; K, potassium; M, mulching; DAT, days after transplanting; DAS, days after sowing; OC, organic carbon; TN, total nitrogen; AP, available (Olsen-) phosphorus; EK, exchangeable potassium

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1. Introduction

Rice–wheat (R–W) cropping systems are practised in south and east Asia within sub-tropical to warm-temperate climatic zones (Timsina and Connor, 2001). In China, these systems are used mainly in an area of 13 million ha in the Yangtze River Basin (Zheng, 2000), where seasonal shortage of freshwater often limits the production of the systems. Among all crops, rice consumed about 90% of total irrigation water (Bhuiyan, 1992). On the other hand, lowland rice is one crop that offers great potential to save irrigation water because its physiological water requirement ($4500 \text{ m}^3 \text{ water ha}^{-1}$) is much less than its actual water consumption and is equivalent to that of some upland crops (Wu and Xie, 1985; Guerra et al., 1998; Si, 2000). Numerous water efficient irrigation regimes for rice have therefore been tested (Mao, 2001) but they are difficult to apply and require large amounts of irrigation water during the rice growing season. Thus, plastic film mulching (PM) has been adopted and developed as a new rice cultivation technique in many regions of China since the 1980s (Zhao and Xiao, 1982; Peng et al., 1999) with the total planting area reaching 100,000 ha (Liang et al., 2000). This system is employed under non-flooded conditions with limited irrigation and is substantially different from both traditional flooded rice cultivation and rain-fed rice cultivation. This new cultivation technique has led to improved water use efficiency, increased soil temperature, inhibition of weed growth and increased yields (Liang et al., 2000). Other mulching materials such as wheat or rice straw and even paper have subsequently been developed in rice production (Ueno and Yamamura, 1997; Wang, 2001; Fan et al., 2002).

The management of straw is another issue that is critical to sustainable agriculture in China. The burning of wheat straw is common because of the short period from wheat harvest to rice transplanting in Chinese R–W systems, particularly in the Chengdu Plain of southwest China. This leads to loss of most organic C and large losses (up to 80%) of N (Raison, 1979), 25% of P and 21% of K (Ponnamperuma, 1984) as well as significant air pollution and the death of beneficial soil fauna and micro-organisms. Utilization of wheat straw is therefore an important environmental issue in southwest China. A similar situation is found in some parts of India where the time interval

between rice harvesting and wheat sowing is very short (Prasad et al., 1999). One possible solution would be to use wheat straw as a soil mulch material in non-flooded rice cultivation in the R–W rotation. Surface retention of some or all of the straw may often be the best option. Rasmussen and Collins (1991) reported that slowly decomposing crop residues on the soil surface increased organic C and total N in the top 5–15 cm of the soil while protecting the surface soil from erosion. Retention of straw on the surface increased soil nitrate concentrations by 46%, N uptake by 29%, and yield by 37% compared to burning (Bacon, 1987; Bacon and Cooper, 1985a,b). A preliminary study by our group in 1998 also indicated a yield advantage of straw mulching in the Chengdu Plain (S.H. Lu, pers. comm.).

The evaluation of non-flooded mulching cultivation systems on growth and nutrient uptake of both rice and wheat crops is critical to the productivity and sustainability of the whole R–W systems. Our hypothesis was that both PM and wheat straw mulching (SM) cultivations alter the crop growth environment, especially root biological activity and/or nutrient availability in the rhizosphere, and then enhance or inhibit the growth and nutrient uptake of rice and ensuing wheat. The objective of the present study was to determine the effects of non-flooded mulching cultivation on grain yield, nutrient acquisition and nutrient balance in Chinese R–W systems.

2. Materials and methods

2.1. Site description

A field experiment was conducted on a Fluvaquent, calcareous grey floodplain soil at Tianhu village, Wenjiang county, Sichuan province ($30^{\circ}42'N$, $103^{\circ}50'E$ and 539 m elevation) from 1999 to 2002. Annual mean temperature is $16.2^{\circ}C$ and cumulative temperatures above 0 and $10^{\circ}C$ are 5937 and 5107 $^{\circ}C$, respectively. The frost-free period is 293 days and total solar radiation is 3834 MJ m^{-2} per year. The region is classified as humid sub-tropical with monsoon climate. Annual precipitation is 947 mm and potential evaporation (1074 mm) is similar to precipitation. The experimental site was located at the centre of Chengdu flood plain. The soil is a sandy loam with a bulk density of

1.12 g cm⁻³ in the top 20 cm and 1.45 g cm⁻³ at the other two depths examined (20–40 and 40–60 cm). Chemical properties in the top 20 cm prior to the experiment gave relatively low values (TN, 1.70 g kg⁻¹; AP, 5.2 mg kg⁻¹; EK, 37.9 mg kg⁻¹; OC, 12.3 g kg⁻¹; and pH 7.8) compared with most soils of this region.

