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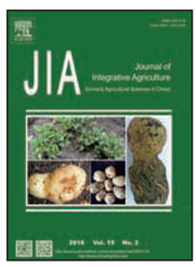

RESEARCH ARTICLE

Effects of plastic film mulching on soil greenhouse gases (CO_2, CH_4 and N_2O) concentration within soil profiles in maize fields on the Loess Plateau, China

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Abstract

To better understand the effects of plastic film mulching on soil greenhouse gases (GHGs) emissions, we compared seasonal and vertical variations of GHG concentrations at seven soil depths in maize (*Zea mays* L.) fields at Changwu station in Shaanxi, a semi-humid region, between 2012 and 2013. Gas samples were taken simultaneously every one week from non-mulched (BP) and plastic film-mulched (FM) field plots. The results showed that the concentration of GHGs varied distinctly at the soil-atmosphere interface and in the soil profile during the maize growing season (MS). Both carbon dioxide (CO_2) and nitrous oxide (N_2O) concentrations increased with increasement of soil depth, while the methane (CH_4) concentrations decreased with increasement of soil depth. A strong seasonal variation pattern was found for CO_2 and N_2O concentrations, as compared to an inconspicuous seasonal variation of CH_4 concentrations. The mean CO_2 and N_2O concentrations were higher, but the mean CH_4 concentration in the soil profiles was lower in the FM plots than in the BP plots. The results of this study suggested that plastic film mulching significantly increased the potential emissions of CO_2 and N_2O from the soil, and promoted CH_4 absorption by the soil, particularly during the MS.

Keywords: greenhouse gas, soil profile, plastic film mulching, growing season

1. Introduction

The buildup of greenhouse gases (GHGs) in the atmosphere is assumed to be responsible for increasing global mean temperature (Tett *et al.* 1999; Crowley 2000). Agricultural land covers 37% of earth's landmass and is responsible for 10–12% of anthropogenic GHGs emissions (IPCC 2007). It has been estimated that agriculture soils contribute approximately 52 and 84% to the global anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions, respectively (Smith *et al.* 2008). Agricultural soil is a complex medium that consists of a broad range of organo-mineral particles and aggregates, where numerous organisms exhibit different physiological processes (Fang and Moncrieff 1999). Soil properties vary temporally, horizontally and vertically (Davidson and Trumbore 1995). As a result of production and consumption and their upward, downward or horizontal

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movements, the temporal and spatial dynamics of GHGs in soil profiles and different patterns of soil GHG concentrations have been reported (Pei *et al.* 2004; Fierer *et al.* 2005; Fang *et al.* 2009; Kusa *et al.* 2010). Furthermore, the spatial heterogeneity of GHG production and accumulation due to diffusion limitation has also been reported (van Groenigen *et al.* 2005; Koehler *et al.* 2012). However, the relationships between GHGs emission and climate, soil characteristics and management are not well known because of the large spatial and temporal variations. Thus, measurements of the GHGs concentration in soils may facilitate a better understanding of the temporal variations in their exchange between the soil and atmosphere.

Plastic film mulching is a common agricultural management practice worldwide and has been adopted for many years, especially in arid regions (Adams 1967; Sharma *et al.* 2011; Wang *et al.* 2011). Plastic film mulching can reduce soil surface evaporation, increase soil temperature and moisture (Adams 1970; Mahrer *et al.* 1984), improve the availability of soil nutrients (Li *et al.* 2004), and promote crop growth and yield (Liu *et al.* 2010; Zhao *et al.* 2012; Braun *et al.* 2013; Gan *et al.* 2013; Ruidisch *et al.* 2013). In addition, plastic film mulching may affect the growth and distribution of plant roots. Thus, plastic film mulching could affect the production, consumption and transport of GHGs in soils (Nishimura *et al.* 2012; Berger *et al.* 2013). However, very few studies have focused on the effects of plastic film mulching on the concentration of GHGs in soil profile in a typical cropping system.

Net soil surface gas fluxes result from production, consumption and transport through the soil profile. To understand where and how soil GHGs are produced, it is important to determine GHG concentrations in the near-surface atmosphere and their distribution throughout different soil profiles (Fang and Moncrieff 1999; Novak 2007). Some studies have shown that approximately 70–80% of the measured soil CO_2 fluxes derived from the top 100 cm of the soil (Davidson and Trumbore 1995; Koehler *et al.* 2012). Thus, we investigated GHGs concentration in the 100-cm soil profile to examine the effects of plastic film mulching on the distribution of GHGs in maize fields on the Loess Plateau.

2. Results

2.1. Soil temperature and soil water-filled pore space

In line with air temperature, soil temperature at different soil depths showed a similar seasonal variation pattern (Figs. 1 and 2). The extent of soil temperature variation over the whole annual cycle decreased with soil depth, with a range of –5.0 to 28.4°C at 0 cm soil depth and 12.4 to 21.6°C at 90 cm soil depth for the plastic film mulching (FM) treatment (Fig. 2). Relative to the bare plot without mulching (BP) treatment, mulching significantly increased the seasonal total of soil temperature during the maize growing season (MS), with an increase of 196.2, 179.2, 156.9, 119.9, 87.5, 41.2 and 33.5°C at soil depths of 0, 7, 15, 30, 50, 70 and 90 cm, respectively (Fig. 2).

In addition, the fluctuations for soil water-filled pore space (WFPS) decreased with greater soil depth for both the FM and BP treatments (Fig. 3). The WFPS varied from 28.5 to

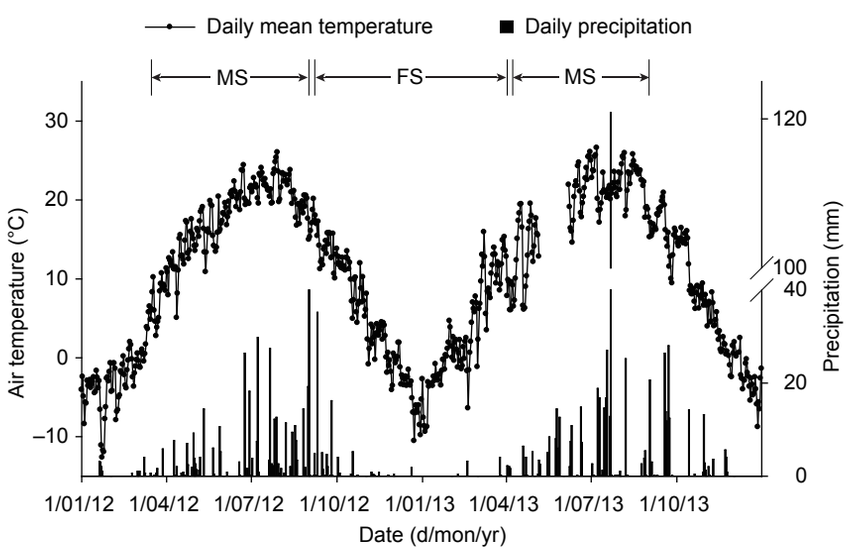

Fig. 1 Daily air temperature and precipitation means in 2012 and 2013. MS and FS denote the maize growing season and the fallow season, the same as below. Extraordinary precipitation of 120.8 mm occurred on 22 July in 2013. Data for air temperature were missing from 7 May to 6 June in 2013 as a result of equipment failure.

