



# Effects of rice straw mulching on N<sub>2</sub>O emissions and maize productivity in a rain-fed upland

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## Abstract

In the hilly areas of southern China, uplands and paddies are located adjacent to each other. Using rice straw as mulch for upland soil may improve crop production and partially replace chemical fertilizers, which may mitigate N<sub>2</sub>O emissions. A field experiment was conducted to investigate the potential of rice straw mulching for mitigating N<sub>2</sub>O emissions and increasing crop production. The treatments included no mulching (CK), 5000 kg ha<sup>-1</sup> of straw mulching (SM5), and 10,000 kg ha<sup>-1</sup> of straw mulching (SM10). Moreover, all the treatments received equivalent amounts of nitrogen, phosphorus, and potassium from chemical fertilizers plus rice straw. Relative to CK, cumulative N<sub>2</sub>O emissions decreased by 23.1 and 33.5% with SM5 and SM10, respectively. Significant positive correlations were observed between N<sub>2</sub>O fluxes and soil water-filled pore space (WPFS) ( $r^2 = 0.495$ ,  $P < 0.05$ ) and between seasonal cumulative N<sub>2</sub>O fluxes and the chemical N fertilization rate ( $r^2 = 0.814$ ,  $P < 0.05$ ). These findings indicate that soil WPFS was the key environmental factor in N<sub>2</sub>O emissions and that the substitution of chemical nitrogen fertilizer with rice straw was the main driver of N<sub>2</sub>O mitigation. Relative to CK, the maize yield increased by 16.5 and 29.6% with SM5 and SM10, respectively, which can be attributed primarily to the increases in soil moisture. The chemical fertilizer input could be decreased and N<sub>2</sub>O emissions could be mitigated through straw mulching, while achieving improved crop yield. This management strategy has great potential, and this study provides an important reference for low-carbon agriculture.

**Keywords** Straw retention · Greenhouse gas · Low-carbon agriculture · Soil moisture

## Introduction

The warming of global climate is an irrefutable fact. N<sub>2</sub>O is one of the long-lasting greenhouse gases that contribute to the depletion of the ozone layer in the stratosphere (Ravishankara et al. 2009). On an equivalent mass basis, the global warming potential of N<sub>2</sub>O is 298 times that of CO<sub>2</sub> in a 100-year time span (Myhre et al. 2013). By 2015, the global atmospheric concentration of N<sub>2</sub>O had increased to 328 ppbv from a pre-industrial value of approximately 270 ppbv (WMO 2016), and

N<sub>2</sub>O has contributed to about 6% of the annual increase in radiative forcing (WMO 2016).

As for anthropogenic N<sub>2</sub>O emissions, 1.7 to 4.8 Tg N<sub>2</sub>O-N year<sup>-1</sup> came from agriculture with the application of nitrogenous fertilizers and 0.8 to 4.1 Tg N<sub>2</sub>O-N year<sup>-1</sup> from other sectors (Ciais et al. 2013). The atmospheric abundance of N<sub>2</sub>O has been on the rise mainly as a result of agricultural intensification to meet food demand for the growing population (Ciais et al. 2013). China provides food for 19% (1.41 billion) of the world's population through agriculture using only 7.5% (106 M ha) of the world's arable land area (FAOSTAT 2017). As such, a high rate of fertilizer application appears to be inevitable to national food security. China is the largest consumer of synthetic N in the world (approximately one third of the world's annual consumption), resulting in significant N<sub>2</sub>O emissions (Galloway et al. 2008; Zou et al. 2010). Upland croplands contributed most to national annual N<sub>2</sub>O emissions, accounting for 79% in 1980 and 92% in 2000 (Zou et al. 2010). Therefore, practices that reduce N<sub>2</sub>O emissions while ensuring high-yield crop production are needed.

