MITIGATION OF YIELD-SCALED GLOBAL WARMING POTENTIAL BY PLASTIC MULCH TECHNOLOGY IN RICE CROPS IN SOUTHWESTERN CHINA

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ABSTRACT

The improved technology of plastic-film mulching (PM) for cultivation has been developed to maintain high yields in rice-based cropping systems in southwestern China where paddy fields usually suffer from water shortage or flash droughts. However, the integrated effects of PM on the global warming potential (GWP) of CH_4 and N_2O emissions, yield-scaled GWP (Y_{GWP}), and net profit (balance between economic benefits and environmental costs) are poorly documented. In addition, the cultivation of ratoon rice [RR, the second rice crop from the stubble left behind after an improved single rice (ISR) variety has been harvested] has become available in this region by adopting PM; however, the responses of CH_4 and N_2O emissions, grain yield, Y_{GWP}, and net profit to changes from the traditional single rice (TSR) into ISR with RR cultivation are still unknown. A series of field experiments were therefore conducted from 2012 to 2017 to investigate (1) the effect of cultivation using PM on Y_{GWP} and net profit as compared with traditional cultivation in flooded fields (FF) and rainfed fields (RF); (2) whether adding nitrification inhibitors [NI; dicyandiamide (DCD) or chlorinated pyridine (CP)] and controlled-release fertilizer (CRF) increases net profit or not under PM conditions; and (3) the changes in CH_4 and N_2O emissions, GWP, grain yield, and net profit by shifting TSR to ISR + RR. Results showed that (1) compared with traditional cultivation in FF and FR, cultivation using PM significantly reduced GWP and Y_{GWP} by 22%−66% and 38−64%, respectively, thus the increasing net profit to approximately 4626−8217 Chinese yuan (CNY) ha^{-1}; (2) CP addition, rather than DCD and CRF, decreased GWP (6%−11%) and Y_{GWP} (7%−13%) as well as *increased net profit (by 277 CNY ha^{-1}); (3) seasonal cumulative CH_4 emissions were similar from TSR and ISR but additional 8.4−30.4 kg ha^{-1} emissions were noted from RR, contributing an additional 8%−10% of the total emissions from ISR + RR. Seasonal cumulative N_2O emission from RR was 0.16−2.35 kg N ha^{-1}, accounting for 11%−42% of the total emissions, which was even higher than that from TSR in 2017. In addition, total rice grain yield for ISR + RR was 10.2−10.4 t ha^{-1}, 19%−22% higher than that of TSR. Overall, compared with those for TSR, the net profit for ISR + RR increased by 1450 CNY ha^{-1} and the total GWP increased by 7%−62%. These findings suggest that PM, particularly with the addition of CP, is an effective strategy to reduce environmental costs and increase economic benefits in rice-based cropping systems that are limited by water shortage; moreover, the findings indicate that RR should be looked at as an opportunity and a possible solution to climate change and food security issues in the future.*

Keywords: GHG emission, grain yield, GWP, net profit, plastic mulch technology, paddy fields, ratoon rice

INTRODUCTION

China is the largest producer of rice in the world, with a total production of 211 million tons in 2016, contributing approximately 28% of the global rice production. In the hilly areas of southern and southwestern China, there is a special kind of rice field that is continuously flooded after rice harvest until transplanting subsequent rice crops. These fields emit substantial amounts of CH_4 over the winter fallow season, contributing approximately 40% of the annual emissions (Cai *et al*. 2003). Draining these fields either partially or completely in the winter fallow season would significantly reduce CH_4 emissions (Yan *et al*. 2009).

However, draining fields of the local farmers is impractical as farmers often face water shortage problems before transplanting rice. For a long time, most farmers in these regions would have had no choice but to keep the paddy fields intentionally flooded after the rice harvest to ensure sufficient water supply for the next rice transplanting; flooding of these rice fields in winters occurs because the drainage conditions of some fields in low-lying areas are too poor to drain the floodwater from the soil. Additionally, paddy fields in China usually suffer flash droughts during the rice season, particularly in southern China (Wang *et al*. 2016).

An improved plastic-film mulching technology (PM) was developed in southwestern China approximately 10 years ago (Lv *et al*. 2009) and was found to be a promising alternative to the flooded rice cultivation system, with advantages such as reducing irrigation water, increasing soil temperature, and maintaining crop yields (Zhang *et al*. 2018). Field experiments in central and northern China have shown that either PM or rice straw mulching significantly reduces CH_4 emissions while increasing N_2O emissions compared with traditional cultivation (Kreye *et al*. 2007; Yao *et al*. 2014). Till date, no comprehensive study has been conducted to evaluate the responses of the global warming potential (GWP) of CH_4 and N_2O emissions from PM in rice-based cropping systems at the annual cycles.