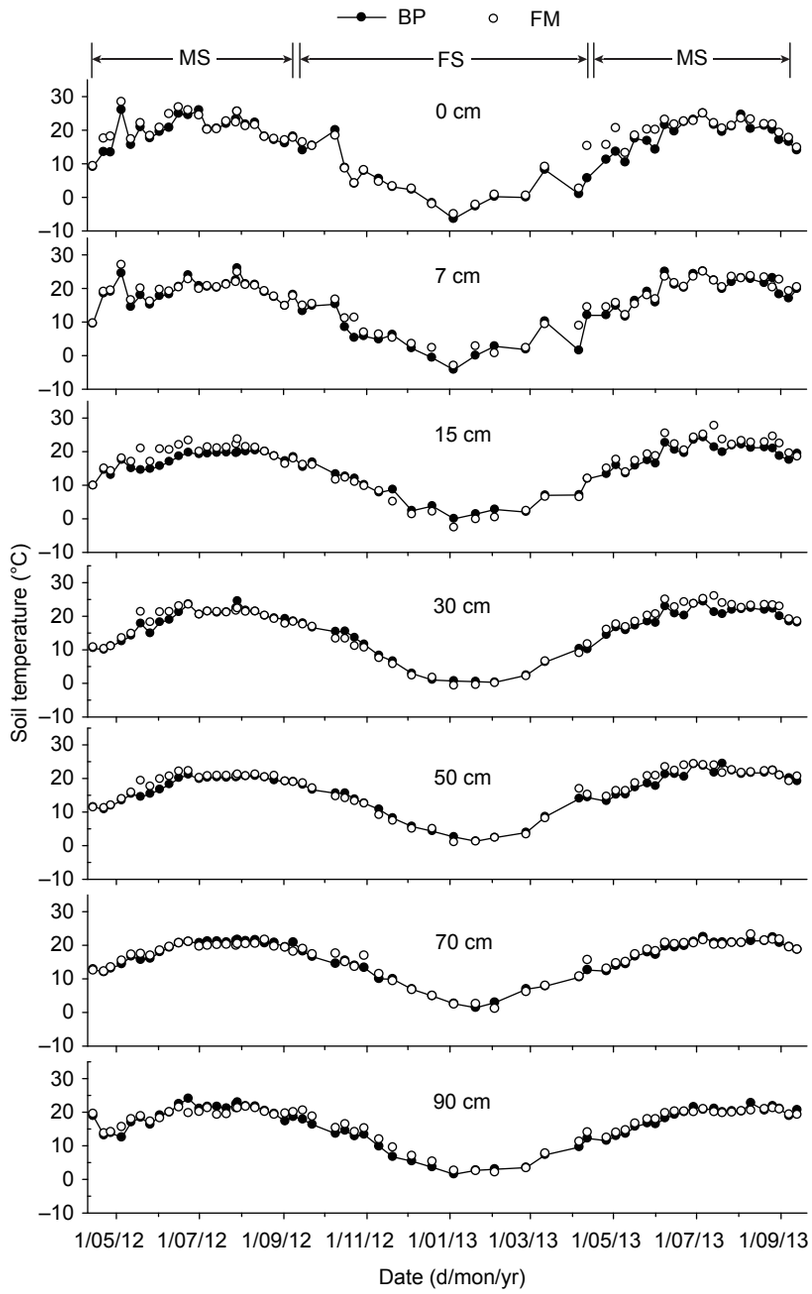

Fig. 2 Soil temperatures at various depths in the bare plot without mulching (BP) and the plastic film mulching (FM) treatments from 2012 to 2013.

99.7% for the FM treatment and from 18.1 to 92.8% for the BP treatment at 7 cm depth. In addition, the WFPS varied from 44.7 to 68.2% for the FM treatment and from 48.5 to 73.0% for the BP treatment at 90 cm depth. Rainfall events were associated with an increase in soil water content at various depths, especially at depths of 7 and 15 cm (Fig. 3). Compared with the BP treatment, the mean WFPSs in the FM treatment were 57.6, 59.4, 63.8, 52.3, 60.1 and 54.3% at depths of 7, 15, 30, 50, 70 and 90 cm during the MS. FM increased the WFPS by 20.7% (7 cm), 17.3% (15 cm), 10.9% (30 cm) and 1.0% (50 cm). However, FM decreased the soil moisture contents at greater depths by 2.8% (70 cm) and 3.6% (90 cm) during the MS; this was due to the hydraulic lift of the maize roots. During the FS, FM increased the WFPS values by 10.7% (7 cm), 5.3% (15 cm), 5.1% (30 cm), 0.5% (50 cm), 0.5% (70 cm) and 1.0% (90 cm).