Uplands and paddies are located adjacent to each other in hilly areas of southern China. Both are vital to food production

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owing to relatively rich water resources and sunshine. However, large amounts of CH<sub>4</sub> emissions are released in paddy fields, especially when straw is returned for nutrient cycling (Zhang et al. 2011), which is common because straw-burning practices are forbidden. Increasing straw biomass makes it impossible to return all of the straw to the soil because such an increase would hinder land preparation and seedling growth. Moreover, rain-fed uplands lack soil organic carbon (SOC) and nutrients, and are prone to droughts in dry seasons. Global climate change has exacerbated this problem, with more frequent occurrence of extreme heat and drought events (Bates et al. 2008). An effective response to climate change should include both mitigation and adaptation. To this end, transferring the surplus rice straw from paddy to upland agroecosystems is an effective practice for improving the soil organic matter, fertility, and moisture of upland soils and reducing CH<sub>4</sub> emissions from paddy fields (Liu et al. 2014b; Zhu et al. 2010). Moreover, the application of rice straw can potentially reduce the use of chemical fertilizers, which, in turn, may reduce N<sub>2</sub>O emissions. To evaluate the efficiency of this practice in mitigating N<sub>2</sub>O and enhancing crop yield, a field experiment was conducted using rice straw as a substitute for chemical fertilizers in the hilly areas of southern China.

## Materials and methods

### Experimental site

The experimental site (28° 55' N, 111° 27' E; altitude 92.2–125.3 m) was located in a hilly area in subtropical China. The region is characterized by a subtropical humid monsoon climate, with an average annual air temperature of 16.5 °C, precipitation of 1448 mm, sunshine of 1513 h, and a frost-free period of 283 days. The soil was developed on quaternary red clay earth. The soil texture is classified as silt clay loam with 34% of clay, 55% of silt, and 11% of sand.

### Field experiment

The present study was based on a long-term field experiment that has been established since 2006 at the Taoyuan Agro-Ecological Experimental Station. It is a randomized block experiment with three replications. Each field plot was 5.1 m × 9.1 m in size. The treatments included (i) no straw mulching with a full dose of chemical fertilizer (CK), (ii) 5000 kg ha<sup>-1</sup> of straw mulching combined with partial chemical fertilizer (SM5), and (iii) 10,000 kg ha<sup>-1</sup> of straw mulching combined with partial chemical fertilizer (SM10). The mulching straw was incorporated into soil by tillage for the next crop. All the treatments received equivalent amounts of nitrogen (N, 240 kg ha<sup>-1</sup>), phosphorus (P, 52.4 kg ha<sup>-1</sup>),

and potassium (K, 286.4 kg ha<sup>-1</sup>) from chemical fertilizers plus rice straw. The applied chemical fertilizers were in the form of urea, superphosphate, and potassium chloride, which contained 46.0% of N, 5.24% of P, and 49.8% of K, respectively. The rice straw contained 38.8% of C, 0.86% of N, 0.06% of P, and 1.91% of K. C:N ratio of the rice straw was approximately 45:1. The SM5 treatment received 196.8 kg ha<sup>-1</sup> of N, 49.6 kg ha<sup>-1</sup> of P, and 191.0 kg ha<sup>-1</sup> of K from chemical fertilizers. The SM10 treatment received 153.5 kg ha<sup>-1</sup> of N, 46.7 kg ha<sup>-1</sup> of P, and 95.5 kg ha<sup>-1</sup> of K from chemical fertilizers. Urea was applied in three splits, 30% as a basal fertilizer when sowing, 20% as a sixth-leaf stage fertilizer, and 50% as a tenth-leaf stage fertilizer. The superphosphate and potassium chloride were applied as basal fertilizers. The sixth-leaf and tenth-leaf stage fertilizers were top-dressed. The basal fertilizer was drill-fertilized to 8–10 cm in depth during seeding, and the topdressing was surface-fertilized. Local maize varieties were used in the long-term experiment. Generally, maize was sowed around the end of May and harvested around the middle of September. Weeds were manually weeded with a hoe. A 3% concentration of carbofuran was used for pest control at the trumpet stage. In 2015, maize was sowed on May 23 at a density of 56 cm × 36 cm and harvested on September 14, and the sixth-leaf stage fertilizers, straw mulching, and tenth-leaf stage fertilizers were applied on June 21, July 1, and July 24, respectively. There was no irrigation throughout the experimental period. Soil samples were collected from three replicated plots for each treatment in April 2015. Twelve soil cores were taken from the upper layer (0–20 cm) of each plot and mixed thoroughly. Soil properties are presented in Table 1. SOC was determined by dichromate oxidation, total N by the Kjeldahl method, total P by NaOH fusion and colorimetric determination, total K by NaOH fusion-flame photometry, and available N by alkali-hydrolytic diffusion. Available P was extracted with 0.03 M NH<sub>4</sub>F–0.025 M HCl and determined by the Mo-Sb colorimetry method. Available K was extracted with 1.0 M ammonium acetate (pH 7.0) and determined by flame photometry. Soil pH was determined in 1:2.5 (w/v) soil to water ratio extracts.