Previous studies have shown that the use of a nitrification inhibitor (NI), such as dicyandiamide (DCD) or chlorinated pyridine (CP), with N fertilizer can effectively reduce N_2O emissions (Li *et al*. 2009 and references therein). Controlled-release fertilizers (CRFs) are also widely used during the rice season and have been found to be a useful alternative for mitigating N_2O emissions from paddy fields (Abao *et al*. 2000; Ji *et al*. 2013). Using NI or CRF under PM conditions during the rice season has been suggested to mitigate N_2O emissions. In addition, considering that PM increases soil temperature during the rice-growing season, we were planning on cultivating ratoon rice (RR) using PM to investigate the effects on CH_4 and N_2O emissions and rice grain yield.

In addition to CH_4 and N_2O emissions, GWP and grain yields and net profit, which is the balance between economic benefits (yield gains and input costs) and environmental costs (GWP costs), need to be estimated in detail for rice cultivation. Therefore, a series of field experiments were conducted from 2012 to 2017 to investigate (1) the effect of PM on GWP, yield-scaled GWP (Y_{GWP}), and net profit from cultivation using PM compared with those from flooded fields (FF) and rainfed fields (RF) under traditional cultivation; (2) whether adding NI (DCD or CP) and CRF under PM conditions increases net profit or not; and (3) the effects on changes in CH_4 and N_2O emissions, GWP, grain yield, and net profit by shifting traditional single rice (TSR) to improved single rice (ISR) with RR cultivation.

THE EFFECT OF PM

The experimental site was located in Ziyang City, Sichuan Province, southwestern China (30°05’ N, 104°34’ E). Three treatments, with four replicates of each, in a randomized block design, were set up from the 2013 winter fallow season to the 2015 rice-growing season: traditional cultivation with either the fields being flooded in the winter fallow season while rainfed during the rice season (FR) or continuously flooded throughout the winter fallow and rice seasons (FF), and plastic-film mulching cultivation (PM) with the water being transported into ditches to keep the soil moist but without standing water on the surface of the ridges throughout the entire rice-growing season, with the plots being kept drained throughout the winter fallow season. For FF and FR, a total of 150 kg N ha^{-1} was applied as urea in two equal splits, namely 50% as basal fertilizer in the seed bed and 50% applied at tillering. In contrast, the same rate of urea was applied completely on the ridges of the PM plots as basal fertilizer and then, the plastic film (0.004 mm) was used as mulch. For more detailed descriptions of FR, FF, and PM please refer to Fig. 1.

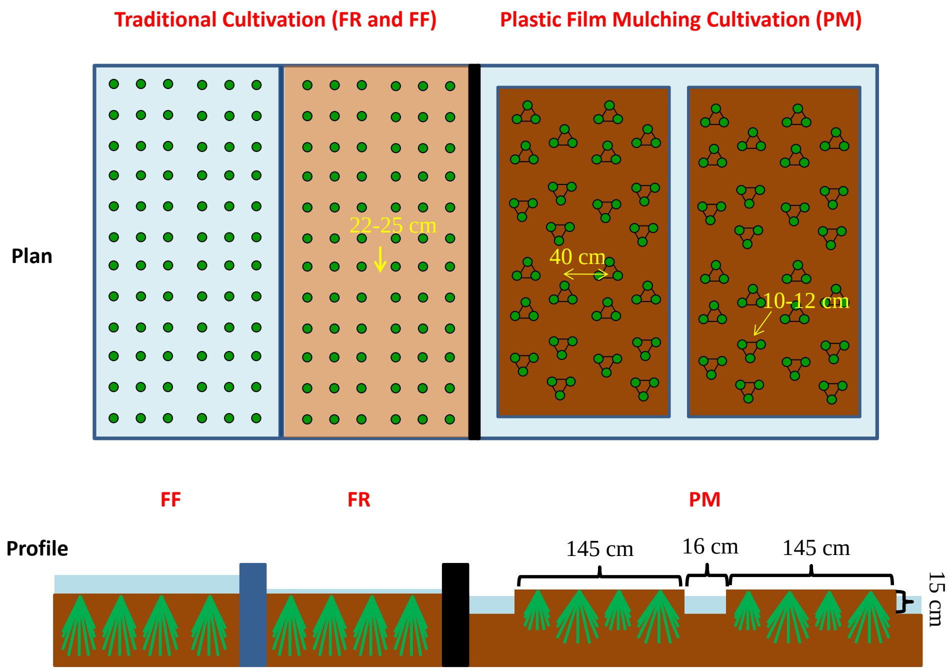

Fig. 1. Diagram of traditional cultivation (FF and FR) and plastic-film mulching cultivation (PM) in this study.