2.2. GHGs concentration in soil profiles

The CO_2 concentrations of the near-surface samples had

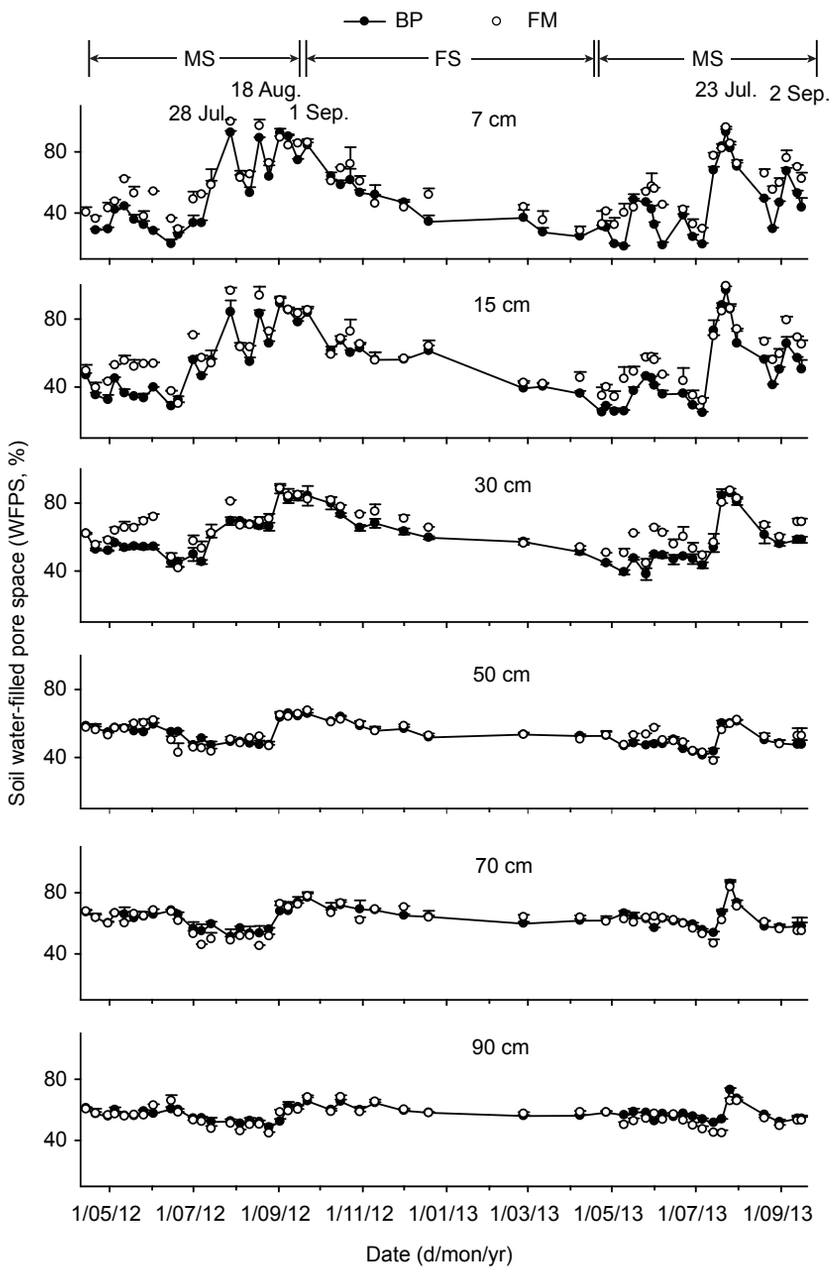

Fig. 3 Soil water-filled pore space (WFPS, %) at various depths in the BP and the FM treatments. The bars represent the standard errors of the means (n=3), the same as below. Dotted lines denote the peaks of soil WRPS.

small fluctuations and indistinct seasonal variation in the range of 323.4 to 892.5 mL m^{-3} in the near-surface gas (at 0 cm soil depth). The subsurface CO_2 concentrations showed strong seasonal variation, with values that varied between 415.0 and 1 1901.3 mL m^{-3} at depths of 7 to 90 cm (Fig. 4). The CO_2 concentrations of the FM and BP treatments increased with increasement of soil depth (Fig. 4). For the FM treatment, the CO_2 concentrations varied from 407.3 to 6 801.9 mL m^{-3} at 7 cm depth, and from 465.9 to 12 714.8 mL m^{-3} at 15 cm depth. For the BP treatment, the CO_2 concentrations varied from 367.6 to 4 796.9 mL m^{-3} at 7 cm depth, and from 512.7 to 9 113.0 mL m^{-3} at 15 cm depth. These results suggested significant respiration in the upper soils. Below 50 cm, the CO_2 concentrations remained relatively constant, which may be mainly related to lower production of the gas.

The CO_2 concentrations in soil profiles were generally 2–10 times higher during the MS (July to September) than during the FS, mainly at depths of 0 to 30 cm (Table 1). During the MS, the CO_2 concentrations for the FM treatment (471.3 mL m^{-3}) were slightly higher than those for the BP treatment (439.8 mL m^{-3}) in the near-surface gas (P>0.05).

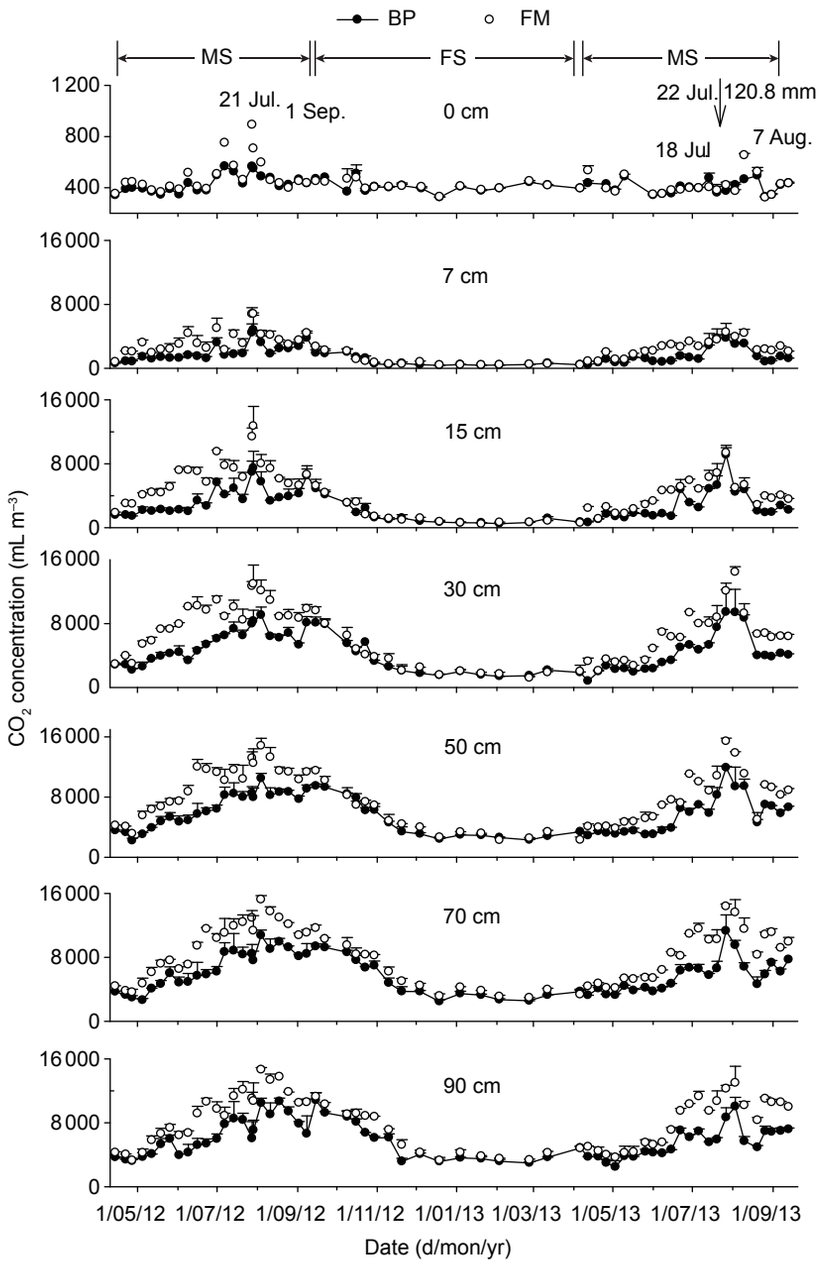

Fig. 4 Soil CO_2 concentrations at various depths in the BP and the FM treatments. Dotted lines denote heavy rainfall events. Solid arrows denote the extraordinary precipitation event (120.8 mm on 22 July in 2013).