### Measurement of N<sub>2</sub>O fluxes

N<sub>2</sub>O samples were collected using a static closed-chamber method generally every 6 to 8 days from May 17 to October 8, 2015. In addition, N<sub>2</sub>O samples were collected 1, 4, and 7 days after fertilization, respectively. The sampling chamber (60 cm wide × 60 cm long × 100 cm high) was made of sandwich foam plates that could minimize changes in air temperature inside the chamber during sampling. The air temperature inside the chamber was monitored during gas collection. A 12-V fan was installed inside the chamber for mixing the gas. In each plot, a chamber-base collar (60 cm wide × 60 cm long) made of a polyvinyl chloride plate was fixed in

**Table 1** General soil (0–20 cm) properties under different treatments in 2015

Treatment	SOC (g kg <sup>-1</sup> )	Total N (g kg <sup>-1</sup> )	Total P (g kg <sup>-1</sup> )	Total K (g kg <sup>-1</sup> )	Available N (mg kg <sup>-1</sup> )	Available P (mg kg <sup>-1</sup> )	Available K (mg kg <sup>-1</sup> )	pH
CK	10.7 ± 0.3	1.15 ± 0.05	0.716 ± 0.010	13.4 ± 0.2	65.4 ± 1.8	15.9 ± 0.8	236 ± 4	5.9
SM5	11.2 ± 0.6	1.23 ± 0.07	0.712 ± 0.052	13.9 ± 0.2	67.1 ± 1.9	16.1 ± 0.6	239 ± 3	5.9
SM10	11.5 ± 0.5	1.28 ± 0.10	0.707 ± 0.032	13.7 ± 0.2	67.8 ± 1.5	16.1 ± 0.5	243 ± 3	5.9

Mean ± standard error. CK, SM5, and SM10 mean 0, 5000, and 10,000 kg ha<sup>-1</sup> of straw mulching, respectively. All the treatments received equal amounts of nitrogen (N), phosphorus (P), and potassium (K) from chemical fertilizers plus rice straw. SOC means soil organic carbon

the soil at a depth of 15 cm and kept there throughout the experiment. Gas samples were taken between 9:20 and 10:40 a.m. Gas samples of approximately 30 mL were transferred from the chambers to pre-evacuated vials using a syringe at 0, 15, 30, 45, and 60 min for calculating the N<sub>2</sub>O change rate. The concentrations of N<sub>2</sub>O were analyzed using a gas chromatograph (Agilent 7890A, Agilent Technologies, USA). N<sub>2</sub>O fluxes were calculated according to the linear change in N<sub>2</sub>O concentrations with the sampling time, chamber headspace height, air pressure, and air temperature within the corresponding chambers (Zheng et al. 2008). N<sub>2</sub>O emissions were sequentially accumulated from the emissions between every two adjacent sets of measurements (Zou et al. 2005).

### Measurement of other data

Maize yields were harvested by hand for each plot. The maize yields from the past 3 years (2013–2015) were used in the present study. Soil temperature and moisture were monitored simultaneously during the collection of the gas samples. Soil temperature at 5 cm was measured using a mercury thermometer. Soil samples for moisture determination at 5 cm were taken from each plot using a 4-cm-diameter gage auger. The soil samples were oven-dried at 105 °C for about 24 h to a consistent weight for determining the gravimetric soil water content, and the soil water-filled pore space (WFPS) was subsequently calculated according to the methods described in Wang et al. (2016). Soil bulk density was measured using a 100-cm<sup>3</sup> cylinder. Daily precipitation, air pressure, and air temperature data were acquired from the meteorological station at the Taoyuan Agro-Ecological Experimental Station.