PM decreased CH_4 emission

Shifting the fields from FF into PM significantly decreased CH_4 emission in both the winter fallow and the rice-growing seasons by 71−85 and 60%−70%, respectively (Table 1). It is well known that under better conditions (including suitable soil redox potential (Eh) and temperature, and abundant substrates, i.e., for methanogenesis), more CH_4 will be produced and emitted. The application of PM kept mean soil water content (SWC) at around 60%−75% during the non-rice and rice seasons, causing annual mean soil Eh to be significantly higher than that in FF (Yang *et al.* under review). Therefore, the higher the soil Eh, the lower the CH_4 production and emission was observed for PM. Moreover, as an important carbon source for methanogenesis, abundant dissolved organic carbon (DOC) favors CH_4

production and emission (Zhang *et al*. 2018). Soil DOC content was much lower under PM, indicating that PM application mitigated CH_4 emission by significantly enhancing Eh and decreasing DOC content, thus greatly depressing CH_4 production as compared to FF.

In contrast, PM decreased annual cumulative CH_4 emission by 27%−35% relative to FR, mainly due to the significant reduction in CH_4 emissions in the winter seasons (Table 1), with substantial decreases in both DOC content and CH_4 production potential by PM being considered to be the reason (Yang *et al*. under review). Moreover, soil temperature may play an important role in CH_4 emission as well. Methane can be produced at 5°C, and a higher temperature (10°C−50°C) is more favorable to methanogenesis (Fey *et al*. 2004). The soil temperature for PM during the winter fallow seasons ranged from 5.0°C to 22.9°C, which is high enough for CH_4 production. Therefore, a relatively lower soil temperature under PM conditions (by 1.6°C) was a possible reason for CH_4 emissions being lower than those under FF and FR during the winter fallow seasons.

PM increased N_2O emission

PM significantly increased annual cumulative N_2O emission by 196%−546% and 9%−20% compared to FF and FR, respectively, an effect which was mainly ascribed to the following possible reasons. Firstly, nitrogen fertilization provides substantial substrates for nitrification and denitrification, and the availability of soil NH_4^+-N in paddy fields plays a critical role in N_2O emissions (Yao *et al*. 2014). The urea supplied to the PM site was entirely (i.e., 100%) applied into the soil as basal fertilizer, whereas the proportion was 50% for FF and FR, which resulted in the concentrations of both NH_4^+-N and NO_3^--N being much greater for PM than for FF and FR at the beginning of the rice seasons (Yang *et al*. under review). Secondly, the mean soil temperature for PM was higher by 1.5°C−1.9°C than that for FF and FR during the rice seasons as the conditions were more conducive to N_2O production and emission (Schindlbacher *et al*. 2004).

Thirdly, far lower SWC under PM conditions was more favorable for N_2O production and its emission. It is reported that a SWC of 40%−100% water-filled pore space is favorable for N_2O transformation and emission, and positive correlations between N_2O emissions and SWC have also been observed (Hou *et al*. 2000; Yan *et al*. 2000). The SWC under PM ranged from 38% to 96% during the non-rice and rice-growing seasons, respectively (Yang *et al*. under review), which was within the optimal range of N_2O production and emissions. When SWC increased up to 127%−158% on average for FF and FR, nitrification would have been largely inhibited and N_2O emissions were hence significantly reduced (Schindlbacher *et al*. 2004).

A high SWC is also detrimental to N_2O diffusion in soil and its release into the atmosphere.