However, the CO_2 concentrations were significantly higher in the FM treatment than that in the BP treatment at all depths of 7 to 90 cm (P<0.01). During the FS, no significant differences were found between the BP and FM treatments in either near-surface air or soil air (P>0.05) (Table 1).

There were no great seasonal variations of CH_4 concentrations in near-surface air or soil air, ranging from 95.1 to 2 686.3 μL m^{-3} (Fig. 5). The CH_4 concentrations within soil profiles in the BP and FM treatments decreased with increasement of soil depth and did not obviously change after the addition of N fertilizer. The CH_4 concentrations in the deep soil layers (50, 70 and 90 cm) were obviously lower than those in the shallow soil layers (0, 7, 15 and 30 cm) (P<0.01), which demonstrated that the soils absorbed CH_4 from the atmosphere and consumed it layer-by-layer. During the MS, CH_4 concentrations in the FM treatment in various soil layers were significantly lower than those in the BP treatment (P<0.05). During the FS, no differences were observed between the BP and FM treatments in near-surface air or soil air.

Table 1 Means of greenhouse gases (GHGs) concentration in soil air at various depths from April 2012 to October 2013

GHGs	Period[1)]	Treatment[2)]	0 cm	7 cm	15 cm	30 cm	50 cm	70 cm	90 cm
CO_2 (mL m^{-3})	MS	BP	423.9±75.4 a[3)]	1 833.8±1 082.1 b	3 179.3±1 828.6 c	4 942.3±2 201.6 d	6 039.4±2 374.2 e	6 278.6±2 281.4 e	6 078.1±2 213.6 e
		FM	452.8±136.6 a	3 310.8±1 767.7 b	5 094.5±2 417.6 c	7 609.8±3 295.1 d	8 814.7±3 310.5 e	9 125.8±3 352.5 e	8 822.4±3 402.8 e
	FS	BP	419.5±120.5 a	835.7±603.7 a	1 557.9±1 332.6 a	3 190.1±2 302.8 b	4 759.0±2 589.9 c	5 031.8±2 475.0 c	5 402.7±2 512.8 c
		FM	421.9±97.5 a	932.5±730.3 a	1 732.1±1 447.3 a	3 558.2±2 430.6 b	5 181.1±2 844.3 c	5 938.2±2 849.9 c	6 246.7±2 725.2 c
CH_4 (μL m^{-3})	MS	BP	2 180.0±305.9 a	1 815.3±360.0 b	1 362.1±413.4 c	892.1±416.2 d	784.6±496.7 de	792.8±413.9 de	685.4±230.3 e
		FM	2 160.6±403.9 a	1 726.7±304.9 b	1 253.9±377.0 c	835.9±402.2 d	701.5±476.3 de	669.4±487.0 de	544.5±255.5 e
	FS	BP	2 267.0±208.4 a	2 037.5±325.4 b	1 436.7±508.8 c	698.2±378.8 d	411.5±27.6 e	468.3±300.0 e	463.2±253.0 e
		FM	2 255.9±231.1 a	2 016.8±301.9 b	1 559.6±392.0 c	892.4±356.9 d	538.3±316.5 e	394.0±238.1 e	411.4±298.4 e
N_2O (μL m^{-3})	MS	BP	411.3±112.1 a	653.5±445.8 b	753.4±501.7 b	825.2±506.2 b	841.5±489.1 b	901.1±559.0 b	875.6±542.5 b
		FM	426.6±160.6 a	896.3±609.1 b	1 082.8±737.4 bc	1 128.5±675.4 bc	1 152.9±686.4 c	1 187.0±694.1 c	1 157.3±727.0 c
	FS	BP	378.4±55.5 a	405.8±61.8 a	454.3±115.7 ab	543.8±205.3 bc	634.6±244.7 c	606.3±201.5 c	624.6±198.9 c
		FM	363.6±58.8 a	386.7±94.4 ab	437.2±166.4 bc	503.1±184.6 bc	597.5±254.9 cd	665.4±306.4 d	692.8±356.2 d

[1)] MS and FS denote the maize growing season and fallow season, respectively.
[2)] BP, bare plot without mulching; FM, plastic film mulching. The same as below.
Mean values (mean±standard deviations, n=46 for MS, n=17 for FS) within the same column followed by the same letters are not significantly different, as determined by ANOVA and Fisher protected LSD (P<0.05).

The N_2O concentrations did not show strong seasonal variations in near-surface air or soil air, and the mean annual concentrations ranged from 260.3 to 4 345.5 μL m^{-3} (Fig. 6). Throughout the observation period, three peaks in 2012 and two peaks in 2013 were observed for N_2O concentrations in subsurface soils, after the application of N fertilizer (April, June and July) during the MS. The highest values were found in July. Compared to the BP treatment, the N_2O concentrations in the FM treatment were much higher during the MS and were slightly lower during the FS. The N_2O concentrations increased more quickly in the FM treatment than the BP treatment following the application of N fertilizer before decreasing suddenly to previous levels.

The mean N_2O concentrations were not obviously different between the various layers (15 to 90 cm), but were significantly higher than those of the near-surface air. In addition, the mean value at 7 cm soil depth (774.9 μL m^{-3}) was significantly higher than that at 0 cm soil depth (424.0 μL m^{-3}) during the MS (P<0.05). At greater depths, N_2O concentrations in the FM treatment exhibited significantly higher than those in the BP treatment (P<0.05). During the FS, no differences were observed with respect to N_2O concentrations in near-surface air or soil air of the 7 to 90 cm when the BP and FM treatments were compared.

2.3. The relationships between GHGs concentration and temperature and moisture

We confirmed the relationships between CO_2 concentration and temperature and moisture (Fig. 7). The correlation coefficient (R^2) for CO_2 was 0.38. The highest CO_2 concentration (8 458.2 mL m^{-3}) occurred when the temperature and WFPS were 21.8°C and 68.9%, respectively (Table 2). The theoretical maximum CO_2 concentrations were lower than the measured CO_2 concentrations because of great variation between layers. We observed that the correlation in the shallow soil was described more accurately than in the deep soil, the correlation coefficient was 0.62 at a depth of 7 cm and the theoretical value (6 316.5 mL m^{-3}) was similar to the measured value (6 629.3 mL m^{-3}). CH_4 concentration was only weakly correlated with temperature and moisture (R^2=0.16; Fig. 8, Table 2) because CH_4 consumption was not sensitive to temperature. The N_2O concentrations in soil air were mainly affected by the soil moisture and temperature, with R^2=0.14 (Fig. 9). The highest N_2O concentration was 1 306.1 μL m^{-3} in soil air when the temperature and WFPS were 24.1°C and 87.1%, respectively (Table 2).