2.2. Field experiment

The field experiment comprised three treatments (two water regimes) during the rice growing season: traditional flooding (TF) as the control, and PM and SM as the two non-flooded mulching cultivation treatments. In the TF treatment, plots were irrigated every 3–5 days to maintain a 3 cm water level until 2 weeks before the rice harvest in line with traditional farming practice. No permanent water layer was maintained on the soil surface during the rice growing season in the PM and SM treatments. Limited irrigation (30–50 mm each time) was provided only from transplanting (late May) to flowering stage (early August) in all non-flooded mulching plots when soil moisture content was lower than 80% of field capacity, depending on the weather conditions. The amounts of rainfall and irrigation water in all treatments during three rice seasons (1999–2001) are listed in Table 1. All the N, P and K fertilizers (150 kg N ha⁻¹ as urea, 90 kg P₂O₅ ha⁻¹ as calcium superphosphate and 90 kg K₂O ha⁻¹ as potassium sulphate) were broadcast and incorporated into the top 15 cm of the soil in all treatments by ploughing prior to

transplanting of rice. Traditional flooded and non-flooded plots were separated by a 2 m wide alley with plastic film inserted into the soil to 60 cm depth, and other plots were separated by a 0.5 m wide irrigation furrow and two 0.3 m levees. All plots were 3 m × 8 m and there were three replicates of each treatment in a fully randomized design, giving a total of nine plots. The rice (*Oryza sativa* L.) variety used was the hybrid ‘Gangyou 527’, supplied by the Institute of Crop Science, Sichuan Academy of Agricultural Sciences (SAAS). The rice seedlings were transplanted at a spacing of 20 cm × 28 cm with two seedlings per hill. Plastic film, 0.005 mm thick and 1.7 m wide, was used to cover the soil in the PM treatment. Wheat straw, harvested from the same field (5250 kg DM ha⁻¹), was used to cover the soil uniformly (equal to about 2 cm height) in the SM treatment to prevent evaporation of soil water in a similar fashion to the plastic film. The average NPK concentrations were 0.48, 0.094 and 1.10%, respectively. The dates of rice transplanting and harvesting were late May (24–26) and mid-September (15–18) during the 3 years from 1999 to 2001.

After the rice harvest each year, wheat (*Triticum aestivum* L.) was planted on the same plots with zero tillage and the removal of rice straw. Each plot was split into two equal sub-plots (3 m × 4 m each) to allow two N application rates (60 and 120 kg N ha⁻¹ as urea) to the wheat, representing reduced (basal application once) and normal (50% basal application + 50% topdressing) N rates, respectively. The same amounts of P and K fertilizers (60 kg P₂O₅ ha⁻¹ as calcium superphosphate and 60 kg K₂O ha⁻¹ as potassium sulphate) with 60 kg N ha⁻¹ of fertilizer N were uniformly applied to the given hills of all plots where wheat seeds were ready to be planted prior to sowing of wheat. The subsequent topdressing of fertilizer N in the corresponding sub-plots receiving 120 kg N ha⁻¹ was uniformly broadcast at the booting stage of wheat (at the end of February). In early November (2–5), the wheat variety ‘SW3243’, supplied by the Institute of Crop Science, SAAS, was sown directly into the soil at two spacings of 10 cm × 15 cm and 10 cm × 25 cm as bunch planting. Most residual plastic film was removed from the field before sowing of wheat in the PM treatment to avoid any negative effects on soil properties. However, the wheat straw left over from the mulching of the rice crop still remained in the field in the SM treatment. The wheat was harvested in mid-May (14–16) each year. No

Table 1
Amounts of irrigation and precipitation in three water regimes: TF, non-flooded PM and SM in three rice seasons from 1999 to 2001

Year	Water input (mm)	TF	PM	SM
1999	Precipitation	787	787	787
	Irrigation	890	50	50
	Total	1677	837	837
2000	Precipitation	457	457	457
	Irrigation	922	134	134
	Total	1379	591	591
2001	Precipitation	638	638	638
	Irrigation	910	84	84
	Total	1548	722	722

irrigation was provided during the three wheat seasons (from 1999–2000 to 2001–2002).

2.3. Crop measurements and plant nutrient analysis

During the first year of the experiment (1999–2000), detailed measurements were made of crop growth and dry matter partitioning, and plant NPK concentrations. During the second year (2000–2001), similar detailed measurements were carried out on rice only. During the second and third years (2000–2001 and 2001–2002), with the exception of the second rice crop, data collection was limited to final straw and grain yields and plant NPK concentrations. Shoot dry matter was determined on samples from areas of $0.3 \text{ m} \times 0.6 \text{ m}$ at early tillering (18–24 DAT), late tillering (40–50 DAT), booting (50–70 DAT), and physiological maturity (104–112 DAT) of rice, and at tillering (47 DAT), booting (83 DAT) and physiological maturity of wheat (196 DAT). Grain and straw yields were determined by harvesting 8 m^2 (rice) or 6 m^2 (wheat) of each plot or sub-plot at maturity. Rice grain yields were adjusted to 140 g kg^{-1} moisture content while wheat grain yields were recorded on a dry matter basis. The sample plants were oven-dried for dry matter content at 60°C for 48 h and were ground and analysed for total nutrient concentrations. Nitrogen, P, and K concentrations in the plant dry matter were determined after wet digestion with H_2SO_4 and H_2O_2 , and N measured by the micro-Kjeldahl procedure, P by the vanadomolybdate method and K by flame photometry. Nutrient uptake was calculated as the product of nutrient concentration and yield of aboveground parts of the crop on a dry matter basis.

Sap nitrate concentration at the base of the wheat stems was measured using a reflectometer at the booting stage (83–90 DAS) during all three wheat growth seasons (from 1999–2000 to 2001–2002). This rapid nitrate test was described by [Jemison and Fox \(1988\)](#) and has been regarded as a useful tool for crop N nutritional diagnosis and N recommendations as discussed by [Liu et al. \(in press\)](#) and [Schenk \(1998\)](#).

2.4. Soil measurement and nutrient analysis

During the 1999 rice season, surface and subsurface (10 cm depth) soil temperatures were measured by

thermometer during the main growth stages of rice (15–92 DAT). Four to seven measurements from the morning to the afternoon were taken on each day of measurement. Soil moisture content at surface depths (0–20 cm) was determined at weekly intervals by oven drying while soil moisture content at all depths (0–20, 20–40, and 40–60 cm) was determined at the major growth stages in line with the plant sampling using the same method.