Table 1. Effect of PM on CH_4 (kg ha^{-1}) and N_2O (kg N ha^{-1}) emissions, GWP (t CO_2-eq ha^{-1}), yield (t ha^{-1}), and Y_{GWP} (t CO_2-eq t^{-1} yield) over the two annual cycles of 2013 to 2015

Year	Treatment	CH_4			N_2O			Annual GWP*	Annual Yield	Annual Y_{GWP}
		WS	RS	Annual	WS	RS	Annual			
2013–2014	FF	120	535	655	0.04	0.11	0.15	22.3	9.11	2.45
	FR	116	241	357	0.05	0.86	0.90	12.5	7.68	1.63
	PM	18	213	232	0.15	0.84	0.98	8.3	9.00	0.93
2014–2015	FF	123	359	481	0.04	0.57	0.62	16.7	9.01	1.85
	FR	114	82	196	0.05	1.48	1.52	7.4	6.95	1.06
	PM	36	108	144	0.34	1.48	1.82	5.7	8.74	0.66

*GWP = [34 × CH_4] + [298 × N_2O]; WS: winter season, RS: rice season.

PM increased grain yield

The grain yield increased significantly by 17%−26% when the fields were changed from FR to PM, mainly as a result of significant increases in effective panicle number per m^2, total filled grains per m^2, and percentage of filled grains (Yang *et al.* under review). The relatively low SWC for PM might have promoted rice growth and uptake of N, P and K, increased nitrogen-use efficiency, improved the percentage of filled grains, and increased grain yields (Tao *et al.* 2015; Zhang *et al.* 2017). In addition, the rice season soil temperature for PM, on average, was 1.5°C higher than that of FR, which was associated with significantly greater tiller numbers and increased plant height (Yang *et al.* under review). This demonstrates that the more suitable SWC and temperature associated with PM is beneficial to rice growth and grain yield.

PM decreased GWP and Y_{GWP}

Shifting the fields from FR and FF into PM increased average annual N_2O emissions by 0.83−1.02 kg N ha^{-1} (Table 1), with the contribution of N_2O emission to total GWP increasing from 1%−6% to 9%, these figs being significantly lower than that of a previous report under different management regimes (Jiang *et al.* 2006). Compared with FR and FF, PM decreased GWP by 64%−83% during the winter fallow seasons due to a marked reduction in

CH_4 emissions (68%−85%). During the rice season, little change in GWP was observed, with no significant differences in CH_4 and N_2O emissions between FR and PM being observed. In contrast, PM substantially decreased CH_4 emissions (60%−70%), resulting in GWP being reduced by 58%−65% as compared to FF. Consequently, relative to FR and FF, PM significantly reduced annual GWP by 22%−66% (Table 1).

Although GWP was reduced under PM, it is also important to determine Y_{GWP} under the framework of sustainable intensified agriculture for achieving high crop yields while reducing greenhouse gas (GHG) emissions. Several investigations have reported Y_{GWP} in a double-cropping rice field in southeastern China (Zhang *et al*. 2016) and a rice–wheat cropping system in central China (Zhang *et al*. 2015). In the current study, annual Y_{GWP} ranged from 0.66 to 2.45 t CO_2-eq t^{-1} yield, values which were higher than those reported in the earlier reports mentioned above but much lower than the estimates from a permanently flooded paddy field in southwestern China (Zhou *et al*. 2018). In addition, relative to FR and FF, PM substantially decreased Y_{GWP} by 38%−64%, due to a significant reduction in GWP and a relative stable or increased grain yield (Table 1).

Table 2. Evaluation of the average net profit by shifting the fields from FF and FR into PM over the two annual cycles of 2013 to 2015

Option	Yield gain (CNY ha^{-1})	Input cost (CNY ha^{-1})	Labor cost (CNY ha^{-1})	GWP cost (CNY ha^{-1})	Net profit (CNY ha^{-1})
FF to PM	−497	740	−4572	−1292	4626
FR to PM	4083	740	−4572	−303	8217

Note: Net profit = Yield gain – [Input cost + Labor cost + GWP cost]; Yield gain = grain yield × price; for detailed information about the calculation and real-time price, please refer to Zhang *et al.* (2018).

PM increased net profit

Agriculture faces great challenges to increase grain yields while at the same time reducing both input costs and environmental costs. In other words, ultimately, it must look to promote the net profit, which is the balance between economic benefits and environmental costs. Increasing, or at least preserving, current crop production levels while reducing or maintaining current input costs is very important in rice cultivation. However, up to the current study, no reports on the effect of PM on net profit were available. Although PM reduced yield gains by 497 CNY ha^{-1}, relative to FF, and increased input costs for the plastic film by 740 CNY ha^{-1}, both labor and GWP costs were decreased greatly by 4572 and 1292 CNY ha^{-1}, causing the net profit to increase by 4626 CNY ha^{-1}. More importantly, PM could significantly increase yield gains, compared to FR, which resulted in a net profit as high as 8217 CNY ha^{-1} (Table 2).

