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Achieving low methane and nitrous oxide emissions with high economic incomes in a rice-based cropping system

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ABSTRACT

Rice cultivation faces increasing challenges to enhance the net ecosystem economic budget (NEEB), which is the balance between economic benefits and environmental costs. Plastic film mulching cultivation (MC) was evaluated for its ability to decrease the global warming potential (GWP) while increasing economic benefits relative to rainfed (RF) and traditional irrigation (TI). To comprehensively assess the effect on NEEB, the CH_4 and N_2O emissions and grain yields in a rice-based cropping system were measured from 2010 to 2014. The effects of urease and nitrification inhibitors (UNIs) and controlled release fertilizer (CRF) were also estimated. Shifting the field management from RF to MC had unclear impact on CH_4 emissions, but increased N_2O emissions by 77%. In contrast, switching TI to MC caused a significant reduction (45–85%) in CH_4 emissions, producing a strong decrease in GWP, although N_2O emissions substantially increased (206–1153%). The decrease in CH_4 emissions was attributed to the reduced dissolved organic carbon and CH_4 production, whereas the increase in N_2O emissions might have resulted from the higher NH_4^+ concentrations and more favorable soil water content. Integrated assessment showed that MC significantly enhanced NEEB by 6136–8362 CNY ha^{-1} y^{-1} relative to RF as the yields increased and input costs reduced. Although MC reduced the yields, the much lower input and GWP costs led to a substantial increase in NEEB (2607–5593 CNY ha^{-1} y^{-1}) relative to TI. Under MC conditions, applying UNIs and CRF obviously increased input costs though it always tended to enhance grain yields, thus decreasing NEEB by approximately 490–960 CNY ha^{-1} y^{-1}, except CP addition, which had a positive effect on NEEB. The results demonstrate that MC, particularly MC + CP, are effective management strategies to reduce the environmental costs and increase the economic benefits of rice fields suffering from a lack of water supply.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHGs). On a 100-year horizon, the global warming potential (GWP) of CH_4 and N_2O emissions ($CH_4 + N_2O$) is 28 and 265 times greater, respectively, than that of carbon dioxide (CO_2) (Myhre et al., 2013). Rice fields have been identified as one of the most important anthropogenic CH_4 sources (Chen et al., 2013; Yan et al., 2009). Nitrogen (N) fertilization and water management also cause substantial N_2O emissions from paddy fields (Cai et al., 1997; Hussain et al., 2015; Zou et al., 2005). The development of agricultural technologies and practices to enhance grain yields and mitigate GHG emissions is crucial for sustainable and productive rice-based systems to increase production to support the increasing population (Pittelkow et al., 2014; Zhang et al., 2013).

China is the largest rice producer in the world, contributing around 28% of the total production of rice globally (FAOSTAT, 2014). Water irrigation plays a fundamental role in rice cultivation, but the paddy fields of Southwest China and the North China Plain usually suffer from a lack of water supply if they are rainfed (RF) during the rice growing season (Kreye et al., 2007; Liu et al., 2003; Yao et al., 2014). It is anticipated that over half of the cultivated area (~1.1 million ha) in Sichuan Province, Southwest China, lacks sufficient water for irrigation (Lv, 2009), and about 15–20 million ha of paddy fields globally will face water shortages by 2025 (Bouman, 2007; Liu et al., 2013). Furthermore, climate change may accelerate future flash droughts in the coming decades (Meehl and Tebaldi, 2004; Wang et al., 2016), which will undoubtedly affect food security (Lesk et al., 2016). To increase grain yields, paddy fields are occasionally forced to waterlog by rain water before rice transplanting and traditionally irrigated (TI) by

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pumping water during the rice growing season (Lv, 2009). Although yields are greatly improved, the cost of TI is high relative to RF, making the technique difficult to adopt widely.

Under these pressures, the plastic film mulching cultivation (MC) method was developed to increase or maintain grain yields, and represents a promising technology to tackle the issues in many regions of China (Liang et al., 2000; Liu et al., 2005, 2003). This technology is also referred to as the "ground cover rice production system" and has been widely applied on the North China Plain (Kreye et al., 2007; Tao et al., 2006) and in central China (Liu et al., 2013; Qu et al., 2012; Yao et al., 2014). However, these studies mainly considered the effect on crop production, and the results show that MC improves N recovery and water use efficiency, inhibits weed growth, and increases soil temperature (Kreye et al., 2007; Liang et al., 2000; Liu et al., 2005). The technology has also been shown to reduce CH_4 emissions but stimulate N_2O emissions from paddy fields during the rice growing season (Yao et al., 2014). Nevertheless, under MC conditions, research on GWP based on both CH_4 and N_2O emissions remains limited.

The addition of urease and nitrification inhibitors (UNIs) such as hydroquinone (HQ), dicyandiamide (DCD) and chlorinated pyridine (CP) with N fertilizer during the rice growing season has been suggested to mitigate N_2O emissions under MC conditions. Many studies have shown that the application of UNIs is an effective method to reduce N_2O emissions (Li et al., 2009a, 2009b; Xu et al., 2002). Controlled release fertilizer (CRF) is also widely used during the rice growing season and has been shown to be a useful option for mitigating N_2O emissions from paddy fields (Abao et al., 2000). Based on a four-year field experiment, Ji et al. (2013) found that applying CRF increased rice grain yields whilst at the same time decreasing N_2O emissions by ~15% relative to urea application. However, the responses of CH_4 emissions to UNIs and CRF applications remain uncertain (Ji et al., 2014). Multi-year field studies examining the effects of UNIs and CRF on GWP with MC are therefore required to evaluate the mitigation benefit of the MC approach.