3. Discussion

3.1. Main thesis

Distinct differences were observed for the CO_2, CH_4, and N_2O concentrations with increasement of soil depth in the spring maize growing seasons on the Loess Plateau. The CO_2 concentrations

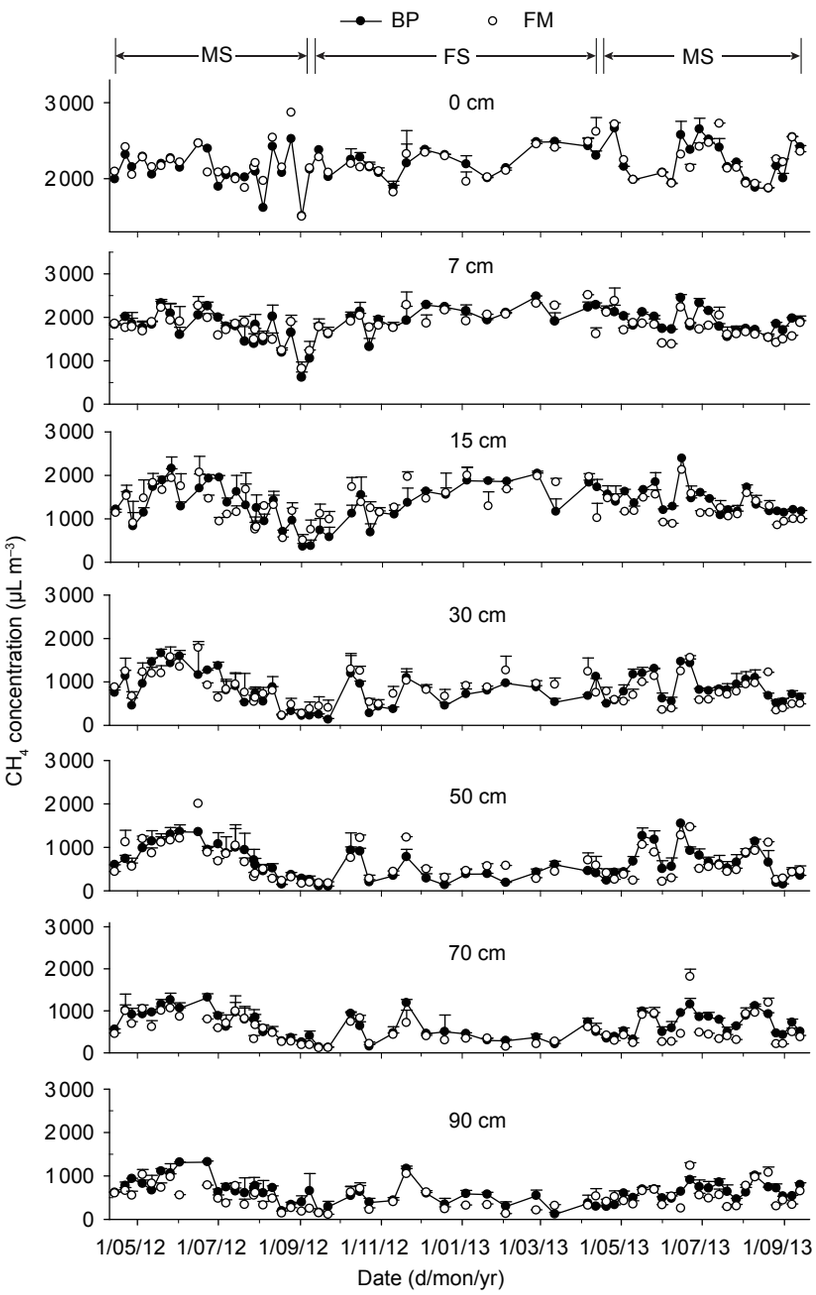

Fig. 5 Soil CH_4 concentrations at various depths in the BP and the FM treatments.

in soil profiles showed strong temporal variations during the MS, with relatively low concentrations during the FS (Fig. 4, Table 1). However, the mean CH_4 concentrations were significantly higher in near-surface air than in soil air, and the CH_4 levels decreased at greater depths without seasonal changes (Fig. 5). The mean N_2O concentrations in soil air increased with increasement of soil depth and rapidly increased after application of N fertilizer throughout the whole soil profile (Fig. 6). Nevertheless, no difference was observed for N_2O concentrations between 0 and 7 cm during the FS (Table 1). The concentrations of CO_2 and N_2O were consistently higher in soil air than in near-surface air, particularly during the MS, suggesting that CO_2 and N_2O diffused from soils to the atmosphere and soils are main producers of the gas. In contrast, CH_4 concentrations were consistently lower in soil air than that in near-surface air, suggesting that soils mainly absorb CH_4 during the whole year. Thus, we confirmed that soil is a significant source of CO_2 and N_2O to our atmosphere and a significant sink for CH_4 on the Loess Plateau.