THE EFFECT OF NI AND CRF ADDITIONS

To further estimate the effect of NI and CRF on GHG emissions, Y_{GWP} and net profit under PM conditions, a three-year field experiment was conducted during the 2012−2014 rice seasons. There were four treatments with four replicates each, in a randomized block design: PM, PM with NI addition (PM + DCD or PM + CP), and PM with CRF application (PM + CRF). For all treatments, urea (at a rate of 150 kg N ha^{-1}), CRF (thermoplastic resin-coated urea, at a rate of 150 kg N ha^{-1}), DCD (dicyandiamide, at a rate of 5% of the urea), and CP (chlorinated pyridine, at a rate of 0.24% of the urea) were applied on the ridges as a single basal fertilizer, and then the plastic film was positioned.

Effect of NIs on CH_4 and N_2O emissions

Under PM conditions, CP addition reduced CH_4 emissions by 2%−11%; however, CH_4 emissions increased following DCD application, albeit non-significantly (Table 3). Although the effect on CH_4 emissions remains contradictory (Malla *et al*. 2005), the application of NIs significantly reduced N_2O emissions from paddy fields (Li *et al*. 2009). Shifting rice cultivation from FF to PM significantly increased N_2O emissions (Table 1), so it was expected that NI addition would reduce the N_2O emissions under PM conditions. Indeed, seasonal N_2O emissions were reduced by 24%−63% or 10%−27% by addition of DCD or CP, respectively (Table 3). The additions of DCD or CP can delay urea hydrolysis and inhibit the nitrification process, meaning it will remain present as NH_4^+ for longer, which improves the N-use efficiency and reduces N loss and N_2O emissions (Zheng *et al*. 2006).

Table 3. Effect of NI and CRF additions under PM conditions on CH_4 (kg ha^{-1}) and N_2O (kg N ha^{-1}) emissions, GWP (t CO_2-eq ha^{-1}), yield (t ha^{-1}), and Y_{GWP} (t CO_2-eq t^{-1} yield) during the 2012−2014 rice seasons

Year	Treatment	CH_4	N_2O	GWP*	Yield	Y_{GWP}
2012	PM	263	0.43	9.14	8.23	1.11
	PM + DCD	267	0.16	9.16	8.35	1.10
	PM+CRF	260	0.25	8.96	8.31	1.08
2013	PM	151	2.11	6.14	8.25	0.74
	PM+CP	149	1.54	5.78	8.32	0.69
	PM+CRF	136	1.88	5.51	8.33	0.66
2014	PM	213	0.84	7.64	9.00	0.85
	PM+DCD	219	0.63	7.73	9.20	0.84
	PM+CP	190	0.75	6.83	9.24	0.74

*GWP = 34 × CH_4 + 298 × N_2O

Effect of CRF on CH_4 and N_2O emissions

Early studies had shown that the application of CRF can reduce CH_4 emissions from paddy fields (Abao *et al*. 2000; Lin *et al*. 2000); however, a report of a significant increase in CH_4 emissions following CRF application has also been published (Li and Fan 2005). In a rice–wheat rotation system, Ji *et al.* (2014) measured a slight reduction in CH_4 emissions by the application of CRF during the rice seasons in 2008−2011. Using the same CRF, CH_4 emissions were found to decrease by 1%−10% in the present study, albeit non-significantly (Table 3). Changing urea into CRF was considered to be an effective approach to regulating N_2O emission from paddy fields. Ji *et al.* (2013) reported that N_2O emissions from a rice–wheat rotation system reduced by 13% following the addition of CRF. In contrast, we found a reduction of 11%−42%, particularly in 2012, with a significant reduction being observed (Table 3). The addition of CRF can maintain a higher NH_4^+-N concentration in the soil, promoting N uptake via rice growth rather than N loss in the form of N_2O emissions (Luo *et al*. 2007). In addition, the application of CRF enhanced the population and activity of soil microbes, resulting in increased N transformation to microbial biomass nitrogen (Luo *et al*. 2010), thus reducing N_2O emissions.

Effects of NI and CRF on GWP, grain yield and Y_{GWP}

Under MC conditions, the GWP was found to decrease by 6%−11% and 2%−10% with the additions of CP and CRF, respectively, whereas the addition of DCD caused only a slight change in the GWP (Table 3). The reduction in GWP observed in the present study by applying CP and CRF can be attributed to the reduction in both CH_4 and N_2O emissions relative to PM (Table 3). The findings suggest that PM with the applications of CP and CRF can help mitigate the GWP of paddy fields.