After three cycles of R–W rotation, soil pH, organic C (OC), total N (TN), Olsen-P (AP) and exchangeable K (EK) were determined for 0–10 and 10–20 cm depths using standard methods as described by [Sparks et al. \(1996\)](#).

2.5. Nutrient balance

Nutrient balances of N, P and K were estimated after three cycles of R–W rotation under TF and non-flooded mulching cultivations. The nutrient balances were calculated by differences between the inputs (from fertilizer and crop straw) and outputs (from uptake by crops). The calculations were made as follows:

Apparent nutrient balance

$$= (\text{nutrient uptake by crops}) \\ - (\text{nutrient additions from fertilizer and crop straw})$$

Other major pathways of NPK inputs or outputs not measured include N inputs from biological N fixation (BNF), rainfall and irrigation, gaseous N losses from ammonia volatilization and denitrification, leaching losses, and P and K losses from runoff and leaching. The apparent nutrient balances therefore estimate only net gains or losses of NPK.

2.6. Statistical analysis

Statistical analysis using SAS software ([SAS Institute, 1996](#)) on grain and straw yields, and nutrient concentration and uptake as well as soil temperature were performed by standard procedures on a randomized plot design for rice and split-plot design for wheat. 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.

Table 2

Effects of non-flooded mulching cultivation on rice grain yields at a rate of 150 kg N ha⁻¹ during the period 1999–2001^a

Mulching ^b	Nitrogen (kg N ha ⁻¹)	1999	2000	2001	Mean
TF	150	5609 b	6760 b	6381 ab	6250
PM	150	6512 a	7779 a	6696 a	6996
SM	150	4799 c	5719 c	5608 b	5375

^a Values with same letters within the same year are not significantly different.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

3. Results

3.1. Rice

3.1.1. Grain yields

Grain yields of rice as affected by non-flooded mulching cultivation are shown in Table 2. ANOVA on grain yield revealed that during the first and second years, the main effects of non-flooded mulching were significant at the 1% level, while during the third year the treatment effects were significant only at the 5% level (data not shown). Yields of TF and non-flooded mulching treatments ranged widely (from 4.8 to 7.8 t ha⁻¹) over the 3-year period during which mean yield rose from 5.6 to 6.8 t ha⁻¹ and then dropped to 6.2 t ha⁻¹. Compared with the TF treatment, rice grain yields were significantly improved by the PM treatment but decreased by the SM treatment during the three rice growth seasons from 1999 to 2001 (Table 2). The average yield increase was 12% for the PM treatment while the average yield decline was 14% for the SM treatment compared with the TF treatment.

3.1.2. Soil temperature

The dynamics of surface and subsurface (10 cm depth) soil temperatures as affected by non-flooded mulching cultivation systems during the 1999 rice growth period are given in Table 3. At early tillering (15–24 DAT), daily mean surface and subsurface soil temperatures were significantly higher in plots with PM but significantly lower in plots with SM than those in plots with TF, respectively. The greatest difference in soil temperature appeared during the period from 14:00 to 16:00 h for both soil depths (data not shown). The increase or decrease in soil temperature caused by

film or straw mulching was maintained until late tillering, although the effects of mulching gradually declined with time (Table 3). Similar observations were made in the other two years (data not shown).

3.1.3. Biomass accumulation

Total biomass accumulation during the growth cycle varied widely between the first 2 years and was strongly influenced by non-flooded mulching cultivation (Fig. 1). In 1999, biomass accumulation (Fig. 1A) showed significant differences among TF, PM and SM treatments after tillering (up to 33 DAT). Total biomass accumulation was greater in the PM treatment but lower in the SM treatment than in the TF treatment. After booting (47 DAT), biomass accumulation in TF and PM treatments was maintained at similar rates and the differences between the two treatments became smaller. In contrast, biomass accumulation in SM treatment was consistently low compared with that in TF and PM treatments (Fig. 1A). In 2000, total biomass accumulation (Fig. 1B) was greater than in 1999 across all treatments, likely due to higher solar radiation and temperatures (data not shown). The ranking of biomass accumulation in 2000 followed the same trend as in 1999 (PM > TF > SM). The increment of biomass accumulation in TF and PM treatments was not obvious after the filling stage (81 DAT) while distinct increase in biomass accumulation was observed in SM treatment

Table 3

Dynamics of daily mean temperature (°C) at soil surface and subsurface (10 cm depth) as affected by non-flooded mulching cultivation systems (1999)^a

Mulching ^b	Early tillering (15–24 DAT ^c)	Mid-tillering (27–36 DAT)	Late tillering (39–50 DAT)	Mean
Soil surface				
TF	31.3 b	30.8 a	28.7 a	30.2
PM	37.5 a	32.6 a	30.5 a	33.5
SM	27.3 c	27.4 b	28.4 a	27.7
Soil subsurface				
TF	27.1 b	24.9 ab	26.2 a	26.0
PM	29.0 a	25.7 a	26.4 a	27.1
SM	24.6 c	23.9 b	25.2 a	24.6

^a Values with same letters within the same column are not significantly different.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

^c Days after transplanting.

Fig. 1. Dynamics of rice shoot biomass as affected by three water regimes of TF (◆), PM (■) and SM (▲) in 1999 (A) and 2000 (B). Bars represent $\pm$ S.E.M.

from filling to maturity stage, indicating a compensatory growth effect in the latter treatment. The 2-year results indicate that SM may inhibit the growth of rice while PM can improve the growth of rice, and this is consistent with the changes in soil temperature as affected by non-flooded mulching cultivation.

