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ORIGINAL PAPER

# Methane uptake in semiarid farmland subjected to different mulching and nitrogen fertilization regimes

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**Abstract** Methane ($CH_4$) uptake by dryland soils is an important part in the global $CH_4$ budget and is sensitive to the management practice. This research measured the annual $CH_4$ flux over 2 years at the rain-fed maize fields in semiarid northwestern China using the static chamber technique. Methane uptake was measured under three mulching practices with the same nitrogen (N) application: no mulching (NM), gravel mulching (GM), and plastic film mulching (FM). In addition, methane uptake was also measured under film mulching management and three different N fertilizer rates: 0 (N0), 250 (N250), and 380 (N380) kg N ha$^{-1}$. The results showed that the rain-fed maize fields acted as a sink for $CH_4$, with the annual mean uptake rate of 21.3–40.8 μg $CH_4$-C m$^{-2}$ h$^{-1}$. The soil $CH_4$ uptake was positively correlated with soil temperature, but negatively correlated with soil moisture; these two factors together explained 35.5–50.9 % of the variance in $CH_4$ uptake. Compared to the NM treatment, the mulching treatments markedly increased the topsoil temperature, but the annual $CH_4$ uptake was significantly reduced by 5.2–6.7 % in the GM treatment and by 26.3 % in the FM treatment, most likely because the increased soil moisture restricted $CH_4$ oxidation and diffusion. The $CH_4$ uptake showed an increasing tendency with the N rate, probably because N fertilization decreased soil moisture and increased soil $NO_3^-$ content. These results help in understanding the effects of agricultural managements on $CH_4$ uptake and to properly assess the role of dryland soils in the global $CH_4$ budget.

**Keywords** Methane uptake · Plastic film mulching · Gravel mulching · Nitrogen fertilization · Semiarid areas · Soil variables

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## Introduction

Global warming and food security are two of the major challenges facing human beings in the twenty-first century (Tilman et al. 2011). Drylands, which comprise approximately 47 % of Earth's land surface (UNEP 2007), have made great contributions to global food production. Meanwhile, drylands also play a part in mitigating climate change, since the semiarid and arid regions account for about 40 % of the global soil sink for atmospheric methane ($CH_4$) (Galbally et al. 2008), which is one of the most potent greenhouse gases, contributing to 15–25 % of global warming (IPCC 2007). However, due to the low uptake capacity (Jacinthe et al. 2014; Le Mer and Roger 2001), soil $CH_4$ uptakes in cultivated soils is scarcely investigated (Barton et al. 2013; Galbally et al. 2008, 2010; Wang et al. 2015), which leaves great uncertainties in $CH_4$ budget. Recently, some research reported the annual $CH_4$ uptake up to 10.2 kg $CH_4$-C ha$^{-1}$ in the semiarid cropland soils (Rong et al. 2015), much higher than the previous results (Galbally et al. 2008). To improve our knowledge of $CH_4$ uptake in dryland regions and to accurately estimate the sink strength, more field measurements are urgently needed in various farming systems and areas.

Soil $CH_4$ uptake is affected by many factors, including soil temperature, soil water content, soil gas diffusivity, and various agricultural management practices (Le Mer and Roger 2001; Tellez-Rio et al. 2015). In dryland regions, soil surface mulching is an important and effective technique to improve crop productivity by alleviating water deficiency impacts and increasing soil temperature. Two common materials used by farmers are gravel and plastic film (Cuello et al. 2015; Gan et al. 2013; Yamanaka et al. 2004). The application of mulching film was estimated to be approximately 700,000 Mg per year around the world, with 80 % of the mulched surface distributed in China (Espí et al. 2006). However, how these mulching practices affect $CH_4$ uptake is still not clear. Since uptake of $CH_4$ is driven by soil temperature (Le Mer and Roger 2001; Gao et al. 2014), the $CH_4$ uptake in the gravel- and plastic film-mulched fields may increase with the elevated temperature caused by the mulching practice. On the other hand, mulching also increases soil moisture, which in turn is likely to inhibit $CH_4$ oxidation by reducing the activity of methanotrophs and limit the diffusions of atmospheric $CH_4$ and oxygen ($O_2$) into the soil (Le Mer and Roger 2001; Smith et al. 2003). In addition, mulching would also affect soil nutrient availability as well as activity and composition of microbial community (An et al. 2015; Liu et al. 2012a), which are directly or indirectly related to soil $CH_4$ oxidation (Bodelier and Laanbroek 2004). The combined effect of these factors needs to be investigated in the fields in order to properly assess the role of mulching practice on $CH_4$ uptake.