Applying NI and CRF under PM conditions always tended to increase grain yield though no significant effect was observed (Table 3). The addition of NI, together with urea, and CRF, has the potential to meet the nutritional needs of rice, which is conducive to rice growth and yield promotion. Previous pot and field measurements had shown that the application of DCD generally increased rice yields (Li *et al*. 2009). In contrast, the effect of CRF on grain yield is more complicated. Although the primary objectives of CRF development are to reduce N loss, improve N-use efficiency, and increase crop grain yields (Li *et al*. 2005; Xu *et al*. 2005), Ji *et al.* (2013) found that the application of CRF increased rice yield in 2009 and 2010, but significantly reduced it in 2008 and 2011.

In the present study, the Y_{GWP} ranged from 0.66 to 1.11 t CO_2-eq t^{-1} yield (Table 3), values which were far lower than those from a rice–wheat rotation system (1.80−2.42 t CO_2-eq t^{-1} yield) reported by Zhang *et al.* (2015) during the rice season. Under PM conditions, the additions of NI and CRF tended to increase rice grain yields and decrease GWP, thus causing Y_{GWP} to decrease. In a rice–wheat rotation system (Li *et al*. 2009), a reduction in GWP and an increase in grain yield was also observed by application of DCD, thus reducing Y_{GWP} by 14%−41%. In a paddy field, CRF addition was found to decrease Y_{GWP} by 33% as a result of a 34% reduction in GWP (Abao *et al*. 2000).

Table 4. Evaluation of the average net profit by applications of NI and CRF under PM conditions over the 2012−2014 rice seasons

Option	Yield gain (CNY ha^{-1})	Input cost (CNY ha^{-1})	GWP cost (CNY ha^{-1})	Net profit (CNY ha^{-1})
DCD addition	437	1141	6	−710
CP addition	404	187	−60	277
CRF application	210	748	−42	−496

Note: Net profit = Yield gain − [Input cost + GWP cost]; Yield gain = grain yield × price; detailed information about the calculation and real-time price please refer to Zhang *et al.* (2018)

Effects of NI and CRF on net profit

Under PM conditions in the current study, DCD addition always increased yield gains and GWP costs; however, the input costs increased much more as a result of its high price, meaning that the net profit decreased by 710 CNY ha^{-1} on average (Table 4). This indicates that the increase in yield gains barely offset the cost of DCD itself, which in turn led to a negative effect on the incomes of farmers. In contrast, CP addition further increased net profit (by 277 CNY ha^{-1}) because of the higher yield gains and lower GWP costs. Although CRF tended to increase yield gains and reduce GWP costs, it decreased the net profit up to 496 CNY ha^{-1}, mainly due to higher input costs. The findings demonstrated that CP application under PM conditions is a more promising management practice than DCD.

GHG EMISSIONS FROM RR FIELDS

Given that PM improved soil temperature during the rice season, we carried out a study to plant RR in concert with PM in the same experimental site which had originally not been suitable for RR growth. Compared with PM, we hypothesized that (1) the cultivation of RR under PM conditions increases both CH_4 emission and GWP in the fields, (2) achieves higher crop yields and yield gains, and (3) ultimately increases the net profit. During the 2016−2017 rice seasons, two treatments were prepared under PM conditions: TSR and ISR with RR growth. The RR involves the production of a second rice crop from the stubble left behind after the single rice had been harvested. In addition, the growth duration of the main rice for ISR was different from that of TSR due to its rice transplanting approximately 15 days earlier (Fig. 2). During the main rice seasons, urea was applied at a rate of 130 kg N ha^{-1} for TSR and ISR on the ridges as basal fertilizer. In contrast, for RR, urea was applied as a topdressing in two splits at a total rate of 330 kg ha^{-1}.

The emissions of CH_4 and N_2O

Different temporal variations in CH_4 and N_2O emission flux were observed between TSR and ISR + RR (Fig. 2). Before TSR transplantation, substantial CH_4 fluxes were measured for ISR. In addition, the timing of the CH_4 flux peak for ISR appeared earlier than that of TSR. There were no measurements of CH_4 emission after TSR harvest but obvious CH_4 fluxes could be observed after ISR harvest for RR (Fig. 2a, b). Seasonally, total CH_4 emission was very similar between TSR and ISR during the main rice seasons whereas another 8.4−30.4 kg ha^{-1} of CH_4 emission was measured during the RR seasons (Table 5). As a whole, seasonal cumulative CH_4 emission for ISR + RR was 11%−15% higher than that of TSR. The contribution of CH_4 emission for RR to ISR + RR was estimated to be 8%−10%.