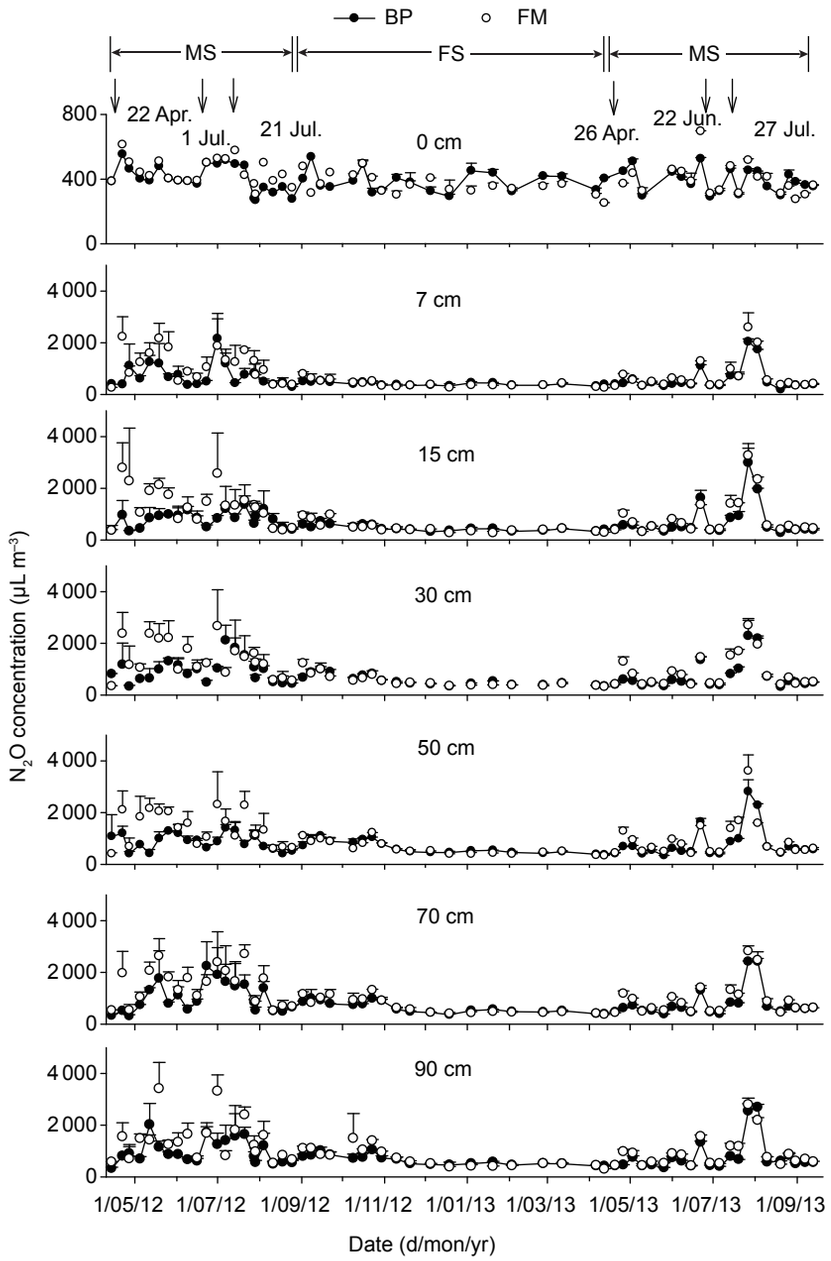

Fig. 6 Soil N_2O concentrations at various depths in the BP and the FM treatments. Solid arrows denote the dates of fertilizer application. Dotted lines denote the peaks of N_2O concentrations.

Compared to bare soils, plastic film mulching increased the soil moisture content, soil temperature, CO_2 concentration and N_2O concentration of soil during the MS over the course of two years (Table 1). However, plastic film mulching did not significantly increase the GHG concentrations in near-surface air during the MS or in soil air during the FS.

3.2. CO_2 concentration in soil profiles

The seasonal patterns of CO_2 concentrations were correlated with soil respiration resulting from the rapid growth of plant roots (Rovira and Vallejo 1997, 2007) and microbial activity (Bardgett *et al.* 1999). Difference in CO_2 concentrations between 0 and 7 cm soil depths was consistently significant (P<0.01) during the MS, while not significant during the FS (P>0.05) (Table 1). The concentration gradient implies upward diffusion of CO_2, and CO_2 production surpassed the gas diffusivity level in the soils during the MS. However, CO_2 production was similar to the gas diffusivity level during the FS. The soil CO_2 concentrations

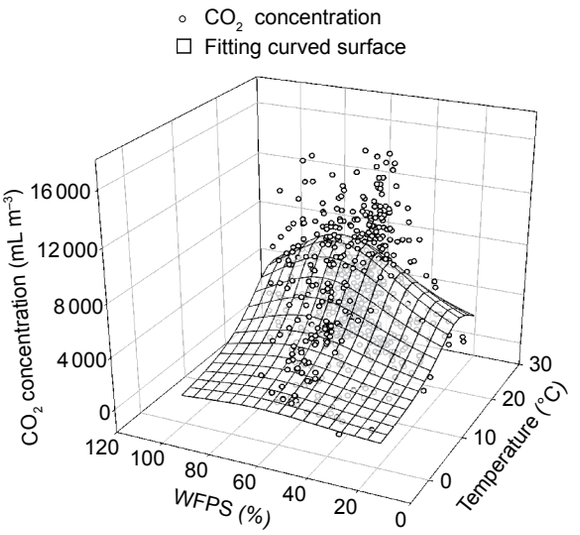

Fig. 7 Three-dimensional diagram of the soil CO_2 concentrations, temperature and WFPS.

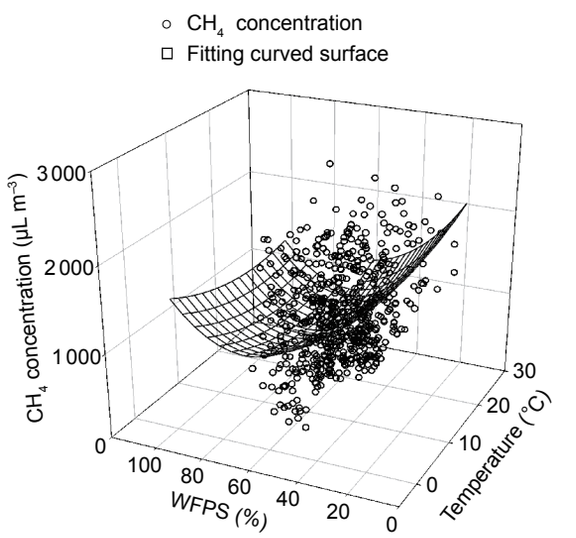

Fig. 8 Three-dimensional diagram of the soil CH_4 concentrations, temperature and WFPS.

responded rapidly to precipitation events, synchronously decreasing after heavy rainfall events (27.4 mm, on 21 July in 2012; 46.0 mm, 1 September in 2012; 27.0 mm, 18 July in 2013; 25.2 mm, 7 August in 2013) and after extraordinary rainfall events (120.8 mm, on 22 July in 2013). This rapid response occurred because the intensity of the rainfall (generally WFPS>70%) reduced the number of air-filled pores and adversely affected the diffusion of CO_2, which decreased CO_2 concentrations throughout the soil profiles (Fang and Moncrieff 1999). Many studies have reported that soil temperature and water content have pronounced

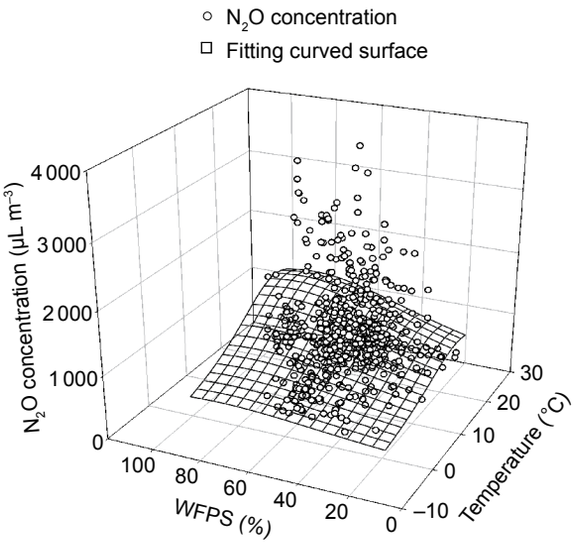

Fig. 9 Three-dimensional diagram of the soil N_2O concentrations, temperature and WFPS.

influences on soil gas effluxes (Davidson and Boone 1998; Borken and Matzner 2009; Bond-Lamberty and Thomson 2010), affecting CO_2 concentrations in soil air. Based on the combined effect of temperature and moisture on soil CO_2, three-dimensional response surfaces were constructed to model a Lorentzian distribution (Fig. 7). The model was a better fit for CO_2 concentrations in the shallow soil than in the deep soil.