3.1.4. Nutrient concentration and uptake

Nutrient concentrations in grain and straw of rice as affected by non-flooded mulching are presented in Table 4. Nitrogen concentrations in grain and straw were not significantly influenced by non-flooded

mulching with the exceptions of 1999 rice straw and 2000 rice grain. The mean N concentrations in grain (1.13–1.26%) and straw (0.65–0.71%) followed the same trend of PM and SM > TF (Table 4). The prolonged growth period in SM and PM treatments could partly explain the relatively high N concentration in grain or straw compared with the TF treatment. However, N concentrations were significantly lower in SM than in TF and PM only at tillering in the first and second years (data not shown), suggesting that the effect of SM on shoot N nutrition occurred mainly during the early growth of rice. Phosphorus

Table 4

Nutrient concentration (%) in rice grain and straw as affected by three water regimes of TF, PM and SM during 3 years^a

Mulching ^b	Nitrogen (kg N ha ⁻¹)	1999		2000		2001		Mean	
		Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Nitrogen									
TF	150	1.24 a	0.61 b	0.98 b	0.59 a	1.17 a	0.75 a	1.13	0.65
PM	150	1.35 a	0.65 ab	1.15 a	0.65 a	1.28 a	0.79 a	1.26	0.70
SM	150	1.19 a	0.77 a	1.07 ab	0.59 a	1.27 a	0.76 a	1.18	0.71
Phosphorus									
TF	150	0.30 a	0.05 a	0.24 a	0.06 a	0.32 a	0.10 a	0.29	0.07
PM	150	0.31 a	0.09 a	0.26 a	0.07 a	0.32 a	0.10 a	0.30	0.09
SM	150	0.30 a	0.08 a	0.24 a	0.07 a	0.34 a	0.09 a	0.29	0.08
Potassium									
TF	150	0.21 a	2.26 b	0.25 a	2.43 b	0.18 b	2.17 a	0.21	2.28
PM	150	0.26 a	2.62 ab	0.27 a	2.51 ab	0.21 b	2.05 a	0.25	2.37
SM	150	0.27 a	2.75 a	0.26 a	2.54 a	0.29 a	2.34 a	0.27	2.53

^a Values with same letters within the same column are not significantly different.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

Table 5
Nutrient uptake (kg ha^{-1}) by rice as affected by non-flooded mulching cultivation from 1999 to 2001^a

Mulching ^b	Nitrogen (kg N ha^{-1})	1999	2000	2001	Mean
Nitrogen					
TF	150	89 ab	98 b	109 a	99
PM	150	105 a	122 a	124 a	117
SM	150	76 b	81 c	102 a	86
Phosphorus					
TF	150	19 ab	22 a	24 a	22
PM	150	22 a	24 a	25 a	24
SM	150	16 b	18 b	21 a	18
Potassium					
TF	150	121 ab	133 b	138 a	131
PM	150	133 a	198 a	139 a	156
SM	150	108 b	127 b	135 a	123

^a Values with same letters within the same column are not significantly different.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

concentrations in grain and straw were not significantly influenced by non-flooded mulching across years (Table 4). The mean P concentrations in grain and straw were 0.29–0.30 and 0.07–0.09%, respectively. Potassium concentrations in grain and straw, however, were significantly influenced by non-flooded mulching only in the third year (grain) and the first and second years (straw). Mean K concentrations were 0.21–0.27% for grain and 2.28–2.53% for straw and followed the sequence SM > PM > TF (Table 4). The distribution of nutrient concentrations in grain and straw showed the integrated effects of non-flooded mulching cultivation on rice growth and NPK availability in soils.

As with grain yield, nutrient uptake by rice was promoted by PM treatment but limited by the SM treatment compared with TF across years (Table 5). Nitrogen uptake by rice showed a continuous increase from 1999 to 2001 for all treatments, which was consistent with the N concentrations in grain and straw (Table 4). Mean N uptake was 99, 117 and 86 kg N ha^{-1} for TF, PM and SM, respectively. Phosphorus and potassium uptake as affected by non-flooded mulching cultivation followed a trend similar to that of N (Table 5). Mean P uptake by rice ranged from 18 to 24 kg P ha^{-1} while mean K uptake was

123–156 kg K ha^{-1} for three treatments. In contrast to the first and second years, no significant effects of non-flooded mulching were found on N, P or K uptake in the third year (Table 5).

3.2. Wheat

3.2.1. Grain yields

Grain yields of wheat as affected by non-flooded mulching to preceding rice and split N rate are presented in Table 6. Compared with rice, individual treatments resulted in a less range of wheat yields from 4.3 to 6.2 t ha^{-1} over 3 years (Table 6). The mean yield of wheat was highest in the first year (5.5 t ha^{-1}), then fell progressively to 5.2 and 4.7 t ha^{-1} in the second and third years, respectively. In contrast to rice, SM treatment led to significantly higher grain yields of wheat at reduced N rate (60 kg N ha^{-1}) during the 3 years compared with TF and PM treatments. There were no significant differences between wheat yields in PM and TF treatments in spite of N rates used. A reduction in fertilizer rate from 120 to 60 kg N ha^{-1} caused a significant yield decline in PM and TF treatments during the first and second years (Table 6). In contrast, in the SM treatment, a higher yield was observed in sub-plots receiving 60 kg N ha^{-1} than in those receiving 120 kg N ha^{-1} (Table 6). These results suggest that soil N supply in the wheat season is increased by SM treatment to preceding rice.