Nitrogen (N) fertilization is another important strategy to increase crop production in dryland farming areas (Li et al. 2009). It is generally believed to have complicated influence on soil $CH_4$ oxidation (Bodelier and Laanbroek 2004). Some researches indicated inhibited $CH_4$ uptake by N fertilization (Hu et al. 2013), especially at high rates (Aronson and Helliker 2010), while others reported no or positive effects of N fertilizer application on the $CH_4$ uptake (Bodelier and Laanbroek 2004; Hernandez-Ramirez et al. 2009; Liu et al. 2012b). The discrepancies between these results can be probably attributed to the differences among studies and sites in the crop type, precipitation, fertilizer type, N application rate, soil properties, and some of other agricultural managements. In the water-limited environment, the fertilizer response depends to a great extent on the soil moisture condition (Zhu et al. 2015). Given the fact that mulching could affect soil conditions (e.g., water content) as well as N cycling in the soil-plant system (Liu et al. 2015), the effect of N fertilization on $CH_4$ uptake may become more complicated under mulching conditions.

In the present study, we performed two field experiments over 2 years to monitor the annual $CH_4$ uptakes from rain-fed maize (*Zea mays* L.) fields in a semiarid region of northwestern China. The first experiment aimed to examine the effects of different mulching practices (gravel and plastic film mulching), and the second to investigate that of different N application rates under film mulching conditions because this practice is more popular and effective (Gan et al. 2013). The objectives of this study were (i) to evaluate the uptake capacity of the rain-fed cropped soils for atmospheric $CH_4$, (ii) to assess the effects of soil surface mulching and N fertilization on $CH_4$ uptake, and (iii) to identify the relationships between soil properties and $CH_4$ uptake in dryland regions.

## Materials and methods

### Site description

The field experiments were conducted from April 2011 to April 2013 at the Changwu Agricultural and Ecological Experimental Station (35.28° N, 107.88° E, 1200 m elevation), which is located in a typical dryland farming area on the Loess Plateau of northwestern China. The area has a semiarid monsoon climate with a mean annual air temperature of 9.2 °C and an average annual precipitation of 582 mm, 73 % of which falls between May and September (i.e., the maize growing season). The average annual evaporation from a free water surface is 1565 mm, with a ratio of precipitation to free evaporation of 0.37. In the two experimental seasons, the mean air temperature was 9.4 and 10.2 °C, respectively, for the year 2011–2012 and 2012–2013, 18.4 and 19.2 °C, respectively, for the maize growing seasons; the average annual precipitation was 642 and 458 mm, respectively, with 477 and 363 mm during the maize growing season (Fig. 1). The soils at this site are Cumuli-Ustic Isohumosols according to the Chinese Soil Taxonomy (Gong et al. 2007), and the soil texture is mainly silt loam soil. The soil properties in the top 20 cm before the start of the experiment was soil bulk density of 1.3 g $cm^{-3}$, pH of 8.4, organic matter of 16.4 g $kg^{-1}$, total N of 1.1 g $kg^{-1}$, available phosphorus (Olsen-P) of 20.7 mg $kg^{-1}$, and available potassium ($NH_4OAc$-K) of 133.1 mg $kg^{-1}$.

