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Response of nitrous oxide emission to soil mulching and nitrogen fertilization in semi-arid farmland

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ABSTRACT

Plastic film and gravel mulching have long been used to improve crop production, but few studies have focused on the effects of these mulching practices on nitrous oxide (N_2O) emissions. Understanding the response of N_2O emission to soil surface mulching is beneficial for improving management practices. We performed two field experiments over two years in northwestern China to measure the annual N_2O emissions using the static chamber technique: first, we compared the N_2O emissions from non-mulched (BP), gravel-mulched (GM) and plastic film-mulched (FM) maize (*Zea mays* L.) fields that received an equivalent nitrogen (N) application rate; second, we monitored the N_2O emissions from film-mulched maize fields that received different N application rates [N applied at 0 (N0), 250 (N250) and 380 (N380) kg N ha^{-1}]. Compared to the BP treatment, both the GM and FM treatments markedly improved the soil temperature and moisture, which significantly increased the maize yields and N uptake but did not increase the N_2O emissions, most likely because the decreased soil mineral N content limited the N_2O production. As a result, the yield-scaled N_2O emissions were markedly reduced in the GM and FM treatments, and a greater reduction was observed in the FM treatment due to the higher grain yield. The N_2O emissions persistently increased with an increasing N rate, but the grain yield peaked in the N250 treatment in which the N input was nearly equivalent to the maize N uptake. Consequently, low yield-scaled N_2O emissions were obtained in the N250 treatment (125 and 155 g N_2O–N Mg^{-1} grain in 2011–2012 and 2012–2013, respectively). Thus, we conclude that film mulching combined with an appropriate N input is a preferable management practice to improve the grain yield and to simultaneously minimize the direct N_2O emission intensity in agriculture.

1. Introduction

Mulching soil with natural or artificial materials is a common management practice in worldwide agriculture. As an important traditional technique, gravel has been used as mulch to cultivate crops for many years (Hanks and Woodruff, 1958). Particularly in developing countries, gravel is a preferred material due to its availability and low cost (Yamanaka et al., 2004). In addition, plastic film, an artificial material, has also long been used (Adams, 1967). Numerous studies have reported that these mulching practices can reduce the soil evaporation, increase the soil moisture and temperature (Adams, 1970; Mahrer et al., 1984; Kemper et al., 1994), and improve the soil nutrient availability (Li et al., 2004), thus greatly promoting crop growth and development. Moreover, soil surface mulching can also prevent seed germination or physically suppress the seedling emergence of weeds (Bond and Grundy, 2001) and inhibit soil-borne pathogens (Katan, 2000). Given these positive effects, the application of gravel and plastic film mulching has broadened in recent years (Sharma et al., 2011; Wang et al., 2011; Berger et al., 2013; Gan et al., 2013; Ruidisch et al., 2013). However, few studies have focused on the effects of these mulching practices on the environment, including greenhouse gas emissions.

Nitrous oxide (N_2O) is a potent greenhouse gas (IPCC, 2007) primarily emitted from fertilized farmlands (Smith et al., 2003; Bateman and Baggs, 2005; Montzka et al., 2011). Studies have reported that N_2O emission is driven by the soil temperature and water content (Smith et al., 2003; Snyder et al., 2009). Thus, the N_2O emissions may be increased in gravel- and plastic film-mulched fields because these mulching practices generally improve the soil temperature and moisture. Nevertheless, yield increases resulting

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from mulching drive plant N absorption (Setiyono et al., 2010), resulting in a reduction in the soil mineral N content and most likely limiting the N_2O production (Barton et al., 2008). Few studies have investigated the effects of plastic film mulching on N_2O emission, and some of these studies have reported that N_2O emissions were increased under conditions of mulching (Arriaga et al., 2011; Nishimura et al., 2012), while other studies have reported opposite results (Berger et al., 2013). To improve our knowledge of the soil surface mulching effects on N_2O emissions and to optimize management practices, additional field measurements consisting of different mulching practices are required in various farming systems and areas.

In this study, we performed two field experiments over two years to measure the annual N_2O emissions from maize fields in a region in northwestern China. The first experiment aimed to investigate different mulching practices (gravel and plastic film mulching), and the second experiment aimed to examine the effects of different N application rates under film mulching conditions because this practice is more effective and popular (Gan et al., 2013). The objectives of this study were to (i) assess the effects of soil surface mulching and fertilization on N_2O emissions and (ii) to identify a preferable management practice to simultaneously obtain a high grain yield and low N_2O emission intensity.

2. Materials and methods

2.1. Site description

The field experiments were performed over two years (2011–2012 and 2012–2013) at the Changwu Agricultural and Ecological Experimental Station (35.28°N, 107.88°E, ca. 1200 m above sea level), which is located on the Loess Plateau of northwestern China. The annual mean air temperature is 9.2 °C, and the average annual rainfall is 582 mm, with 73% of the total amount of rain falling during the maize growth season. The main cropping system in this area includes harvesting one crop of maize or wheat per year. According to the Chinese Soil Taxonomy, the soils at this site are Cumuli-Ustic Isohumosols (Gong et al., 2007). The soil properties in the top 20 cm are as follows: bulk density 1.3 g cm^{-3}, pH 8.4, organic matter 16.4 g kg^{-1}, total N 1.05 g kg^{-1}, available phosphorus (Olsen-P) 20.7 mg kg^{-1}, available potassium (NH_4OAc-K) 133.1 mg kg^{-1}, and mineral N 28.8 mg kg^{-1}.

2.2. Field experiments and crop management

Two experiments were performed to measure the N_2O emissions. In the first experiment (Exp. 1), three different mulching practices were examined using the same N fertilizer application rate (225 kg N ha^{-1}): a bare plot without mulching (BP, Fig. 1A), gravel mulching (GM, Fig. 1B), and plastic film mulching (FM, Fig. 1C). In the second experiment (Exp. 2), three different N application rates under plastic film mulching conditions were examined: no N applied (N0), N fertilizer applied at a rate of 225 kg N ha^{-1} plus manure (cow dung) applied at rate of 25 kg N ha^{-1} (N250), and N fertilizer applied at rate of 380 kg N ha^{-1} (N380). Each treatment involved alternating wide (60 cm) and narrow (40 cm) row spacing. The mulching treatments were manually mulched with gravel (2–4 cm in size) or plastic film. Each experiment was arranged in a completely randomized block design with three replicates, and the plot size was 56 m^2 (7 m × 8 m).