The CO_2 concentrations were higher in the FM treatment than in the BP treatment in 2012 and 2013 during the MS, and were the lowest during the FS. The main reason may be that CO_2 production was higher in the film-mulched soils than in the non-mulched soils. Some authors have reported that plastic mulching advanced the MS by approximately 3–4 d and accelerated maize growth, delayed leaf senescence, and increased biomass production (Bu *et al.* 2013a, b). As well as the rapid growth of aboveground parts, roots were also growing. Therefore, we infer that the root growth of maize under the plastic film-mulched promoted soil respiration and enhanced soil CO_2 production.

3.3. CH_4 concentration in soil profiles

Our results showed that the CH_4 concentrations in near-surface air and shallow soil air exhibited no remarkable seasonal patterns, there was a concentration gradient of CH_4 in the top 30 cm (Table 1). This suggests that CH_4 oxidation was the strongest in the upper soil layers (above 30 cm), agreeing with Wagner *et al.* (1999). The CH_4 concentrations were not closely correlated with the temperature or moisture content of the soil (P>0.05), which was consistent

Table 2 Polynomial equations relating GHGs concentrations to temperature (°C) and soil water-filled pore space (%, WFPS)

GHGs $SC_{CO_2,N_2O}=\frac{a}{\left[1+(\frac{\text{Temperature}-x_0}{b})^2\right]\left[1+(\frac{\text{Moisture}-y_0}{c})^2\right]}$

	Treatment	n[1)]	R^2	P-value	x_0	y_0	a	b	c
CO_2	BP	301	0.45	<0.0001	22.86***	71.05***	7769.36***	10.76***	33.04***
	FM	301	0.40	<0.0001	21.33***	64.34***	9198.58***	6.26***	63.32***
	All	602	0.38	<0.0001	21.84***	68.86***	8458.17***	7.98***	42.19***
N_2O	BP	295	0.19	<0.0001	34.82	86.65***	1901.85	18.68***	54.30***
	FM	296	0.11	<0.0001	20.99***	94.34	1266.70***	13.02***	114.76
	All	591	0.14	<0.0001	24.12***	87.09***	1306.82***	15.30***	68.21***

$SC_{CH_4}=y_0+a(\text{Temperature})+b(\text{Moisture})+c(\text{Temperature})^2+d(\text{Moisture})^2$

	Treatment	n	R^2	P-value	y_0	a	b	c	d
CH_4	BP	288	0.25	<0.0001	3216.54***	–15.96	–65.42***	0.26	0.46***
	FM	294	0.11	<0.0001	4010.24***	–43.88	–82.72***	1.11	0.61***
	All	582	0.16	<0.0001	3460.21***	–33.34	–69.50***	0.85	0.51***

[1)] n, number of observations.
*, significance at P<0.05; **, significance at P<0.01; ***, significance at P<0.001.

with Zhang *et al.* (2001) and Stewart *et al.* (2013). Striegl (1993) and Yu *et al.* (2013) suggested that methanotrophic consumption and decomposition were mainly limited by O_2 diffusion. Gulledge and Schimel (1998) revealed that consistently wetter or drier conditions could reduce CH_4 consumption, due to strong diffusion limitation. From July to September, the CH_4 concentrations decreased as the amount of rainfall increased, consistent with the findings of Mosier (1991), Adamsen *et al.* (1993) and Gao *et al.* (2014). FM significantly decreased the CH_4 concentration of the soil during the MS, and slightly affected the concentrations during the FS, due to increasement of absorption and oxidation of methanotrophic microorganisms because temperatures were closer to optimal values.

3.4. N_2O concentration in soil profiles

N_2O concentrations in near-surface air and soil air showed great temporal and vertical variability. There were three peaks in 2012 and two peaks in 2013 for N_2O concentrations, following the applications of N fertilizer in each year. At higher depth, peak times were delayed by several days in 2012 and 2013. This result corresponds with Smart *et al.* (2011) and Alsina *et al.* (2013). Therefore, we found that these transitory peaks in soil gas were largely restricted to the upper soils (30 cm depth) due to rapid diffusion; they were generally related to the WFPS, soil temperature and soil management strategy (Smart *et al.* 2011; Schellenberg *et al.* 2012; Liu *et al.* 2014; Sanz-Cobena *et al.* 2014). In January, the N_2O concentrations at 7 cm soil depth were lower than those at 0 cm soil depth, implying that soils might become temporal sinks for atmospheric N_2O. This result probably was due to intense consumption of atmospheric N_2O by denitrifiers. An increase in soil temperature (within limits) is beneficial to nitrification and denitrification processes and accelerates N_2O production (Smith *et al.* 2003). The average temperature (between 20 and 23°C) during the summer in the study area is suitable for nitrification. Thus, it is easy to understand why high concentrations occurred in the soils.

Compared with the BP treatment, the N_2O concentrations in the FM treatment were generally higher throughout the soil profiles during the monitoring period. However, there were no differences for N_2O concentrations between the BP and FM treatments in near-surface air. The results of this study show that FM could promote soil gas production beneath the film, which was inconsistent with the speculation of Berger *et al.* (2013). However, Berger *et al.* (2013) reported reduced N_2O emissions from their film-mulched soil, presumably because the mulch film restricted the production of N_2O.

4. Conclusion

Mean concentrations of CO_2 in near-surafce air were remarkably low compared to those in soil air. In addidtion, CO_2 concentrations increased with increasement of soil depth and showed obvious seasonal variations, with higher concentrations during the MS than during the FS. However, mean concentrations of CH_4 were higher in near-surface air than in soil air. CH_4 concentrations decreased with increasement of soil depth and did not exhibit obvious seasonal variations. The mean N_2O concentrations increased with increasement of soil depth, and rapidly increased after urea application throughout the profile. Compared with no mulching, plastic film mulching significantly increased the mean concentrations of CO_2 and N_2O within soil profiles, and decreased the mean concentrations of CH_4, especially

during the MS.

This paper provides valuable information about soil profiles and the seasonal variations in GHG concentrations. Future studies are required to elucidate the mechanisms of GHG production-consumption-transport in more details under more homogenous conditions, and to evaluate the effect of plastic film mulching on gas exchanges between the soil and the atmosphere.

5. Materials and methods

5.1. Site description

The experiment was conducted between 2012 and 2013 at the Changwu Agri-Ecological Station on the Loess Plateau, China (35.28°N,107.88°E, approximately 1 200 m a.s.l). This station is located in a typical, semiarid farming area with an average annual temperature of 9.2°C. The average annual rainfall in this region is 582 mm, with 73% of the rain falling during the MS, and an annual evaporation from the free water surface is 1 565 mm. Generally, this region is dominated by an annual single cropping season (wheat or maize). According to the international soil classification (Soil Survey Staff 2003), the soil at the study site is classified as Cumuli-Ustic Isohumosols (Gong *et al.* 2007). Soil samples were taken from the experimental field site before planting in 2009, with a texture of 4% sand, 59% silt, and 37% clay. The top 20 cm of soil had a bulk density of 1.3 g cm^{-3}, a pH of 8.4, an organic matter content of 16.4 g kg^{-1}, a total N content of 1.05 g kg^{-1}, an Olsen-P content of 20.7 mg kg^{-1}, an NH_4OAc-extractable K content of 133.1 mg kg^{-1}, and a mineral N content of 28.8 mg kg^{-1}.