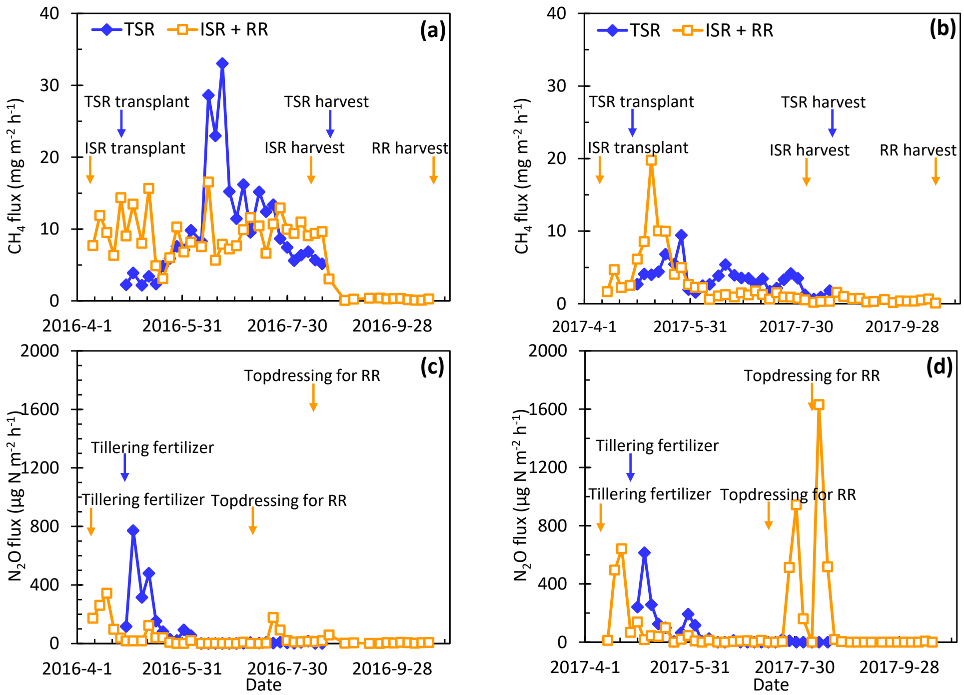

Fig. 2. Temporal variation of CH_4 and N_2O emissions during rice seasons in 2016−2017.

For N_2O emission, high flux peaks are generally observed after fertilizer application at tillering and topdressing for TSR, ISR, and RR (Fig. 2c, d). Subsequently, little N_2O emission could be measured during most of the season. Seasonally, total N_2O emission for TSR was significantly higher in 2016 but lower in 2017 than that of ISR (Table 5). During the ratoon rice seasons, total N_2O emission was 0.16−2.35 kg N ha^{-1} for RR. As a whole, the seasonal cumulative N_2O emission for ISR + RR was 29% lower in 2016 but 247% higher in 2017 than that of TSR. The contribution of N_2O emission from RR to the total for ISR + RR was found to be 11%−42% (Table 5).

To our knowledge, this is the first report on GHG emissions from RR fields in China. About 25 years ago, Lindau and Bollich (1993) measured CH_4 emissions from RR fields with two treatments [plants with (urea) and without fertilizer] in Louisiana, USA, and they found that CH_4 emissions from the main rice season and the RR season were 240−340 and 220−520 kg ha^{-1}, respectively. In the current study, CH_4 emissions from the RR season was much lower than that from the main rice season. Large differences in CH_4 emissions between the two reports can possibly be attributed to different climatic and soil environments, rice cultivation methods, field water and fertilizer management practices, and so on.

Rice grain yield, GWP, and Y_{GWP}

During the main rice seasons, rice grain yield for ISR was in the range 8.54−9.08 t ha^{-1}, which was 5.8% higher than that of TSR in 2016 though yields from the two systems were was almost the same as one another in 2017 (Table 5). For RR, the grain yield was 1.10−1.89 t ha^{-1}, resulting in a total yield for ISR + RR 19%−22% higher than that of TSR. In addition, the contribution of RR to total yield of ISR + RR was 11%−18%. However, field experiments in Hubei Province, China (Dong *et al*. 2017) showed that rice grain yield for RR ranged from 4.05 to 5.83 t ha^{-1} (or 32%−37% of the annual total), which was much higher than the values obtained in the present study. Therefore, combinations of suitable rice varieties and the best related management practices should be investigated in this region in the future.