In the two experiments, N fertilizer in the form of urea (N 46%) was applied three times for all of the N-fertilized treatments. Forty percent of the N fertilizer was manually distributed over the soil surface prior to sowing and then plowed into the subsurface as a basal dressing. Thirty percent of the N fertilizer was applied at the jointing stage, and the remaining thirty percent was applied at the silking stage using a hole-sowing machine following precipitation. For each plot, 40 kg P ha^{-1} in the form of calcium superphosphate (P_2O_5 12%) and 80 kg K ha^{-1} in the form of potassium sulfate (K_2O 45%) were applied together with the basal N fertilizer. Manure for the N250 treatment was also applied prior to planting.

A high-yielding maize hybrid (Pioneer 335) was selected for use in this study. The plant density in Exp. 1 was 65,000 plants ha^{-1}, which was comparable to the densities in most farmers' fields (Chen et al., 2009), and in Exp. 2, the plant density was 85,000 plants ha^{-1}, which was determined using the Hybrid-Maize model (Yang et al., 2004) with the aim of obtaining a high grain yield. In each year, the maize was planted at the end of April and harvested at the end of September. During the maize growth season, there was no irrigation, and the soil water supply was solely dependent on natural rainfall for all of the treatments.

2.3. Measurement of N_2O emissions

Annual N_2O emissions were measured using the static chamber technique. Stainless steel base frames (50, 50 and 15 cm in length, width and height, respectively) were installed in the soil to a depth of 15 cm prior to planting (each covering half of the wide and narrow row spacing). A water channel was located at the top of the frame to seal the top chamber airtight during the sampling period (see Fig. 1). The top chambers were 50 cm length × 50 cm width × 50 cm height, and two small fans were installed at opposite positions at the top of each chamber to evenly mix the air inside the chamber. To minimize the air temperature changes inside the chamber, each side of the chamber was covered with a Styrofoam coating. Two maize plants were placed in each chamber area and cut to 50 cm in height to fit the height of the chamber when their stalks grew too high (in early July), but this cutting would not significantly affect the total seasonal N_2O emissions (Gao et al., 2014).

The N_2O emissions were measured every four and fifteen days during the maize growing (MS) and fallow season (FS), respectively. After the fertilization and precipitation events, gas samples were collected daily for ten days and four days, respectively. On each sampling day, the gas samples were collected between 8:30 a.m. and 11:30 a.m. using 50 ml polypropylene syringes equipped with 3-way stopcocks at 0, 10, 20 and 30 min after the chambers were closed. For the FM treatment in Exp. 1, the N_2O emissions and soil variables were only measured in 2012–2013.

The gas samples were analyzed on the sampling day using gas chromatography (Agilent 7890A, Shanghai, China) equipped with an electronic capture detector (ECD). The carrier gas was pure N_2 (99.999%) at a flow rate of 21 ml min^{-1}. The temperatures for the ECD detector and column oven were 300 and 60 °C, respectively. The N_2O emission rate was calculated from the linear increase in the concentrations in the chamber during the sampling period, and the cumulative emissions were estimated using linear interpolation. The yield-scaled N_2O emissions were calculated by dividing the annual N_2O emission by the maize grain yield.

2.4. Environmental and soil variables

The daily precipitation was recorded from an automatic weather station that was located approximately 50 m from our experimental field.

The soil temperatures at the surface and at a depth of 10 cm and the air temperature inside the chambers were measured using portable digital thermometers (JM624, Jinming Instrument Ltd., Tianjin, China) at the first and fourth sampling. The mean of the two readings represented the temperature of the sampling day. In the following analysis, we used the mean temperature of the two soil layers to represent the soil temperature for each treatment.