### Experimental design and field management

The $CH_4$ fluxes were monitored in two field experiments with each one organized in a completely randomized block design of three replicates. Each treatment area was 56 $m^2$ (7 m × 8 m). In the first experiment (Exp. 1), three treatments were setup with the same N fertilizer application rate (225 kg N $ha^{-1}$), including one plot with no mulching (NM), one with gravel mulching (GM), and one with plastic film mulching (FM). In the second experiment (Exp. 2), three N application rates in a film-mulched maize field were examined: no N applied (N0),

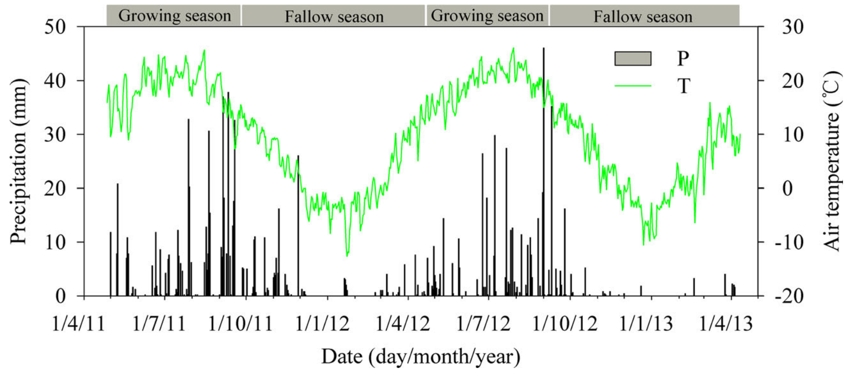


**Fig. 1** Daily precipitation (*P*) and mean air temperature (*T*) during field experiments

optimized N application for high-yielding film-mulched maize at a rate of 250 kg N ha$^{-1}$ (N250, Liu et al. 2014b), and high N application at a rate of 380 kg N ha$^{-1}$ (N380). The mulching treatments were manually mulched with a piece of transparent polyethylene plastic film (0.008 mm in thick) or 5–6 cm thick gravel (2–4 cm in size) over the plot.

In both experiments, N fertilizer in the form of urea (N 46 %) was applied three times for all N-fertilized treatments. After ridging the treatment plots, 40 % of the N fertilizer was manually broadcast as basal dressing over the soil surface before sowing and then plowed into the subsurface. The remaining N fertilizer was applied at the jointing and silking stages each with 30 % by using a hole-sowing machine following precipitation. In addition, 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 prior to sowing for all the plots.

All the treatments in the two experiments involved an alternating wide (60 cm) and narrow (40 cm) row spacing. The maize hybrid Pioneer 335 was used in this study. The plant density in Exp. 1 was 65,000 plants ha$^{-1}$, comparable to the densities in most farmers' fields in the area; the plant density in Exp. 2 was increased to 85,000 plants ha$^{-1}$ with a purpose to obtain high grain yields (Liu et al. 2014a). The maize seeds were sown to a depth of 5 cm using a hand-powered hole-drilling machine at the end of April and the cobs were harvested at the end of September. During the maize growing season, there was no irrigation, with the natural rainfall as the only water source for maize growth.

### Measurement of $CH_4$ fluxes

The annual $CH_4$ fluxes were measured manually using the closed static chamber method (Zheng et al. 2008). The stainless steel base frames (50 cm length × 50 cm width × 15 cm height) were inserted into the soil to a depth of 15 cm before sowing, with the sides at the middle lines of the wide and narrow row spacing, and a water-filled groove was located at the top of the frame to seal the upper chamber airtight during the period of sampling. The upper chambers were 50 cm length × 50 cm width × 50 cm height, equipped with two small fans at opposite angles 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 they were cut to 50 cm in height to fit the height of the chamber when the stalks grew too high (in early July). The details of cutting maize stalks were presented and discussed by Gao et al. (2014).

The $CH_4$ fluxes were measured every 4 days in the maize growing season and every 15 days during the fallow season. After fertilization and precipitation, gas samples were collected daily for 10 and 4 consecutive days, respectively. On each sampling day, the gas samples were collected using 50 ml polypropylene syringes equipped with three-way stopcocks. The sampling was between 8:30 a.m. and 11:30 a.m., at 0, 10, 20, and 30 min after the chambers were closed. For the FM treatment in Exp. 1, the $CH_4$ fluxes were only measured in 2012–2013.