### Statistical analyses

Statistical analyses were performed with SPSS 17.0 (SPSS, Inc., USA). The statistically significant differences between different treatments were tested by Tukey test at the 5% level using one-way analysis of variance (ANOVA). The correlation analyses were performed using Pearson correlation analysis.

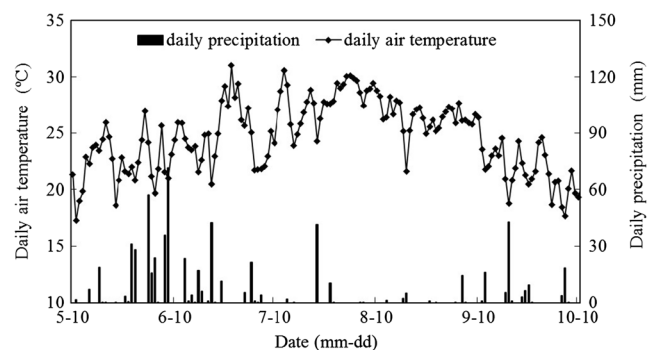
## Results

### Environmental and soil conditions

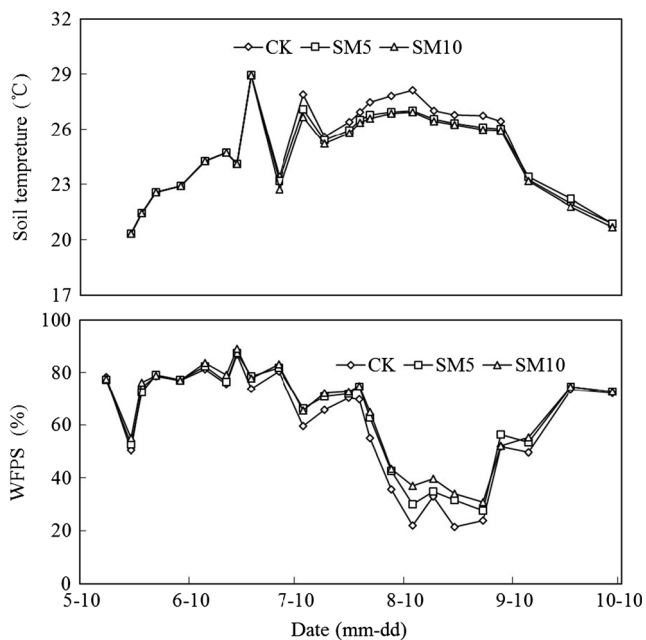
Plots of daily precipitation and air temperatures, as well as soil moisture (WFPS) and temperature, are shown in Figs. 1 and 2. The total precipitation during the maize season (May 23–September 14) was 501 mm, 72% of which occurred in the first month of the season. The air temperature during the maize season ranged from 20.8 to 31.0 °C (with an average of 25.4 °C). Higher air temperatures were reported during the middle of the season. The soil moisture content fluctuated with precipitation. The WFPS in the top 5-cm layer of soil ranged from 50 to 89% in the early season owing to greater precipitation. Drought persisted from August to September owing to high temperatures and rare precipitation, leading to a decrease in WFPS to 21%. There were only 10 mm of precipitation in August and 30 mm in the first half of September. Relative to CK, straw mulching (SM5 and SM10) decreased the water loss from evaporation, thus maintaining relatively greater soil WFPS. Soil temperatures ranged from 20.3 to 29.0 °C, showing similar trends to air temperatures. The soil temperature decreased by 0.2–1.2 °C under the straw mulch. Furthermore, relative to CK, SM5 and SM10 decreased the soil temperature from July 5 to September 6 by an average of 0.57 and 0.74 °C, respectively.