The mean temperature and daily precipitation at the site were recorded at the Changwu Meteorological Monitoring Station, situated within 50 m of the experimental site. The annual average solar radiation varied from 131 to 137 W m^{-2}. The annual precipitation was 480.8 mm in 2012 and 577.3 mm in 2013 (Fig. 1). During the MS, the precipitation was 363.4 mm in 2012 and 411.5 mm in 2013, accounting for 75.6 and 71.3% of the annual totals, respectively. On 22 July, 2013, an extraordinary precipitation event with 120.8 mm of rainfall occurred. Exceptionally intense rainfall occurred from 8 July to 22 July in 2013 (totaling 233.4 mm). The daily average air temperature varied from approximately –5.0°C in January to approximately 23°C in August.

5.2. Experimental design and crop management

The field experiment included two treatments: BP and FM. A planting pattern of alternating wide (60 cm) and narrow (40 cm) row spacing was used for each treatment. The FM treatment was manually mulched with a piece of transparent plastic film (0.008 mm in thick) laid over the plot. Two treatments were maintained throughout the year with three replicates in 56 m^2 plots (8.0 m×7.0 m) in a randomized block design. After ridging treatment plots, chemical fertilizer was broadcast over the soil at rates of 90 kg N ha^{-1} (in the form of urea, N 46%), 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%). Next, the soil was plowed to incorporate the fertilizer. Additional nitrogen was applied in the form of urea (N 46%) using a hole-sowing machine in the furrows at a rate of 67.5 kg N ha^{-1} at the jointing and silking stages (Table 3). The maize was sown in April at a depth of 5 cm and at a density of 65 000 plants ha^{-1} and was harvested in September. Natural rainfall was the only source of soil water.

5.3. Gas sample collection and measurements

Soil-air samplers used in each plot were multiport gas wells, composed of poly-vinyl chloride (PVC) tubes with a 50 mm outer diameter and a 44-mm inner diameter (Cates and Keeney 1987). These sampling wells were composed of six gas chambers and were installed at depths of 7, 15, 30, 50, 70 and 90 cm (covering a range of 2.5 cm above and below each depth). Each gas chamber was capped with a septum that was suitable for gas sampling *via* a tubule (4-mm diameter**)** connected to the soil surface. Twelve air holes were then drilled in the lower part of the gas chamber wall (2-mm diameter) and these were covered by nylon mesh. Each gas tubule, made of organic glass, passed through a septum connected to a short piece of rubber tubing and a plastic three-way stopcock. This system remained closed at normal time. A soil-air sampler was placed into pre-drilled holes that were made using a 7-cm-diameter soil auger. The spaces around the tubes were backfilled with soil to maintain the integrity of the upper soil layers. We used a pencil rod to press the soil gently around the tubes. Before sampling, we set up the device by extracting and discarding 150 mL of soil air from each tube. The tubes were allowed

Table 3 Details of the time of crop management activities and fertilization

Year	Base fertilizer (40%, urea)	Sowing	The first topdressing (30%, urea)	The second topdressing (30%, urea)	Harvesting
2012	18 April	21 April	21 June	14 July	8 September
2013	18 April	23 April	30 June	16 July	12 September

to equilibrate for 48 h.

Gas samples were collected weekly from each gas chamber in the morning between 8:00 and 11:00. Between April 2012 and September 2013, the CH_4, CO_2 and N_2O concentrations were measured concurrently from the near-surface air above the soil surface (0 cm) and soil air at depths of 7, 15, 30, 50, 70 and 90 cm. The soil-air sampler was allowed to equilibrate for 1 min before sampling. A 10 mL plastic syringe was connected to the device by the three-way stopcock to circulate and mix the chamber gas before sampling 10 mL of the gas. The gas samples were analyzed by injecting 1 mL of the gas directly into a gas chromatograph (Agilent 7890A) with a flame ionization detector (FID) and an electron capture detector (ECD). The FID was set at 250°C to determine the CO_2 and CH_4 contents, and the ECD was set at 300°C to determine the N_2O content. The ratio of the area on the chromatograph of sample gas to that of a standard was multiplied by the concentration of the standard to determine the relative concentration of the sample; every eighth sample tested was the standard.

5.4. Soil variables

When sampling gas, the soil temperature was measured at depths of 7, 15, 30, 50, 70 and 90 cm using portable digital thermometers (JM624, Jinming Instrument Ltd., Tianjin, China). For convenience of expression, 7, 15, 30, 50, 70 and 90 cm were used to represent the depth of 0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm, respectively. Soil samples were collected each week at depths of 7 and 15 cm and every two weeks at depths of 30, 50, 70 and 90 cm during the MS. In addition, soil samples were collected every 20 or 30 d (approximately) at various depths during the FS. However, no soil samples were collected when the soil was frozen from December to early February of the following year. During sampling, three sub-samples were randomly collected from the areas between the maize rows using a 4-cm-diameter soil auger. These samples were combined to obtain a single aggregated sample for each plot. Next, the samples were oven-dried at 105°C for constant weight to determine soil gravimetric water content. Furthermore, the soil water-filled pore space (WFPS) was subsequently calculated using eq. 1 (Gao *et al.* 2014):

$$\text{WFPS}=\frac{W_s\times\rho_b}{1-\frac{\rho_b}{\rho_s}}\times 100\% \quad (1)$$

Where, W_s is soil gravimetric water content (%) at each soil depth, ρ_b is the soil bulk density (g m^{-3}) at each soil depth and ρ_s is the average soil particle density (2.65 g m^{-3}). Soil bulk density was measured using a cutting-ring (volume up to 100 cm^3). These data were collected every two weeks at soil depths of 7 and 15 cm, and every one month at soil depth of 30 cm. Average annual values of 1.43, 1.50 and 1.40 g cm^{-3} were used for depths of 50, 70 and 90 cm in our calculations. The deviations from the measured mean were less than the variations of WFPS in the soil and had little effect on the calculation.

5.5. Statistical analyses

The differences between the treatments were analyzed using one-way analysis of variance (ANOVA) followed by a *t*-test for least significant differences (LSD) at $P<0.05$ or $P<0.01$, respectively. The mean values, standard deviations, significance and correlation coefficients were estimated using SPSS16.0 (SPSS for Windows 10.0.1, SPSS Inc.) and Excel (Microsoft Corp., USA).

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