Table 6
Residual effects of non-flooded mulching cultivation to preceding rice on wheat grain yield (kg ha^{-1}) at two N rates

Mulching ^a	Nitrogen (kg N ha^{-1})	1999	2000	2001	Mean
TF	60	4545	4838	4506	4630
	120	5610	5263	4509	5127
PM	60	4710	4310	4387	4469
	120	5888	5433	4769	5363
SM	60	6240	5906	5064	5737
	120	6038	5473	4918	5476
LSD _{0.05} (M)		591	187	n.s. ^b	
LSD _{0.05} (N)		482	153	n.s.	

^a TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

^b Not significant.

Fig. 2. Dynamics of shoot biomass of wheat (1999–2000) as affected by three water regimes of TF (◆), PM (■) and SM (▲) in rice and two N rates (60 and 120 kg N ha⁻¹) in wheat. Bars represent $\pm$ S.E.M.

3.2.2. Biomass accumulation

Total biomass accumulation of wheat (1999–2000) as influenced by non-flooded mulching to previous rice and N rate is presented in Fig. 2. At tillering (47 DAS), biomass accumulation was relatively small (0.3–0.5 t ha⁻¹) and no significant differences were observed among all treatments across two N rates. At booting (83 DAS), biomass accumulation in SM treatment (1.3 t ha⁻¹) was significantly greater than that in TF and PM treatments (0.7–0.9 t ha⁻¹). Total biomass accumulation at maturity in the SM treatment reached 12.0 t ha⁻¹ while the corresponding biomass accumulations were only 10.0–10.3 t ha⁻¹ in other two treatments at a rate of 60 kg N ha⁻¹ (Fig. 2A). In contrast, the differences in biomass accumulation among SM, TF, and PM treatments were much smaller at a rate of 120 kg N ha⁻¹ (Fig. 2B), indicating that the growth promoting effects on wheat biomass accumulation by SM to preceding rice was significant only at lower N input levels.

3.2.3. Nutrient concentration and uptake

Nutrient concentrations in grain and straw of wheat as affected by non-flooded mulching to preceding rice and N rate are presented in Table 7. At reduced N rate (60 kg N ha⁻¹), N concentrations in straw were significantly different among TF, PM and SM treatments while no significant differences in grain N were observed among those treatments. Nitrogen concentrations in both grain and straw were increased by

120 kg N ha⁻¹ compared with 60 kg N ha⁻¹ across non-flooded mulching treatments and over years. However, the mean increment of N concentration at normal N rate (120 kg N ha⁻¹) was greater in grain for TF and PM treatments but greater in straw for SM treatment than at the reduced N rate, indicating the over-fertilization to wheat at an N rate of 120 kg N ha⁻¹ for SM treatment. P concentrations in grain and straw were not significantly affected by non-flooded mulching treatment and N rate over years (Table 7). The mean P concentrations showed narrow variations in grain (0.37–0.42%) and in straw (0.06–0.08%). K concentrations in straw were only significantly affected by non-flooded mulching to preceding rice in the first year and by the N rate in the third year while K concentrations in grain were not during 3 years (Table 7). SM to preceding rice led to the highest mean K concentrations (1.18–1.30%) in straw, followed by PM (1.10–1.13%) and then TF (0.99–1.05%).

Nutrient uptake by wheat as affected by non-flooded mulching to preceding rice and N rate is presented in Table 8. Nitrogen uptake by wheat was significantly influenced by non-flooded mulching treatments at a rate of 60 kg N ha⁻¹, following the sequence SM > TF and PM over 3 years. However, no significant differences in N uptake among TF, PM and SM treatments were observed at a rate of 120 kg N ha⁻¹. These N concentration and uptake data suggest that SM to preceding rice could meet the N requirement of wheat at a reduced N rate.

Table 7

Nutrient concentration (%) in grain and straw of wheat as affected by three water regimes of TF, PM and SM in rice and two N rates in wheat during 3 years

Mulching ^a	Nitrogen (kg N ha ⁻¹)	1999/2000		2000/2001		2001/2002		Mean	
		Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Nitrogen									
TF	60	1.48	0.28	1.46	0.36	1.45	0.39	1.46	0.34
	120	1.59	0.36	1.56	0.44	1.63	0.46	1.59	0.42
PM	60	1.48	0.30	1.49	0.35	1.51	0.47	1.49	0.37
	120	1.79	0.38	1.60	0.41	1.57	0.56	1.65	0.45
SM	60	1.45	0.38	1.59	0.40	1.47	0.45	1.50	0.41
	120	1.50	0.56	1.61	0.45	1.58	0.58	1.56	0.53
LSD _{0.05} (M)		n.s.	0.09	n.s. ^b	n.s.	n.s.	n.s.		
LSD _{0.05} (N)		n.s.	0.07	n.s.	n.s.	n.s.	0.11		
Phosphorus									
TF	60	0.43	0.10	0.45	0.07	0.31	0.07	0.40	0.08
	120	0.45	0.09	0.48	0.07	0.32	0.06	0.42	0.07
PM	60	0.42	0.08	0.44	0.05	0.31	0.06	0.39	0.06
	120	0.41	0.10	0.45	0.05	0.31	0.06	0.39	0.07
SM	60	0.38	0.07	0.42	0.05	0.30	0.05	0.37	0.06
	120	0.41	0.10	0.43	0.05	0.29	0.06	0.38	0.07
LSD _{0.05} (M)		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.		
LSD _{0.05} (N)		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.		
Potassium									
TF	60	0.56	1.00	0.46	0.84	0.47	1.14	0.50	0.99
	120	0.56	1.04	0.48	0.89	0.52	1.23	0.52	1.05
PM	60	0.52	1.25	0.45	0.95	0.51	1.11	0.49	1.10
	120	0.59	1.14	0.47	0.92	0.50	1.33	0.52	1.13
SM	60	0.50	1.33	0.48	1.01	0.46	1.21	0.48	1.18
	120	0.55	1.49	0.51	1.04	0.46	1.36	0.51	1.30
LSD _{0.05} (M)		n.s.	0.16	n.s.	n.s.	n.s.	n.s.		
LSD _{0.05} (N)		n.s.	n.s.	n.s.	n.s.	n.s.	0.15		

^a TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

^b Not significant.