Table 5. Measurements of CH_4 (kg ha^{-1}) and N_2O (kg N ha^{-1}) emissions, GWP (t CO_2-eq ha^{-1}), yield (t ha^{-1}), and Y_{GWP} (t CO_2-eq t^{-1} yield) during rice seasons in 2016−2017

Year	Treatment	CH_4			N_2O			Yield			Total	Total
		MS	RS	Total	MS	RS	Total	MS	RS	Total	GWP*	Y_{GWP}
2016	TSR	275	–	275	2.17	–	2.17	8.58	–	8.58	10.4	1.21
	ISR + RR	276	30.4	306	1.38	0.16	1.54	9.08	1.10	10.2	11.1	1.09
2017	TSR	89	–	89	1.62	–	1.62	8.52	–	8.52	3.8	0.45
	ISR + RR	95	8.4	103	3.28	2.35	5.63	8.54	1.89	10.4	6.1	0.59

*GWP = [34 × CH_4] + [298 × N_2O]; MS: main rice season, RS: ratoon rice season

Total GWP for ISR + RR was 6.1−11.1 t CO_2-eq ha^{-1}, which was 7%−62% higher than that of TSR (Table 5). This increase was mainly attributed to the much longer growth duration with far heavier N fertilization for ISR + RR (Song *et al*. accepted). Taking grain yield and GWP together for consideration, no significant difference in total Y_{GWP} was observed between TSR and ISR + RR. The results indicate that the cultivation of RR not only largely increased grain yields, but also increased GWP, thus having a slight effect on Y_{GWP} when shifting TSR into ISR + RR as a whole. To ensure national and global food securities in future, RR will attract much attention in rice agriculture. Consequently, the study of GHG emissions from RR fields may become a major challenge, especially with increasing climate change that will further accelerate water scarcity in rice-based cropping systems in future.

Table 6. Evaluation of the average net profit by cultivation of ratoon rice under PM conditions over the rice seasons in 2016–2017

Option	Yield gain (CNY ha^{-1})	Input cost (CNY ha^{-1})	Labor cost (CNY ha^{-1})	GWP cost (CNY ha^{-1})	Net profit (CNY ha^{-1})
ISR + RR	6064	592	3867	156	1450

Note: Net profit = Yield gain – [Input cost + Labor cost + GWP cost]; Yield gain = grain yield × price; for detailed information about the calculation and real-time prices, please refer to Zhang *et al.* (2018)

Net profit

Compared with TSR, ISR + RR significantly increased net profit by 1450 CNY ha^{-1} though the costs of input, labor, and GWP were greatly increased. The increased net profit arose because the yield gain was much greater than the negative effects on costs, which completely offset these increased costs (i.e., input, labor, and GWP) which in turn led to a positive effect on economic income (Table 6). It is a matter of fact that ISR + RR can not only achieve more rice production relative to TSR but also save substantially in terms of labor and irrigation water input as compared to the double-rice cropping system (Munda *et al*. 2009). In addition, the rice quality is better in the RR season than in the main rice season (Liu *et al*. 2002), which results in the unit price paid for RR being much higher than that for TSR and ISR. There is no doubt that the RR system is a good method to increase food production in areas where the period of favorable temperature for rice production is too short for double rice but too long for single rice, and where labor scarcities or water shortages constrain crop establishment.

CONCLUSION

In view of practical problems concerning the reduction in grain yields and economic incomes arising from frequent droughts, water shortages, or low temperatures in early spring in the hilly regions of southwestern China, the application of PM demonstrated significantly reduced CH_4 emissions and GWP relative to winter-flooded paddy fields. In addition, the preservation of soil heat and moisture was also achieved by PM, resulting in high and stable crop yields, Y_{GWP} mitigations, and enhanced benefits. Under PM conditions, CP addition was found to further decrease Y_{GWP} and increase net profit. More importantly, the cultivation of RR in this region became available with the application of PM, and, as a result, both rice grain yield and net profit were significantly increased. The findings suggest that PM, particularly with CP addition, is an effective strategy to reduce environmental costs and increase economic benefits in rice-based cropping systems, which are limited by water shortage, and further indicate that RR should be looked at as an opportunity and potential solution to climate change and food security issues in the future.

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