The gas samples were analyzed immediately after sampling, using a gas chromatography (Agilent 7890A, Shanghai, China) equipped with a flame ionization detector (FID). The carrier gas was pure $N_2$ (99.999 %). The temperatures for the FID detector and column oven were 250 and 60 °C, respectively. The $CH_4$ uptake rate was calculated using the linear regression method. The uptake on non-sampling days was estimated by linear interpolation between every two adjacent intervals of the measurements (Mosier et al. 2006), and the annual uptake was calculated by summing up the daily fluxes.

### Additional parameters

Soil samples at the 0–20-cm depth were taken every 8 and 15 days during the maize growing and fallow season, respectively. After the fertilization and precipitation, the soil samples were taken once every other day within the 10 days following fertilization and within the 4 days following precipitation. However, no soil sample was taken 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 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 1 M KCl solution, and the extracts were analyzed using an automated flow injection analyzer (FLOWSYS, Italy).

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

### Statistical analyses

All statistical analysis was performed using the SPSS version 18.0 (SPSS Inc., Chicago, USA). The differences between the treatments in $CH_4$ uptake and soil parameters were analyzed using a one-way analysis of variance (ANOVA) and considered significant at $P < 0.05$ compared to the least significant difference (LSD). Relationships between $CH_4$ uptake and soil environmental variables were analyzed using SigmaPlot 10.0 software (Systat Software Inc., San Jose, CA, USA). The effect of soil temperature, WFPS, and soil $NO_3^-$ and $NH_4^+$ content on $CH_4$ uptake was evaluated by using the stepwise multiple linear regression model. Variables introduced into the models were tested at critical level alpha = 0.05.

## Results

### $CH_4$ uptake

The rain-fed maize field was shown to act as a sink for atmospheric $CH_4$ (Fig. 2). The mean $CH_4$ uptake rate was 39.5 and 28.8 μg $CH_4$-C $m^{-2}$ $h^{-1}$ for the Exp. 1 in the 2011–2012 season and the 2012–2013, respectively, and 31.8 and 22.6 μg $CH_4$-C $m^{-2}$ $h^{-1}$ for the Exp. 2 in the 2 years, respectively. Temporally, the $CH_4$ uptake presented an increased tendency from March to July every year, with the maximum of 41.8–75.5 μg $CH_4$-C $m^{-2}$ $h^{-1}$. The rate then decreased and maintained at a relatively low level in winter. Such seasonal pattern was in accordance with the dynamics of air temperature (Fig. 1). Uptake of $CH_4$ was inhibited by frequent and heavy precipitation, e.g., the period of late July 2011 and late June 2012 (Figs. 1 and 2). In contrast, the $CH_4$ uptake markedly increased within a short time after soil tillage in late April (Fig. 2).

The average $CH_4$ uptake rate was shown to change with the mulching practice and N application. The two mulching practices generally decreased soil $CH_4$ uptake rate (Fig. 2). In 2011–2012, the average $CH_4$ uptake rate for the GM treatment (38.1 μg $CH_4$-C $m^{-2}$ $h^{-1}$) was significantly lower than that of the NM treatment (40.8 μg $CH_4$-C $m^{-2}$ $h^{-1}$). However, the $CH_4$ uptake rate for the GM treatment (30.8 μg $CH_4$-C $m^{-2}$ $h^{-1}$) was not significant different from that for NM (31.9 μg $CH_4$-C $m^{-2}$ $h^{-1}$) in 2012–2013. The FM treatment further significantly reduced the $CH_4$ uptake rate to 23.7 μg $CH_4$-C $m^{-2}$ $h^{-1}$ in 2012–2013. The N fertilization significantly stimulated soil $CH_4$ uptake, except the N250 treatment in 2012–2013 (Fig. 2). The average $CH_4$ uptake rate for the N0, N250, and N380 treatments were 29.9, 32.3, and 33.2 μg $CH_4$-C $m^{-2}$ $h^{-1}$ from 2011 to 2012 and were 21.3, 22.3, and 24.2 μg $CH_4$-C $m^{-2}$ $h^{-1}$ from 2012 to 2013, respectively.