### Maize production

The maize yields under different treatments from 2013 to 2015 are shown in Fig. 3. Maize yield ranged from



**Fig. 1** Dynamics of daily precipitation and air temperature in 2015

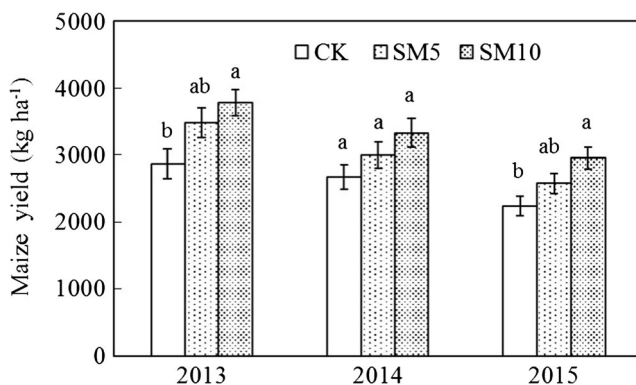


**Fig. 2** Soil temperature at 5-cm depth and soil water-filled pore space (WFPS, %) in the top 5 cm of the soil profile under different treatments in 2015. See Table 1 for descriptions of CK, SM5, and SM10

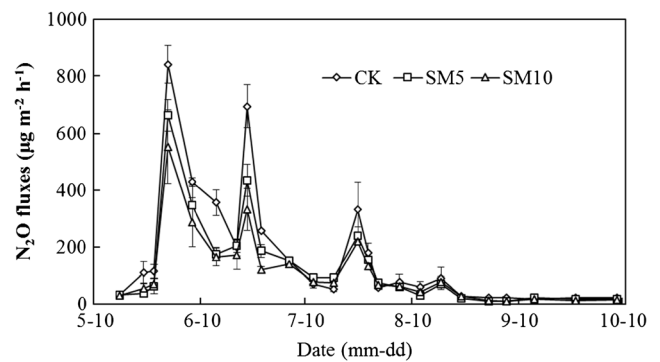
2239 kg ha<sup>-1</sup> with CK in 2015 to 3791 kg ha<sup>-1</sup> with SM10 in 2013. The maize yield was the highest for SM10, followed by SM5 and CK. From 2013 to 2015, average maize yields increased by 16.5 and 29.6% with SM5 and SM10, respectively, relative to CK (2952 kg ha<sup>-1</sup>).

### N<sub>2</sub>O fluxes and key factors

N<sub>2</sub>O fluxes varied greatly with the nitrogen fertilizer application and the course of the growing season (Fig. 4). Pulses in N<sub>2</sub>O emissions were observed following every nitrogen fertilizer application, with specific peaks approximately 1 week after basal fertilization and a couple of days after the topdressing application. Ranked from the highest to the lowest, peak



**Fig. 3** Maize yields under different treatments from 2013 to 2015. Different letters within the same year indicate significant difference ( $P < 0.05$ ) among the treatments. The bar accompanying each column indicates the range of standard error (SE) of the mean. See Table 1 for descriptions of CK, SM5, and SM10



**Fig. 4** Variation in N<sub>2</sub>O emissions under different treatments throughout the experimental period. The bar accompanying each point indicates the range of standard error (SE) of the mean. See Table 1 for descriptions of CK, SM5, and SM10

values occurred with basal fertilization, followed by sixth-leaf stage and then tenth-leaf stage fertilizations. High emissions persisted for approximately 2 weeks after basal and sixth-leaf stage fertilization and approximately 1 week after tenth-leaf stage fertilization. N<sub>2</sub>O fluxes tapered off during the last 5 weeks of the maize season but remained at a relatively low level 3 weeks after the maize harvest (around 20 µg m<sup>-2</sup> h<sup>-1</sup>).