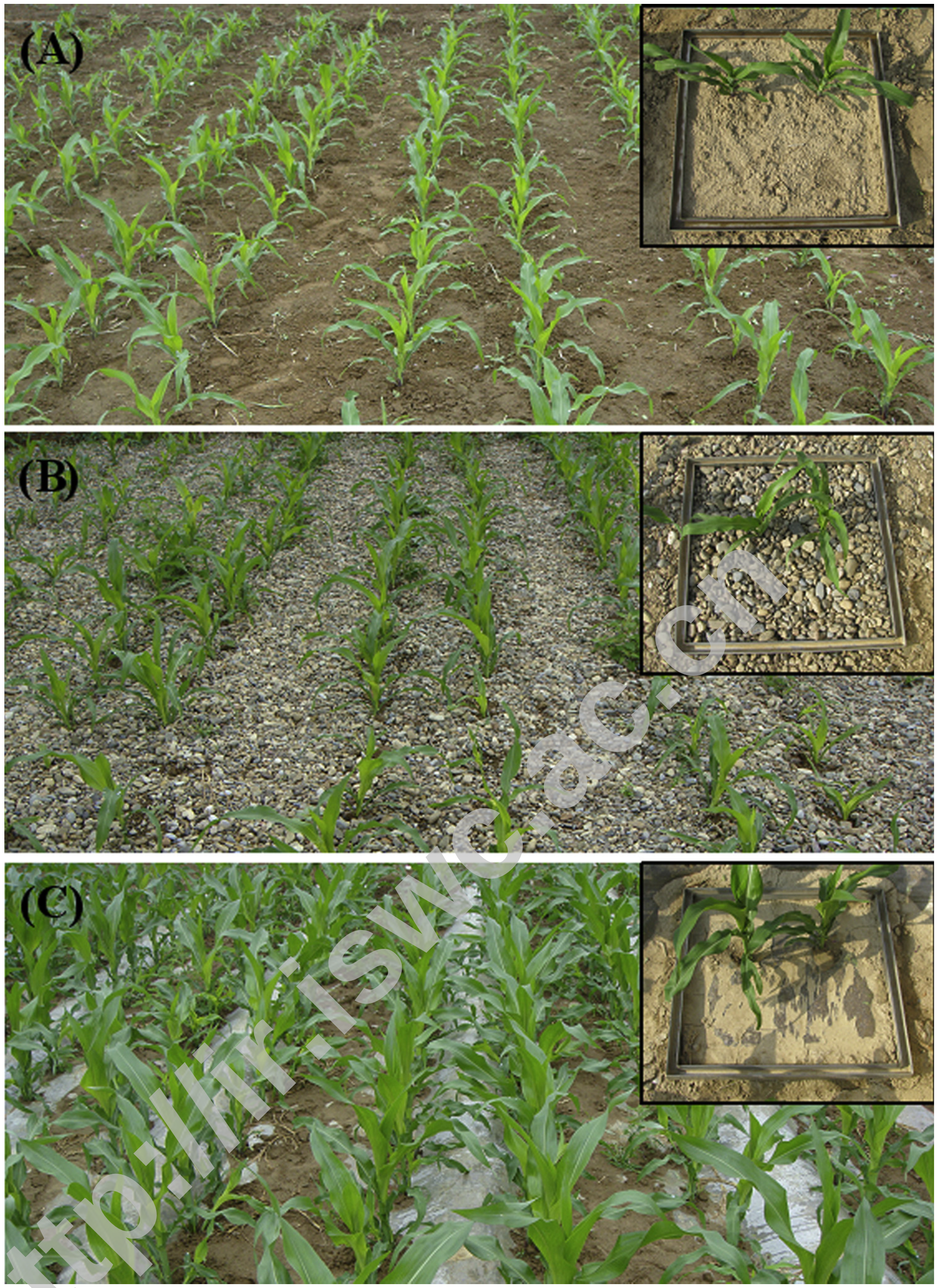

Fig. 1. Photographs showing a bare plot without mulching (A), gravel mulching (B) and plastic film mulching treatment (C).

Soil samples at a 0–20 cm depth were collected every eight and fifteen days during the MS and FS season, respectively. After the fertilization and precipitation events, the soil samples were collected once every two days within the ten days following fertilization and within the four days following precipitation. However, no soil sample was collected during the period of soil freezing (December to early March next year). On each sampling occasion, three sub-samples were taken randomly between the maize rows using a 4-cm-diameter soil auger and were then mixed into one sample for each plot. The samples were oven-dried at 105 °C for 24 h to a consistent weight to determine the gravimetric soil water content, and the soil water-filled pore space (WFPS) was subsequently calculated. To determine the soil NO_3^- and NH_4^+ content, representative fresh sub-samples (5 g) were extracted using 50 ml of a 1 mol L^{-1} KCl solution, and the extracts were analyzed using an automated flow injection analyzer (FLOWSYS, Italy).

2.5. Grain yield and aboveground N uptake

At harvest, a 10-m^2 (4 rows each 2.5 m long) area in each plot was manually harvested to determine the biomass and grain yield. The samples were dried to a constant weight at 80 °C to determine the yields and were then ground for N content analyses (micro-Kjeldahl). The grain yield was expressed at 15.5% moisture.

2.6. Statistical analyses

The means and standard deviations were calculated for all of the parameters. The differences between the treatments were analyzed

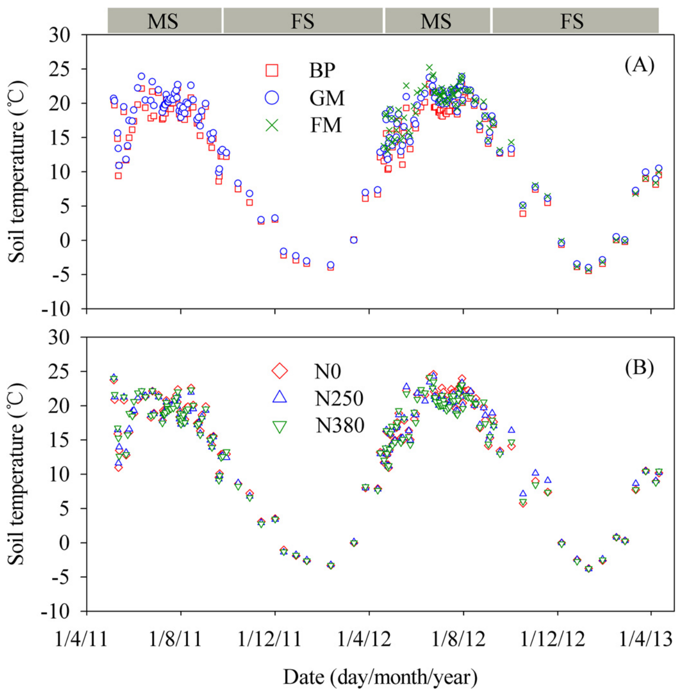

Fig. 2. The mean soil temperature of the surface and at a depth of 10 cm for the different mulching treatments (A) and N application rates (B). MS and FS denote the maize growing season and fallow season, respectively. BP, bare plot without mulching; GM, gravel mulching; FM, plastic film mulching; N0, no N applied; N250, N applied at 250 kg N ha^{-1}; N380, N applied at 380 kg N ha^{-1}.