The annual $CH_4$ uptakes for the Exp. 1 and Exp. 2 ranged from 2.22 to 2.38 kg $CH_4$-C $ha^{-1}$ and 1.72 to 1.91 kg $CH_4$-C $ha^{-1}$ in 2011–2012, and from 1.43 to 1.94 kg $CH_4$-C $ha^{-1}$ and 1.31 to 1.50 kg $CH_4$-C $ha^{-1}$ in 2012–2013, respectively (Table 1). Compared to that of the NM treatment, the annual $CH_4$ uptake was significantly decreased by 5.2–6.7 % in the GM treatment and by 26.3 % in the FM treatment. The annual $CH_4$ uptakes showed no significant difference between the N0 and N250 treatments, though an increased tendency was observed with the N application rate. However, the annual uptakes in the N380 treatment were significantly increased by 11.0–14.5 % compared to the N0 treatment. For all of the treatments in the two experiments, the annual uptakes in 2011–2012 were significantly higher than those in 2012–2013.

### Soil temperature, WFPS, and soil mineral N content

The two mulching practices showed significant effects on soil temperature and water content (Table 2). Averaging across the seasons, the mean soil temperature was 0.9 and 1.1 °C higher in the GM treatment, respectively, for 2011–2012 and 2012–2013, and 1.5 °C higher in the FM treatment for 2012–2013 compared to that of the NM treatment (14.9 °C in 2011–2012 and 15.4 °C in 2012–2013). The soil water contents also increased under mulching conditions. In 2011–2012, the averaged WFPS of the GM treatment (47.6 %) was significantly higher than that of the NM treatment (45.1 %), but no significant difference was observed between these two treatments in 2012–2013 (47.6 and 47.0 %, respectively). By the FM treatment, the WFPS was further increased and averaged 50.6 % in 2012–2013, which was significantly higher than those of the NM and GM treatments. The mean soil $NO_3^-$ and $NH_4^+$ contents were slightly lower in the GM and FM treatments than those of the NM treatment, though no significant difference was found among the three treatments (Table 2).