P uptake by wheat was not significantly influenced by non-flooded mulching in most cases in spite of the decline in total uptake in the third year (Table 8). Mean P uptake by wheat range from 22 to 27 kg P ha⁻¹ across N rates. K uptake by wheat was significantly influenced by non-flooded mulching in the first and second years but not influenced by N rate across years (Table 8). The trend in K uptake was similar to that of N uptake, ranked by the sequence SM > PM ≥ TF at both N rates.

3.3. R–W cropping systems

3.3.1. System productivity

Total annual and mean system productivity for R–W cropping systems as affected by non-flooded mulching and N rate are listed in Table 9. System productivity for individual treatments and years showed a relatively narrow range (from 10.1 to 12.4 t ha⁻¹), while for the mean of 3 years across treatments it ranged from 10.9 to 12.4 t ha⁻¹. In

Table 8

Nutrient uptake (kg ha^{-1}) by wheat following rice as affected by non-flooded mulching to preceding rice and N rate from 1999–2000 to 2001–2002

Mulching ^a	Nitrogen (kg N ha^{-1})	1999–2000	2000–2001	2001–2002	Mean
Nitrogen					
TF	60	92	90	82	88
	120	108	107	93	103
PM	60	87	80	91	86
	120	129	112	105	115
SM	60	112	119	92	108
	120	121	111	104	112
LSD _{0.05} (M)		10.1	7.0	n.s. ^b	
LSD _{0.05} (N)		8.3	5.8	n.s.	
Phosphorus					
TF	60	25	27	21	24
	120	30	29	21	27
PM	60	24	22	21	22
	120	31	28	23	27
SM	60	28	29	23	27
	120	30	27	22	26
LSD _{0.05} (M)		n.s.	2.5	n.s.	
LSD _{0.05} (N)		3.2	n.s.	n.s.	
Potassium					
TF	60	80	70	70	77
	120	87	75	77	80
PM	60	94	62	80	79
	120	99	80	93	91
SM	60	109	97	84	97
	120	120	89	90	100
LSD _{0.05} (M)		14.3	13.7	n.s.	
LSD _{0.05} (N)		n.s.	n.s.	n.s.	

^a TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

^b Not significant.

general, system productivity followed the same sequence of PM > TF > SM in spite of N inputs to the whole cropping system. Across years, system productivity was greater under normal N input ($150\text{--}120 \text{ kg N ha}^{-1}$) than under reduced N input ($150\text{--}60 \text{ kg N ha}^{-1}$) for TF and PM treatments (Table 9). However, the normal N input led to a slight decline in system productivity in the SM treatment compared with the reduced N input, suggesting that a reduction of 60 kg N ha^{-1} may be sufficient for wheat following rice under SM conditions.

Table 9

Annual and mean total system productivity^a (kg ha^{-1}) for R–W systems under three water regimes in rice and two N rates in wheat

Mulching ^b	Nitrogen (kg N ha^{-1}) ^c	Year 1	Year 2	Year 3	Mean
TF	150–60	10154	11598	10887	10880
	150–120	11219	12023	10890	11377
PM	150–60	11222	12089	11083	11465
	150–120	12400	13212	11465	12359
SM	150–60	11039	11625	10672	11112
	150–120	10837	11192	10526	10851
Mean		11145	11956	10920	11340

^a Total system productivity refers to combined yields of rice and wheat, respectively.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

^c The first value is for rice and the second is for wheat.

3.3.2. Apparent nutrient balance

Total nutrient balance in the three cycles of R–W cropping system is presented in Table 10. Apparent N balance was largely influenced by TN inputs to the R–W systems. Reduced N rate ($150\text{--}60 \text{ kg N ha}^{-1}$) caused much lower net N balance compared with higher N rate ($150\text{--}120 \text{ kg N ha}^{-1}$). At the reduced N rate, TN inputs were 630 kg N ha^{-1} in TF and PM treatments while they were 705 kg N ha^{-1} in SM treatment due to the N addition from wheat straw (75 kg N ha^{-1}) as mulch material. Total N outputs (uptake by crops) were comparable ($560\text{--}609 \text{ kg N ha}^{-1}$) with the TN inputs in TF, PM and SM treatments. Hence, net N balances were relatively low ($21\text{--}123 \text{ kg N ha}^{-1}$). At the normal N rate, however, the higher TN inputs than at the reduced N rate in the three treatments did not produce correspondingly higher N outputs (only $13\text{--}88 \text{ kg N ha}^{-1}$). Thus the net N balances ($113\text{--}310 \text{ kg N ha}^{-1}$) were much greater at normal N rate than at reduced N rate. Among the three treatments, PM led to the lowest net N balance due to the highest N outputs whereas SM led to the highest net N balance due to the highest N inputs and the lowest N outputs. Apparent P and K balances were not significantly affected by the N input levels during the 3 years of R–W rotation (Table 10). Net P balance was positive due to the much higher P inputs than P outputs in spite of N rate. In contrast, net K balance was always negative because the total K inputs were