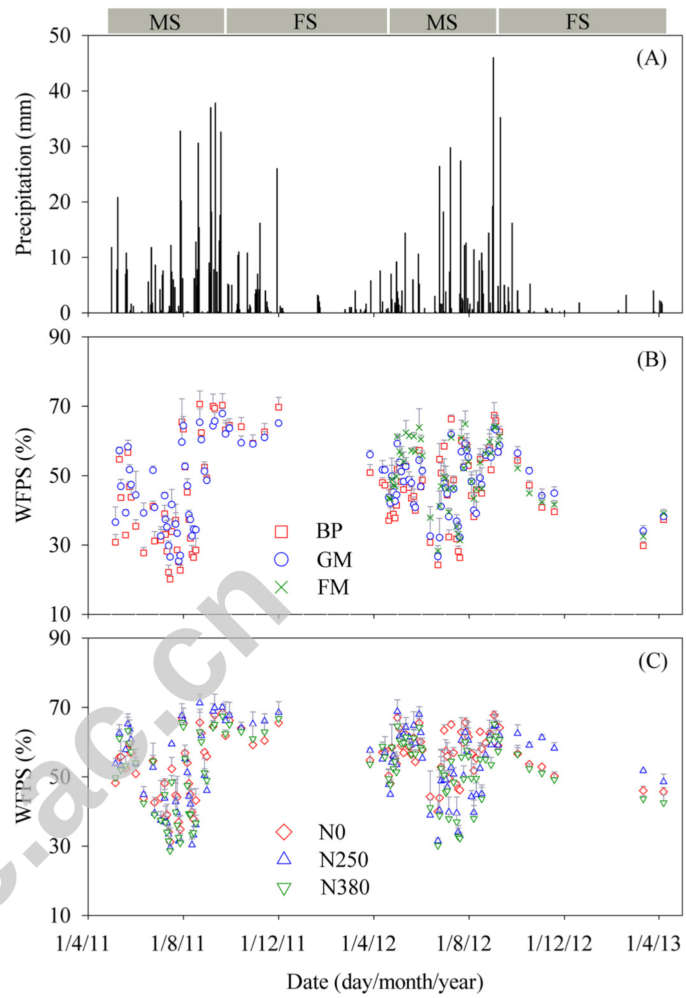

Fig. 3. Precipitation (A) and soil water-filled pore space (WFPS) in the top 20 cm for the different mulching treatments (B) and N application rates (C). The bars represent standard deviations of the means (n = 3). Definitions of the codes for the seasons and treatments are shown in the footnotes of Fig. 2.

using a one-way analysis of variance (ANOVA) and were considered significant at $P < 0.05$ compared to the least significant difference (LSD). The Pearson correlation analysis was performed to investigate the correlations between the N_2O emission and soil variables.

3. Results

3.1. Soil temperature, precipitation, WFPS and soil mineral N content

Both the GM and FM treatments increased the soil temperature (Fig. 2A). Compared to the BP treatment, the mean soil temperature increased by 0.9 and 1.1 °C, respectively, for the GM treatment in 2011–2012 and 2012–2013, and increased by 1.5 °C for the FM treatment in 2012–2013. Under plastic film mulching conditions, the soil temperatures were similar for the N0, N250 and N380 treatments (Fig. 2B).

The precipitation during the 2011–2012 and 2012–2013 seasons was 642 and 458 mm, with 477 and 363 mm falling during the MS season, respectively (Fig. 3A). The WFPS at the top 20-cm soil layer markedly increased after heavy precipitation and then rapidly decreased due to soil evaporation and/or plant transpiration (Fig. 3B and C). Compared to that of the BP treatment, the WFPS was significantly ($P < 0.05$) higher in the GM and FM treatments. The averaged WFPS values were 45.1% (20.1–70.6%) and 47.6% (25.4–67.8%) for the BP and GM treatments in 2011–2012, respectively, and were 47.0% (24.2–67.4%), 47.6% (26.6–63.6%) and 50.6% (28.3–64.9%) for the BP, GM and FM treatments in 2012–2013, respectively (Fig. 3B). Compared to the N0 treatment, the N250 and N380 treatments decreased the WFPS most likely due to the higher rate of plant transpiration (Fig. 3C).

The soil NO_3^- and NH_4^+ contents in the top 20-cm profile showed a high response to N fertilization that significantly increased after fertilization. Thereafter, the NH_4^+ content rapidly decreased to the baseline level, but the NO_3^- content was constant at a high level for a relatively long period of time (Fig. 4). Compared to those of the BP treatment, the soil NO_3^- and NH_4^+ content tended to be lower in the GM and FM treatments, particularly during the middle and later MS season. The averaged soil mineral N contents ($NO_3^- + NH_4^+$) were 36.6 and 32.5 mg N kg^{-1} dry soil for the BP and GM treatments from 2011 to 2012, respectively, and 41.9, 37.2 and 38.6 mg N kg^{-1} dry soil for the BP, GM and FM treatments from 2012 to 2013, respectively (Fig. 4A and B). From silking to maturity, the GM and FM treatments significantly ($P < 0.05$) decreased the soil mineral N content by 12.4% in 2011 and 21.2–24.5% in 2012 compared to the BP treatment (Fig. 4A and B). Compared to the N0 treatment, the N250 and N380 treatments significantly ($P < 0.001$) increased the soil NO_3^- and NH_4^+ content, and the highest values were observed in the N380 treatment (Fig. 4C and D).

3.2. N_2O emissions

In the two experiments, the N_2O emission rates for the N-fertilized treatments markedly increased and peaked at approximately 4–5 days after fertilization. The rates then decreased during the MS season and were maintained at a relatively low level during the FS season. For the N0 treatment, the N_2O emission rate was maintained at a low level across all of the seasons except for some small spikes after tillage and some precipitation events (Fig. 5). In Exp. 1, the average N_2O emission rates were similar for the different mulching treatments and were 39.7 and 39.8 μg N_2O m^{-2} h^{-1} for the BP and GM treatments from 2011 to 2012, respectively, and 49.1, 50.7 and 48.6 μg N_2O m^{-2} h^{-1} for the BP, GM and FM treatments from 2012 to 2013, respectively. However, the GM and FM treatments increased the N_2O emissions after N fertilization. Within the ten days following the N application (total of thirty days), the average N_2O emission rates increased by 7.5% for the GM treatment from 2011 to 2012 and by 19.6 and 17.0% for the GM and FM treatments from 2012 to 2013, respectively (Fig. 5A). In Exp. 2, the N fertilization significantly ($P < 0.001$) increased the N_2O emission rate. For the N0, N250 and N380 treatments, the average N_2O emission rates were 12.9, 42.0 and 71.7 μg N_2O m^{-2} h^{-1} from 2011 to 2012 and were 12.0, 52.0 and 80.8 μg N_2O m^{-2} h^{-1} from 2012 to 2013, respectively (Fig. 5B).