N<sub>2</sub>O fluxes ranged from 10 to 840 µg m<sup>-2</sup> h<sup>-1</sup> among different treatments throughout the maize season, with average rates of 192, 148, and 128 µg m<sup>-2</sup> h<sup>-1</sup> for the CK, SM5, and SM10 plots, respectively. Straw mulching (accordingly less nitrogen fertilization) decreased N<sub>2</sub>O emissions, which were primarily released during N<sub>2</sub>O emission pulses. After these pulses, the difference in the N<sub>2</sub>O fluxes for all treatments was insignificant. Throughout the entire maize season, cumulative N<sub>2</sub>O fluxes from CK plots (5.21 ± 0.57 kg ha<sup>-1</sup>) were significantly higher than those from SM5 (4.00 ± 0.41 kg ha<sup>-1</sup>) and SM10 plots (3.46 ± 0.67 kg ha<sup>-1</sup>). Relative to CK, cumulative N<sub>2</sub>O fluxes decreased by 23.1 and 33.5% with SM5 and SM10, respectively.

No significant correlations were observed between N<sub>2</sub>O fluxes and the soil temperature ( $r^2 = 0.153$ ,  $P = 0.21$ ). Significant correlations were observed between N<sub>2</sub>O fluxes and WFPS ( $r^2 = 0.495$ ,  $P < 0.05$ ), indicating that soil WFPS was the key environmental factor in N<sub>2</sub>O emissions. Significant relationships were also found between cumulative N<sub>2</sub>O fluxes and chemical N fertilization rates ( $r^2 = 0.814$ ,  $P < 0.05$ ), suggesting that substituting chemical nitrogen fertilizers with rice straw was the main driver of N<sub>2</sub>O mitigation with straw mulching.

## Discussion

### Improved maize production under straw mulching strategy

To maintain high maize yields, farmers use high amounts of chemical fertilizers, focusing less on preserving soil moisture in rain-fed areas. This study showed that straw mulching



increased maize yield consistently for 3 years through both the SM5 and SM10 treatments. On average, maize yield increased by 16.5 and 29.6%, while chemical nitrogen applications dropped by 18.1 and 36.2% with SM5 and SM10, respectively. Straw mulching increased soil moisture, which was probably the main contributor to the improvement in maize yield in this study. Unlike plastic film mulching, which was previously found to increase soil temperature (Cuello et al. 2015; Liu et al. 2014a; Ramakrishna et al. 2006), straw mulching decreased soil temperature. This is favorable for crop growth and soil moisture retention during the summer season, which is accompanied by high temperatures. Additionally, soil organic matter increased with straw mulching (Table 1), which is in agreement with that of a field study conducted in the same region (Liu et al. 2014b). The improvement of soil organic matter in turn enhanced soil fertility.

### Decreased N<sub>2</sub>O emissions with straw mulching strategy

Global nitrogen fertilizer consumption is expected to increase, which is a growing environmental concern because such fertilizers are considered to be the dominant contributor to N<sub>2</sub>O emissions from agricultural soils. Many studies have shown that N<sub>2</sub>O fluxes increase with increasing N fertilization rate, especially immediately after fertilization (Chen et al. 2014; Hoben et al. 2011; McSwiney and Robertson 2005; Shcherbak et al. 2014). In the current study, N<sub>2</sub>O emissions could be decreased by transferring the surplus rice straw from paddy fields to the adjacent upland fields and decreasing N fertilization rates, while several peaks in N<sub>2</sub>O fluxes were observed only immediately after the application of N. We found a significant positive correlation between the cumulative N<sub>2</sub>O flux and the chemical N fertilization rate. On the other hand, a previous meta-analysis showed that straw mulching itself tends to increase N<sub>2</sub>O emissions (Shan and Yan 2013). Repeated addition of rice straw as organic matter in the present study has influenced soil properties. An increasing tendency of SOC and total N can be observed with increased addition of rice straw (Table 1), which may have exerted an influence on soil biological functions of the soil as well as N<sub>2</sub>O emission. In the current study, the reduction of N<sub>2</sub>O emissions was mainly ascribed to the partial substitution of urea with straw. The difference among the treatments with regard to N<sub>2</sub>O emissions primarily occurred during pulse emissions, which lasted 1 to 2 weeks after N application.