Table 10

Net nutrient balances in three cycles of R–W systems as affected by non-flooded mulching cultivation and N rate

Mulching ^a	Nitrogen (kg N ha ⁻¹) ^b	Fertilizer input (1)	Addition from straw (2)	Uptake by crops (3)	Net balance (=1 + 2 – 3)
Nitrogen (kg N ha ⁻¹)					
TF	150–60	630	0	560	70
	150–120	810	0	604	206
PM	150–60	630	0	609	21
	150–120	810	0	697	113
SM	150–60	630	75	582	123
	150–120	810	75	595	310
Phosphorus (kg P ha ⁻¹)					
TF	150–60	197	0	138	59
	150–120	197	0	145	52
PM	150–60	197	0	138	59
	150–120	197	0	153	44
SM	150–60	197	15	135	77
	150–120	197	15	134	78
Potassium (kg K ha ⁻¹)					
TF	150–60	375	0	612	–237
	150–120	375	0	632	–257
PM	150–60	375	0	706	–331
	150–120	375	0	742	–367
SM	150–60	375	173	660	–112
	150–120	375	173	669	–121

^a TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.^b The first value is for rice and the second is for wheat.

much lower than the total K outputs. Among the three treatments, net P balance in SM was higher than that in TF and PM, mainly due to the P addition from wheat straw (15 kg P ha⁻¹), whereas the P outputs (134–153 kg P ha⁻¹) were similar in the three treatments at two N rates. Mean K balance in SM (–120 kg K ha⁻¹) was significantly greater than that in TF (–247 kg K ha⁻¹) and PM (–349 kg K ha⁻¹) across two N rates mainly because of considerable K inputs (173 kg K ha⁻¹) from wheat straw (Table 11). The above NPK balance results suggest that the same N, P and K rates to R–W systems may not be appropriate for TF, PM and SM treatments for sustainability of the whole R–W systems.

3.3.3. Changes in soil properties

Some selected soil properties in the 0–10 and 10–20 cm layers as affected by non-flooded mulching

cultivation during 3 years of R–W systems are presented in Table 11. Soil pH in 0–10 cm was significantly influenced by non-flooded mulching cultivation, whereas 10–20 cm soil pH was not affected after 3 years. SM and PM caused a distinct decline in the 0–10 cm soil pH compared with TF. Soil organic carbon (OC) and total nitrogen (TN) contents were not significantly affected by non-flooded mulching cultivation in both soil layers, probably due to their very large pools in the soil. In contrast, soil AP in 0–10 cm (8.3–12.0 mg kg⁻¹) and 10–20 cm (2.9–4.1 mg kg⁻¹) layers and EK in the 0–10 cm (24.1–33.7 mg kg⁻¹) layer were significantly affected by non-flooded mulching cultivation, following the same sequence of SM > TF and PM. Soil available K in the 10–20 cm (17.7–19.3 mg kg⁻¹) layer, however, was not significantly different among TF, PM and SM treatments. In general, most soil properties (except pH) were improved or not influenced

Table 11

Selected soil properties as affected by non-flooded mulching cultivation at normal N rate ($150\text{--}120\text{ kg N ha}^{-1}$) after three cycles of R–W systems^a

Mulching ^b	pH (H ₂ O, 1:2.5)	OC (g kg ⁻¹)	TN (g kg ⁻¹)	AP (mg kg ⁻¹)	EK (mg kg ⁻¹)
0–10 cm layer					
TF	7.6 a	16.0 a	2.21 a	8.7 ab	24.1 b
PM	7.2 b	16.4 a	2.24 a	8.3 b	28.9 ab
SM	7.2 b	16.9 a	2.22 a	12.0 a	33.7 a
10–20 cm layer					
TF	7.8 a	11.3 a	1.17 a	2.9 b	17.7 a
PM	7.6 a	11.5 a	1.20 a	3.6 ab	19.3 a
SM	7.6 a	12.0 a	1.42 a	4.1 a	19.3 a

^a Values within the same row at the same layer are not significantly different.

^b TF: traditional flooding; PM: plastic film mulching; SM: wheat straw mulching.

by non-flooded mulching cultivation, particularly the SM treatment compared with TF treatment after three cycles of R–W rotation, suggesting that non-flooded mulching has no negative effects on soil fertility in the short term. In addition, it must be stressed that the available K contents in the two soil layers across three treatments were lower than in the original soil (0–20 cm), indicating a declining trend in soil available K under continuous R–W systems. The changes observed in soil nutrient status, particularly P and K availability, were consistent with the apparent nutrient balances.

4. Discussion

4.1. Crop growth, yields and nutrient uptake

Rice is traditionally grown in submerged conditions with a stable water layer that maintains an anaerobic environment. Non-flooded mulching cultivation, as a new water-saving technology, significantly altered the rice growth environment through changes in soil water, temperature and nutrient status. For example, the N forms and even availability will change largely from TF (anaerobic) to non-flooded mulching (aerobic) condition. In the present study, PM increased the biomass accumulation and grain yield of rice, presumably due to increased soil temperature during the rice growing period, particularly at early tillering.

Higher soil temperatures from PM would have accelerated nutrient transformations (e.g. N ammonification and nitrification) and may have provided a better root growth environment. Thus PM enhanced root growth, tiller number (data not shown) and shoot biomass accumulation in this study. Shen et al. (1997) reported that plastic mulching cultivation produced larger and more vigorous root systems and improved early tillering due to higher temperatures compared with the traditional flooded system. According to the studies by Liang et al. (1999) and Wu et al. (1999), more white roots with higher biological activity were found during the whole growing period of rice under PM conditions compared with TF, suggesting that PM rice may have the potential to absorb more nutrients from the soil. This was confirmed by our results (Table 5).