The cumulative N_2O emissions showed no difference between the BP, GM and FM treatments, ranging from 1.82 to 1.83 kg N_2O–N ha^{-1} from 2011 to 2012 and 2.22 to 2.27 kg N_2O–N ha^{-1} from 2012 to 2013. The cumulative N_2O emissions for the N250 treatment were 1.96 kg N_2O–N ha^{-1} from 2011 to 2012 and 2.36 kg N_2O–N ha^{-1} from 2012 to 2013. These values were significantly higher compared to those of the N0 treatment (0.72 and 0.65 kg N_2O–N ha^{-1} from 2011 to 2012 and 2012 to 2013, respectively) but significantly lower compared to those of the N380 treatment (3.19 and 3.52 kg N_2O–N ha^{-1} from 2011 to 2012 and 2012 to 2013, respectively) (Table 1).

For all of the treatments in the two experiments, the annual N losses in terms of N_2O emissions represented 0.78–0.84% from 2011 to 2012 and 0.93% to 1.01% from

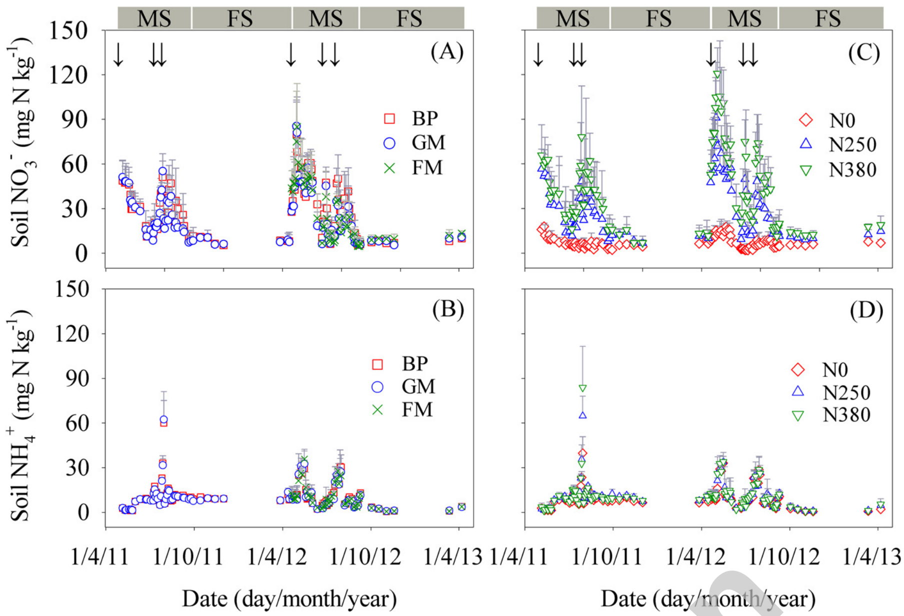

Fig. 4. Seasonal dynamics of the soil NO_3^- and NH_4^+ content in the top 20 cm for the different mulching treatments (A and B) and N application rates (C and D). The bars represent the standard deviations of the means (n = 3). Definitions of the codes for the seasons and treatments are shown in the footnotes of Fig. 2. Arrows denote the dates of fertilizer application.

2012 to 2013 for applied N, and the N_2O emissions during the FS season accounted for 18.9–29.2% and 24.1–32.2% of the annual emissions from 2011 to 2012 and 2012 to 2013, respectively (Table 1).

We found that the N_2O emissions were significantly and positively correlated with the soil temperature and the soil NO_3^- and NH_4^+ content. Surprisingly, a negative correlation was observed between the N_2O emissions and the WFPS in this study (Table 2).

3.3. Grain yield and N uptake

Both the GM and FM treatments significantly increased the grain yield compared to the BP treatment. The enhancements were 5.1 and 6.3 Mg ha^{-1} in 2011 and 1.7 and 3.7 Mg ha^{-1} in 2012 for the GM and FM treatments, respectively. Moreover, the two mulching treatments also markedly increased the aboveground N uptake. Compared to the BP treatment, the N uptake for the GM and FM treatments was increased by 37.4 and 54.5% in 2011 and by 9.0 and 28.7% in 2012, respectively (Table 3).

In Exp. 2, the grain yield and N uptake significantly increased with the N fertilization. Compared to those of the N0 treatment, the grain yield for the N250 treatment was increased by 7.2 Mg ha^{-1} in 2011 and 10.3 Mg ha^{-1} in 2012, and the N uptake was increased by 172 kg ha^{-1} in 2011 and 218 kg ha^{-1} in 2012. However, no further increases in the grain yield and N uptake were obtained when the N application rate increased from 250 to 380 kg ha^{-1} (Table 3).

3.4. Yield-scaled N_2O emissions

The yield-scaled N_2O emissions for the two experiments are shown in Fig. 6. In Exp. 1, both the GM and FM treatments decreased the yield-scaled N_2O emission. Compared to that of the BP treatment, the yield-scaled N_2O emissions for the GM treatment significantly decreased from 259 to 150 g N_2O–N Mg^{-1} grain from 2011 to 2012 and slightly decreased from 235 to 202 g N_2O–N Mg^{-1} grain from 2012 to 2013. From 2012 to 2013, the yield-scaled N_2O emissions decreased further to 167 g N_2O–N Mg^{-1} grain in the FM treatment compared to that of the GM treatment, although there was no significant difference between these two treatments (Fig. 6A and B).

In Exp. 2, the yield-scaled N_2O emissions increased with the N application rate. For the N250 treatment, the yield-scaled N_2O emissions were 125 g N_2O–N Mg^{-1} grain from 2011 to 2012 and 155 g N_2O–N Mg^{-1} grain from 2012 to 2013, which were significantly lower compared to those of the N380 treatment (221 and 245 g N_2O–N Mg^{-1} grain from 2011 to 2012 and 2012 to 2013, respectively), but the value in 2012–2013 was similar to that of the N0 treatment (134 g N_2O–N Mg^{-1} grain) (Fig. 6C and D).