Besides GHGs emissions, GWP and grain yields, the net ecosystem economic budget (NEEB), which is the balance between the economic benefits (yield gains and input costs) and the environmental costs (GWP costs), should be examined in detail for rice cultivation. In one study that examined a rice-based cropping system in China, the grain yields and net ecosystem GHGs exchanges were reported with two different fertilizers (N and chicken manure) under TI and MC conditions (Yao et al., 2014). Meanwhile, at the national scale, the production of higher rice yields with lower environmental costs was investigated within the 57 main agro-ecological areas of China using integrated soil–crop system management (Chen et al., 2014). However, the effects of MC alone, as well as MC together with UNIs and CRF applications, on NEEB, remain poorly understood. We hypothesized that (1) the NEEB of MC will be significantly greater than that of RF, as its grain yields are much higher; (2) the NEEB of MC will be considerably larger than that of TI, because MC may significantly decrease both the input and GWP costs; and (3) compared with MC, the addition of UNIs and the adoption of CRF possibly further enhance NEEB as a result of the increased grain yields and decreased GWP costs.

Accordingly, in this study, a five-year field experiment was conducted in a rice-based cropping system in Sichuan Province, Southwest China. The CH_4 and N_2O emissions, CH_4 production potential, soil dissolved organic carbon (DOC), soil microbial nitrogen (MBN) and carbon (MBC) contents, NH_4^+ concentration, rice grain yields and number of rice tillers, and climatic factors (e.g. rainfall and air temperature), were simultaneously measured during the rice growing season. The objectives of the study were to: (1) investigate the effects of MC and the addition of UNIs (HQ, DCD and CP) and CRF (thermoplastic resin-coated urea) on CH_4 and N_2O emissions and the corresponding GWP; (2) estimate the effect of these agricultural practices on the NEEB; and (3) recommend the optimal field management strategy to reduce the GWP and simultaneously maximize the economic benefits of paddy fields under water-deficient conditions.

2. Material and methods

2.1. Site description and experimental design

The field experiment was conducted at Ziyang City, Sichuan Province, China (30°05′N, 104°34′E), from 2010 to 2014. Experimental plots were established at two sites (Site 1 and Site 2) on the farm at the Soil Fertilizer Experiment Station in Ziyang. The soil parent material is purple shale and the soil properties at Site 1 are as follows: initial pH of 8.2; total N of 0.19%; total carbon (C) of 3.0%. At Site 2, the initial pH, total N and total C were 8.2, 0.17% and 3.4%, respectively.

Climate information, including precipitation and temperature, was provided by the weather station of the Experiment Station. Annual precipitation was about 700–950 mm in 2010–2014, with 63–77% occurring during the rice growing season and 35–50% was from July and August (Fig. S1a and b). The mean annual air temperature was stable over the five years, with values of 17.6–18.8 °C (Fig. S1c). Mean soil temperature ranged from 23.3 °C to 23.6 °C, 22.2 °C to 24.0 °C and 23.8 °C to 26.1 °C for RF, TI and MC, respectively. It was higher for MC than RF and TI by 1.5 °C and 2.0 °C, respectively (Fig. S1d).

Four treatments were established at Site 1 during the rice seasons from 2010 to 2011: RF, TI and two different MC treatments. Each of the MC plots were prepared with four raised ridges (5 × 1.45 m) and mulched with transparent plastic film (0.004 mm). In half of the MC plots, we added UNIs (HQ and DCD) together with N fertilizer (referred to as MC + HQ/DCD). There were six treatments at Site 2 during the rice seasons of 2012–2014: RF, TI, and four different MC treatments. These MC treatments were MC only, or they received UNIs (DCD or CP) with urea fertilization or CRF (referred to as MC + DCD, MC + CP and MC + CRF, respectively). All treatments in the two experimental sites were performed with four replicates and laid out in a randomized block design.

For all MC treatments (MC, MC + DCD, MC + HQ/DCD, MC + CP and MC + CRF), the raised ridges were surrounded by ditches (0.16 m wide and 0.15 m deep) that were waterlogged throughout the entire rice growing season. In contrast, the soil on the ridges was kept continually moist, without standing water, by irrigation in the ditches. After the rice harvest, rice residues were completely removed and all experimental plots were kept fallow during the winter period. In the winter fallow seasons of 2010–2014, Sites 1 and 2 were all drained well, except in the 2011 winter fallow season because of heavy rainfall and associated poor drainage. The local farmers collected the plastic film from all the MC plots and plowed all the experimental fields before rice transplantation in the following rice season.

Urea (150 kg N ha^{-1}) was applied in the RF and TI treatments at 50% as basal fertilizer and 50% as tillering fertilizer. For all MC treatments, urea or CRF was applied at a rate of 150 kg N ha^{-1} on the ridges as single basal fertilizer, and then the plastic film was positioned. For all treatments, 90 kg ha^{-1} of KCl, 15 kg ha^{-1} of $ZnSO_4 \cdot H_2O$ and 600 kg ha^{-1} of $Ca(H_2PO_4)_2$ were applied together with urea as basal fertilizer. Rice (*Oryza sativa L.*) was transplanted at the third to fourth leaf stage, using the triangular sparse planting technique, in all MC treatments (18 hills m^{-2}), whereas the RF and TI treatments (24 hills m^{-2}) were cultivated conventionally (Lv et al., 2009). Further details of the field management and application of the UNIs and CRF are given in Table S1.

2.2. Field sampling and measurements

The CH_4 and N_2O emissions were simultaneously measured using the static chamber method (Zhang et al., 2016a). The chamber (0.4 × 0.4 × 1.3 m) was stainless steel, and stainless-steel bases supporting the chamber were permanently installed before the experiment and remained in place until the study finished. For the RF and TI