N<sub>2</sub>O is produced in soils essentially through the processes of nitrification and denitrification, which are closely related to soil moisture content (Granli and Bøckman 1994; Zaman et al. 2008). Significant positive correlations were observed between N<sub>2</sub>O emissions and soil WFPS in this study, and these are consistent with the findings of previous studies (Allen et al. 2010; Chen et al. 2014; Cuello et al. 2015; Migliorati

et al. 2014; Venterea and Coulter 2015; Wang et al. 2016). High N<sub>2</sub>O emissions primarily occurred following N application, coinciding with high soil moisture content. The fertilization rate at the tenth-leaf stage was higher than that at the sixth-leaf stage, but N<sub>2</sub>O emissions were lower, which may be attributable to the lower soil WFPS at the tenth-leaf stage. Owing to almost no precipitation at higher temperatures, a dry period emerged after topdressing at the tenth-leaf stage and lasted more than a month, causing a relatively small peak in N<sub>2</sub>O emissions after topdressing. Top-dress application is a general management practice after or during precipitation events; however, such a practice results in abundant N substrate and favorable soil moisture content for N<sub>2</sub>O production. High rainfall intensity may have caused leaching of mineral nitrogen, which is normally related to the amount of mineral N applied. Both gaseous N-losses and leaching of nitrate may play important roles for losses of N from the CK treatment, while a large part of N was retained in the organic N fraction in the SM5 and SM10 treatments.

The optimum temperature for N<sub>2</sub>O production in cultivated soils has been shown to range from 25 to 40 °C (Granli and Bøckman 1994). Some researchers have reported positive correlations between N<sub>2</sub>O emissions and soil temperature (Allen et al. 2010; Ding et al. 2007; Li et al. 2013; Liu et al. 2014a; Migliorati et al. 2014). In the current study, no such correlation was observed. This may be attributable to the high intensity of N<sub>2</sub>O emissions after N application when the soil temperature was relatively low (Fig. 2).

### Achieving low-carbon agriculture with ex situ application of rice straw in uplands

Straw retention is expected to increase soil fertility. However, paddies are an important source of CH<sub>4</sub> emissions, which could be greatly enhanced by straw retention. A 3-year field investigation conducted at the same experimental station as the current study demonstrated that straw retention increased CH<sub>4</sub> emissions by 380 kg ha<sup>-1</sup> year<sup>-1</sup> (Shang et al. 2011). At the same time, upland crop production in hilly areas is often limited by water shortage and low soil fertility. These disadvantages could be overcome by transferring rice straw to upland fields when paddies are adjacent to upland fields. In the current study, rice straw mulching not only increased upland crop yield, but also decreased the chemical fertilization rate and N<sub>2</sub>O emissions. A considerable amount of energy is required for the production, transportation, and application of chemical fertilizers. For example, about 6.38 and 0.73 kg of CO<sub>2</sub>-equivalent are estimated to be emitted in the production of 1 kg nitrogen and 1 kg phosphorous fertilizer, respectively (Lu et al. 2008; Dubey and Lal 2009). In the current study, N<sub>2</sub>O emissions were reduced by 1.21–1.75 kg ha<sup>-1</sup> season<sup>-1</sup>, which is equivalent to 361–522 kg ha<sup>-1</sup> season<sup>-1</sup> CO<sub>2</sub> emissions. Additionally, straw mulching has been reported to

suppress weed growth effectively (Ramakrishna et al. 2006), reducing herbicide and energy use. Similar to straw mulching, as reported by Cuello et al. (2015), plastic film mulching increased crop productivity by 8–33%, but plastic film mulching significantly decreased soil organic matter content and largely increased N<sub>2</sub>O emissions. These findings support the conclusion that straw mulching is an attractive and environmentally friendly option for achieving low-carbon agriculture.

## Conclusions

Uplands and paddies are the two most important adjacent agroecosystems in the hilly areas of southern China. However, uplands are constrained by low soil fertility and insufficient moisture, while paddy fields are associated with large amounts of CH<sub>4</sub> emissions with rice straw retention. Transferring rice straw to upland fields is an excellent “best of both worlds” strategy. This study demonstrated that rice straw mulching on upland soil improved soil fertility, moisture, and maize production and simultaneously reduced the chemical fertilization rate and N<sub>2</sub>O emissions. These results indicate that the transfer of rice straw to upland fields is an effective strategy towards achieving low-carbon agriculture, which could also be applicable to similar areas in the world.

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