4. Discussion

4.1. N_2O emissions

Both the GM and FM treatments increased the soil temperature (Fig. 2A) and water content (Fig. 3B), which was consistent with previous studies (Sharma et al., 2011; Wang et al., 2011). The N_2O production in the soil generally increases under conditions of high soil moisture and temperature (Smith et al., 2003; Ruser et al., 2006), which were also observed in our study. Within the ten days after N fertilization, the average N_2O emission rate increased by 7.5% from 2011 to 2012 and by 17.0–19.6% from 2012 to 2013 in the GM and FM treatments compared to that of the BP treatment (Fig. 5A). However, the mean annual N_2O emission rate and

Table 1
Cumulative N_2O emissions (kg N_2O–N ha^{-1}) for different mulching treatments (Exp. 1) and N application rates (Exp. 2) from 2011 to 2012 and 2012 to 2013.

Treatment		2011–2012			2012–2013		
		MS[a]	FS	Total	MS	FS	Total
Exp. 1	BP[b]	1.42 ± 0.12a[c]	0.41 ± 0.06a	1.83 ± 0.12a (0.81%)	1.70 ± 0.24a	0.57 ± 0.04a	2.27 ± 0.28a (1.01%)
	GM	1.36 ± 0.10a	0.46 ± 0.03a	1.82 ± 0.08a (0.81%)	1.68 ± 0.17a	0.59 ± 0.03a	2.27 ± 0.16a (1.01%)
	FM				1.57 ± 0.21a	0.65 ± 0.07a	2.22 ± 0.28a (0.99%)
Exp. 2	N0	0.51 ± 0.07c	0.21 ± 0.03c	0.72 ± 0.09c	0.44 ± 0.12c	0.21 ± 0.01c	0.65 ± 0.13c
	N250	1.50 ± 0.07b	0.46 ± 0.05b	1.96 ± 0.06b (0.78%)	1.69 ± 0.21b	0.66 ± 0.02b	2.36 ± 0.19b (0.94%)
	N380	2.59 ± 0.28a	0.60 ± 0.08a	3.19 ± 0.37a (0.84%)	2.67 ± 0.28a	0.85 ± 0.06a	3.52 ± 0.33a (0.93%)

[a] MS, maize growing season; FS, fallow season.
[b] BP, bare plot without mulching; GM, gravel mulching; FM, plastic film mulching; N0, no N applied; N250, N applied at 250 kg N ha^{-1}; N380, N applied at 380 kg N ha^{-1}.
[c] Values are expressed as the mean ± standard deviation (n = 3). The values within the columns for each experiment (Exp.) followed by different letters are significantly different at P < 0.05. The values in the parentheses indicate the percentage of applied N lost as N_2O.

Table 2
Pearson correlation coefficients (r) between the N_2O emissions and soil variables for different mulching treatments (Exp. 1) and N application rates (Exp. 2).

Variable	All		Exp. 1						Exp. 2					
			BP[d]		GM		FM		N0		N250		N380	
	n[b]	r	n	r	n	r	n	r	n	r	n	r	n	r
T_{soil}[c]	854	0.302***[a]	154	0.398***	154	0.391***	84	0.327**	154	0.462***	154	0.339***	154	0.372***
WFPS	549	−0.087*	99	−0.003	99	−0.051	54	−0.015	99	−0.150	99	−0.123	99	−0.060
NO_3^-	531	0.461***	96	0.244*	96	0.194*	51	0.230	96	0.193*	96	0.407***	96	0.366***
NH_4^+	531	0.204***	96	0.263**	96	0.205*	51	0.228	96	−0.077	96	0.191*	96	0.211*

[a] * Significant at $P < 0.05$; ** Significant at $P < 0.01$; *** Significant at $P < 0.001$.
[b] n, number of observations.
[c] T_{soil}, the mean soil temperature of the surface and the 10-cm depth (°C); WFPS, the soil water-filled pore space in the top 20 cm (%); NO_3^-, the soil NO_3^- content in the top 20 cm (mg N kg^{-1}); NH_4^+, the soil NH_4^+ content in the top 20 cm (mg N kg^{-1}).
[d] Definitions of the codes for the treatments are shown in the footnotes of Table 1.

Table 3
Grain yield and aboveground N uptake for different mulching treatments (Exp. 1) and N application rates (Exp. 2) in 2011 and 2012.

Treatment		Grain yield (Mg ha^{-1})		N uptake (kg N ha^{-1})	
		2011	2012	2011	2012
Exp. 1	BP[a]	7.1 ± 0.8b[b]	9.6 ± 0.4c	155 ± 5c	180 ± 10b
	GM	12.2 ± 0.7a	11.3 ± 0.4b	213 ± 14b	197 ± 10b
	FM	13.4 ± 0.6a	13.3 ± 0.8a	239 ± 9a	232 ± 12a
Exp. 2	N0	8.5 ± 0.7b	4.9 ± 1.4b	100 ± 4b	70 ± 21b
	N250	15.7 ± 0.8a	15.2 ± 0.6a	272 ± 2a	288 ± 11a
	N380	14.5 ± 0.5a	14.4 ± 0.6a	266 ± 13a	267 ± 7a

[a] Definitions of the codes for the treatments are shown in the footnotes of Table 1.
[b] Values are expressed as the mean ± standard deviation (n = 3). The values within the columns for each experiment (Exp.) followed by different letters are significantly different at $P < 0.05$.

the cumulative annual N_2O emissions (Table 1) showed no differences among the three treatments, inconsistent with previous studies. Nishimura et al. indicated that the N_2O production was markedly higher in the film-mulched soil compared to that of the non-mulched soil due to the higher soil temperature and moisture underneath the film; thus, larger amounts of N_2O were emitted into