In contrast, SM inhibited shoot biomass accumulation and grain yield of rice, probably due to a decline in soil temperature, particularly during the early growing period of rice. Lower soil temperatures limited the biological activity of rice roots and inhibited their capacity to absorb nutrients. According to a preliminary study by Hasegawa et al. (2001), the critical soil temperature for normal growth of rice roots ranged from 24 to 27 °C, which was similar to the soil temperature at 10 cm depth in our study (Table 2). In a soil-column study, Wang (2001) found that the growth and grain yield of rice in SM treatment were similar to those in TF and PM treatments when the soil temperatures in those treatments were the same, further indicating that soil temperature could be a major factor influencing the growth of rice mulched with straw. Meanwhile, N immobilization caused by the initial degradation of wheat residue with a wide C/N ratio would decrease soil available N (mineral N content) in the SM treatment (Rao and Mikkelsen, 1976). For example, we observed typical N deficiency symptoms in rice mulched with straw at tillering, suggesting a greater N requirement by rice in the SM treatment. As a result, SM prolonged the growth of rice since re-greening and tillering and led to a decrease in grain yield.

The residual effect of non-flooded mulching to preceding rice on wheat was another concern for whole-system productivity. The biomass accumulation, grain yield and nutrient uptake of wheat were significantly higher in SM treatment than in TF and

PM treatments at reduced N rate (60 kg N ha^{-1}) but were similar at normal N rate (120 kg N ha^{-1}). Compared with the normal N rate, similar grain yields and nitrogen uptake of wheat were achieved at reduced N rate in the SM treatment. However, a reduction of 60 kg N ha^{-1} led to a significant decline in grain yield and nutrient uptake of wheat in the TF and PM treatments. A rapid nitrate test on wheat at booting (data not shown) further indicated that basal N application was adequate to meet the wheat N requirement in the SM treatment while N topdressing was required in the TF and PM treatments. This meant that considerable extra N in the SM treatment was available in the wheat season. This can be explained on the basis of N re-mineralization from immobilized N due to SM to rice, or greater N availability in the soil due to lower N uptake in the SM treatment in the rice season. Aulakh et al. (2000) also reported residual effects of green manure on wheat yields in R–W rotations. In a 4-year experiment, they found that the supply of nutrients through the integrated use of green manure (20 Mg ha^{-1}) and fertilizer N (60 kg ha^{-1}) in rice produced greater yields of rice and wheat while reducing the use of fertilizer N by 50% in rice and 25% in wheat. Prasad et al. (2002) also observed residual effects of green manure applied to rice on pod yields of groundnut following rice.

PM had the same or a relatively higher system productivity (total grain yields of rice plus wheat) compared with TF across two N levels due to the priming effects on rice yield. In contrast, system productivity in the SM treatment was lower than in the TF treatment although the system grain yield gap between SM and TF could be largely eliminated at reduced N rate in wheat. The nutrient management system in which all NPK fertilizers were applied once as basal application in the rice season under non-flooded mulching conditions, particularly in the SM treatment in the present study, would not be conducive to efficient use of nutrients (especially N) and would need to be improved by further studies on R–W systems (Singh and Singh, 2001).

4.2. Nutrient balance, system sustainability and application potential

Apparent nutrient balances in the R–W systems showed that PM always led to less nutrient balances

compared with TF, suggesting that soil fertility exhaustion could occur under PM conditions. Hu et al. (1999) reported an 8% decline in OC and TN in a paddy field under PM conditions. However, our results have not shown any decrease in soil OC, TN, AP or EK in the PM treatment (Table 11). The long-term effects of PM on soil fertility require much more attention in China as this cultivation practice is increasing in popularity in many areas of the country, especially in arid and semi-arid regions. In the SM treatment, higher net nutrient balances were found due to the return of wheat straw as mulch material compared with the TF treatment. From the viewpoints of nutrient balance and soil fertility, the SM production system may be more sustainable than the PM production system. In addition, the extra low soil K availability combined with negative K balance in the R–W systems in the present study suggested that higher K inputs from fertilizer, straw or manure be necessary to sustain the high system productivity.

The potential for using non-flooded mulching cultivation depends firstly on economic factors, i.e. the difference between the income and the cost. It is quite clear that farmers will not adopt non-flooded mulching cultivation unless the system brings more net income than the traditional cultivation system. Thus, only when a comparable or higher system productivity was achieved without a significant increase in inputs have farmers tended to use this new water-saving cultivation method in R–W systems. On the other hand, the long-term environmental risks (i.e. greenhouse gas emission and nitrate leaching) of non-flooded mulching cultivation in R–W systems should also be taken into account (Liang et al., 2000). The TF system produced relatively stable grain yields of rice and wheat but needed large amounts of irrigation water. SM is good for sustainable material recycling and the succeeding wheat crop but at the cost of lower system productivity due to the decline in rice yields. Thus it is important to improve the SM system productivity through integrated nutrient management (e.g. larger N inputs to rice and smaller N inputs to wheat). In PM, the system productivity is comparable with, or relatively higher than that of TF, while the main problems in this system include the cost of plastic film, labour, and removal of residual plastic. In many mountain areas of China, low temperature and water shortage are two important stress factors

that limit rice production in R–W systems. The PM system is probably suitable for these mountain areas through the improvement of soil temperature and water conservation (Peng et al., 1999). The SM system, however, might be more suitable for those lowland regions where water and temperature conditions are less limiting.

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