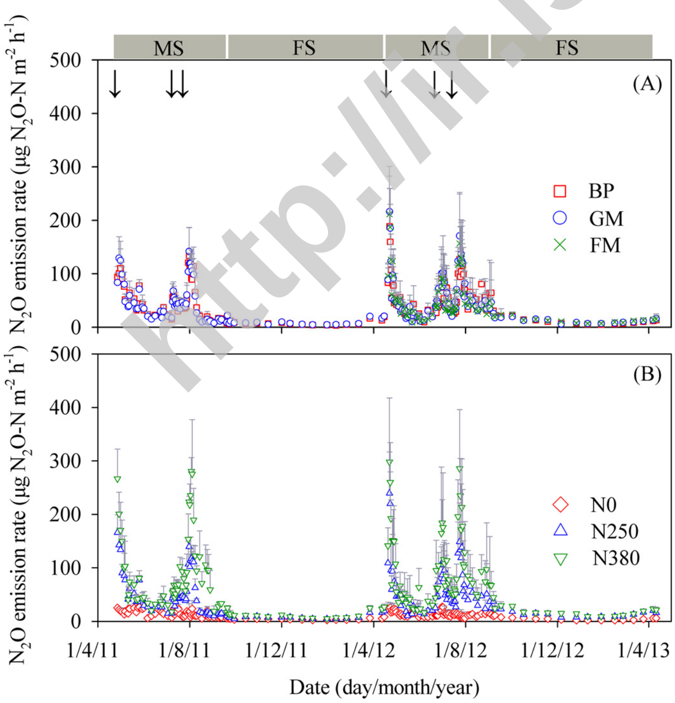

Fig. 5. Seasonal dynamics of N_2O emissions for the different mulching treatments (A) and N application rates (B). The bars represent the standard deviations of the means (n = 3). Definitions of the codes for the seasons and treatments are shown in the footnotes of Fig. 2. Arrows denote the dates of fertilizer application.

atmosphere via permeation through the mulch film (Nishimura et al., 2012). Nevertheless, Berger et al. (2013) reported a reduction in the N_2O emission from the film-mulched soil. The authors demonstrated that the sandy soils in their study area showed a fast infiltration and seepage of water, making it difficult to maintain high soil moisture. In addition, the mulch film most likely intercepted the rainfall and resulted in lower soil moisture in the mulched soil, thus restricting the N_2O production in their study. The soil mineral N, as a substrate of soil microbial nitrification and denitrification, greatly affects N_2O production (Bateman and Baggs, 2005; Mcswiney and Robertson, 2005; Allen et al., 2010), which may explain our findings. In the present study, the GM and FM treatments significantly increased the maize N uptake (Table 3) and thus decreased the soil mineral N content, particularly during the middle and later parts of the growth season (Fig. 4A and B). As a result, except for a short period where there would be large amounts of available N in the soil after N fertilization, the positive effects of a higher soil temperature and moisture on the N_2O production would be offset by a lower soil mineral N content during most of growth seasons in the GM and FM treatments. Barton et al. (2008) also indicated that plant growth competed for available soil N with soil microbes, thus limiting the N_2O production. These results demonstrated that promoting the crop N uptake was significant in reducing N_2O emission.

In the present study, N application was the major factor driving N_2O emissions (Fig. 5 and Table 1). Previous studies have reported that the N_2O emission linearly or exponentially increased with N application rates depending on the type of soil, climate conditions, crop types and N fertilization rates (Mcswiney and Robertson, 2005; Stehfest and Bouwman, 2006; van Groenigen et al., 2010; Hoben et al., 2011; Ma et al., 2013). The increased N_2O emission with N rates was mainly due to the N applications, which markedly increased the soil NO_3^- and NH_4^+ content (Fig. 4C and D) and provided a sufficient substrate for microbial nitrification and denitrification to produce N_2O (Hoben et al., 2011; Liu et al., 2011).

For all of the N-fertilized treatments that were examined in the two experiments, the N lost as N_2O emissions represented

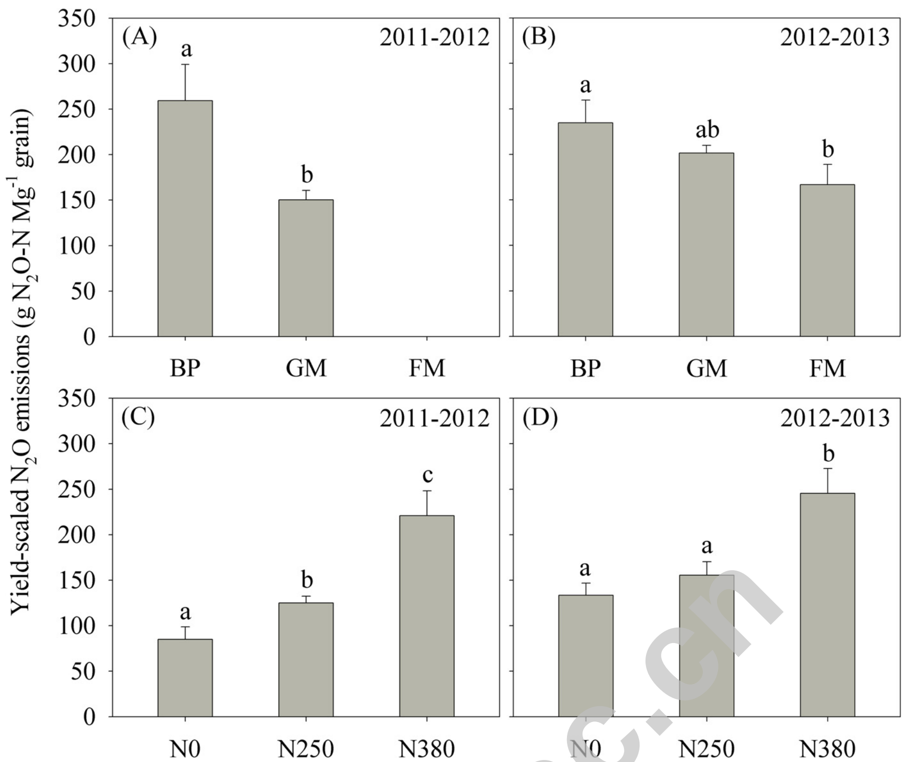

Fig. 6. Yield-scaled N_2O emissions for the different mulching treatments (A and B) and N application rates (C and D). The bars represent the standard deviations of the means ($n=3$). Different letters on the graph indicate significant differences at $P<0.05$. Definitions of the codes for the treatments are shown in the footnotes of Fig. 2.

0.78–1.01% of the applied N (Table 1), which was comparable to the findings of other studies. A default value of 1.0% was suggested by the IPCC (2006) to estimate the N_2O emissions from N-fertilized soils in the uplands. In a study using a meta-analysis, Linquist et al. (2012) reported that 1.06% of the applied N was emitted as N_2O in maize fields. Our results were also within the range of 0.03–1.45% that was reported by Ma et al. (2010) for a maize system in Canada. However, Liu et al. (2011) reported smaller values (0.42–0.72%) compared to our results in the Loess Plateau of China, most likely because these authors measured the N_2O emissions only during the maize growth season but not year-round, thus underestimating the N_2O emissions.

Most of the reported studies measured the N_2O emissions only during the crop growth season or over a short period of time (Ma et al., 2010; Arriaga et al., 2011; Hoben et al., 2011; Liu et al., 2011; Berger et al., 2013), and a few studies measured the N_2O emissions annually (Barton et al., 2008; Allen et al., 2010; Hu et al., 2013). The present study indicated that a large proportion of N_2O (18.9–32.2%) was emitted during the FS season (Table 1). Similar results were also reported by Barton et al. (2008), who demonstrated that 55% of the annual N_2O emission in Western Australia occurred when the soil was fallow. Thus, year-round measurements are essential to precisely estimate the regional and national N_2O emission inventory.

We found positive correlations between the N_2O emission and soil temperature and soil NO_3^- and NH_4^+ content (Table 2), consistent with previous studies (Barton et al., 2008; Allen et al., 2010; Liu et al., 2011). However, an unexpected result regarding the relationship between the N_2O emissions and the WFPS was observed (Table 2). As a key environment factor, soil moisture can promote the production and transport of substrates and N_2O, strongly driving the N_2O emission (Mcswiney and Robertson, 2005). In this study, because the N_2O emission peaks due to N fertilization (Fig. 5) and the rainy season (July–September, Fig. 3A) did not coincide well, the N_2O emissions negatively responded to the WFPS during these years. However, in a specific period of time, the relationship between the N_2O emission and the WFPS was positive. For example, within the fifteen days after N fertilization for all of the N-fertilized treatments in the two experiments, the Pearson correlation coefficient between the N_2O emission and the WFPS was 0.445 ($P<0.001$).

4.2. Yield-scaled N_2O emissions

The GM treatment markedly reduced the yield-scaled N_2O emissions by 42.0% from 2011 to 2012 and by 14.1% from 2012 to 2013 compared to that of the BP treatment (Fig. 6A and B), mainly because the GM treatment significantly increased the maize grain yield (Table 3), but did not increase the N_2O emissions (Table 1). Due to the higher grain yield (Table 3), the FM treatment further reduced the yield-scaled N_2O emission by 17.2% compared to that of the GM treatment from 2012 to 2013 (Fig. 6B). The increase in the food demand and changes in climate require management practices that should maximize the crop productivity of existing croplands as well as minimize the negative environmental effects (Tilman et al., 2011; Grassini and Cassman, 2012). Recent studies have demonstrated that increasing the crop yields and closing the yield gaps can effectively reduce the greenhouse gas intensity (Cui et al., 2013; Valin et al., 2013). The results of the present study indicate that FM is a preferable method to decrease the direct N_2O emission intensity by increasing the grain yield.

In Exp. 2, the yield-scaled N_2O emissions significantly increased with N applications (Fig. 6C and D). Similarly, Liu et al. (2011) reported that the yield-scaled N_2O emission dramatically increased by 92% when the N fertilizer rate increased from 120 to 330 kg ha^{-1}. Moreover, van Groenigen et al. (2010) reported that the yield-scaled N_2O emission was low when the N surplus (N application minus crop N uptake) was negative or nearly zero but progressively increased when N was applied in excess of the crop requirement. In the present study, the N input in the N250 treatment nearly equaled the maize N uptake (Table 3) and was comparable to the rates (average 237 kg N ha^{-1} via manure and fertilizer) that are recommended for high-yield maize in China (Chen et al., 2011). As a result, low yield-scaled N_2O emissions were obtained in this treatment at 125 and 155 g N_2O–N Mg^{-1} grain from 2011 to 2012 and 2012 to 2013, respectively (Fig. 6C and D), which were comparable to the values that were estimated for optimized high-yield maize systems in China (140 g N_2O–N Mg^{-1} grain, Cui et al., 2013) and in central Nebraska, USA (138 g N_2O–N Mg^{-1} grain, Grassini and Cassman, 2012). In addition to the rational N input, the adoption of improved crop management practices using these treatments was also responsible for the low yield-scaled N_2O emissions because these practices could markedly increase the grain yield (Sangoi, 2000; Chen et al., 2011). In addition, our results showed that excessive N application (i.e., 380 kg N ha^{-1}) was not able to further increase the grain yield (Table 3) but significantly increased the yield-scaled N_2O emissions (Fig. 6C and D). Thus, a rational N input is essential to minimize N_2O emissions while maintaining or increasing the crop yield.

5. Conclusions

An analysis of the results from the experiments performed over two years suggested that both the GM and FM treatments did not increase the cumulative N_2O emissions, but both of the treatments dramatically reduced the yield-scaled N_2O emissions due to the higher grain yield compared to that of the BP treatment. Moreover, the FM treatment was more effective in decreasing the N_2O emission intensity than was the GM treatment. Our results also indicated that a rational N input is essential for achieving high yield and low yield-scaled N_2O emissions. These findings contribute to our understanding of soil surface mulching and N application effects on N_2O emissions. In addition, these results may provide valuable information for optimizing management practices to improve crop production and simultaneously reduce the direct N_2O emission intensity in semi-arid farmland.

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