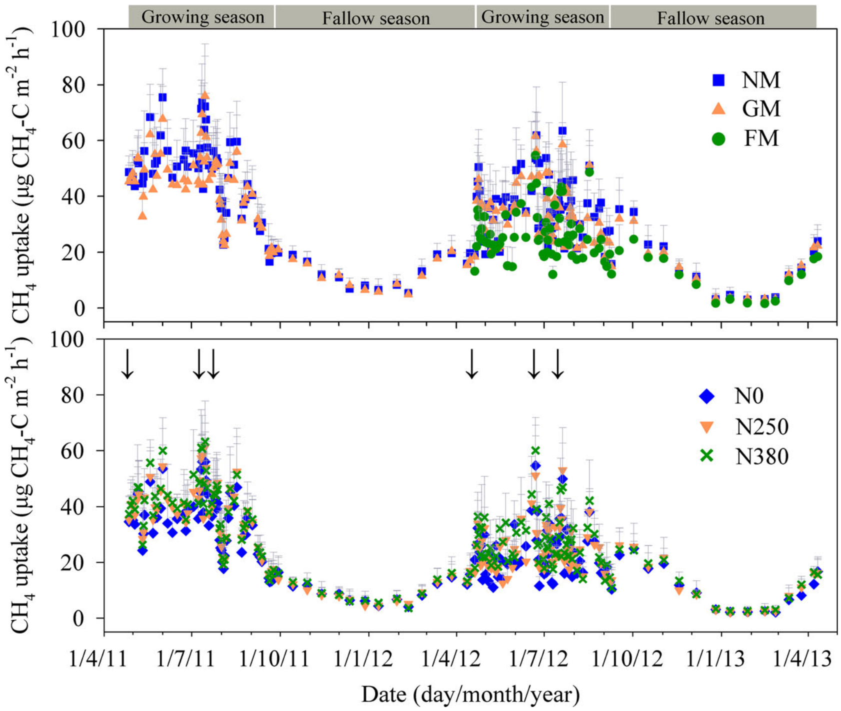


**Fig. 2** Seasonal dynamics of $CH_4$ uptake in soils of different mulching treatments and N application rates. *Bars* represent the standard deviations of the means ($n = 3$). *NM*, bare plot with no mulching; *GM*, gravel mulching; *FM*, plastic film mulching; *N0*, no N applied; *N250*, N applied at 250 kg N $ha^{-1}$; *N380*, N applied at 380 kg N $ha^{-1}$. *Arrows* denote the dates of fertilizer application

The soil temperature under film mulching conditions was not significantly influenced by N application, with an average of 15.7 °C in 2011–2012 and 16.7 °C in 2012–2013 (Table 2). On the other hand, the soil water content decreased with the N application rate (Table 2). From 2011 to 2012, the average WFPS of the N0 treatment (52.6 %) was similar to that of the N250 treatment (52.4 %), but significantly higher than that of the N380 treatment (50.5 %). From 2012 to 2013, the averaged WFPS for the N0, N250, and N380 treatments was 56.6, 53.7, and 51.9 %, significantly different from each other.

**Table 1** Annual $CH_4$ uptake (kg $CH_4$-C $ha^{-1}$) for different mulching treatments (Exp. 1) and N application rates (Exp. 2) in 2011–2012 and 2012–2013

| Treatment | | 2011–2012 | 2012–2013 |
|---|---|---|---|
| Exp. 1 | NM[a] | 2.38 ± 0.04a[b] | 1.94 ± 0.06a |
| | GM | 2.22 ± 0.05b | 1.84 ± 0.05b |
| | FM | – | 1.43 ± 0.01c |
| | Mean | 2.30 | 1.74 |
| Exp. 2 | N0 | 1.72 ± 0.03b | 1.31 ± 0.02b |
| | N250 | 1.83 ± 0.05ab | 1.39 ± 0.09ab |
| | N380 | 1.91 ± 0.08a | 1.50 ± 0.05a |
| | Mean | 1.82 | 1.40 |

[a] *NM* bare plot with no 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 $ha^{-1}$

[b] Values are expressed as mean ± standard deviation ($n = 3$). The values within the columns for each experiment (Exp.) followed by different lowercase letters are significantly different at $P < 0.05$ level

The soil $NO_3^-$ content was significantly increased by N application, averaging 6.6 mg N $kg^{-1}$ dry soil in N0, 26.2 mg N $kg^{-1}$ dry soil in N250, and 35.8 mg N $kg^{-1}$ dry soil in N380 in 2011–2012; for the same N application rates, the soil $NO_3^-$ content was 7.9, 34.7, and 49.7 mg N $kg^{-1}$ dry soil, respectively, in 2012–2013 (Table 2). In the two experimental seasons, the soil $NH_4^+$ content was similar for the three treatments except for the N0 treatment in 2011–2012, which was significantly lower than that of the two N-fertilized treatments (Table 2).

## Relationships between $CH_4$ uptake and soil variables

The regressions of daily $CH_4$ uptake rates against soil temperature, WFPS, and soil $NO_3^-$ and $NH_4^+$ content are depicted in Fig. 3. Uptake of $CH_4$ decreased exponentially with the increase of WFPS, accounting for 32.4 % of the variance for the Exp. 1 ($P < 0.0001$) and 40.0 % for the Exp. 2 ($P < 0.0001$). On the contrary, the $CH_4$ uptake increased linearly with the soil temperature and soil $NO_3^-$ content. Changes in soil temperature explained 38.5 % ($P < 0.0001$) and 40.9 % ($P < 0.0001$) of the variance respectively in Exps. 1 and 2, while the changes in soil $NO_3^-$ content explained 4.1 % ($P = 0.0015$) and 2.2 % ($P = 0.0125$) of the variance for the two experiments, respectively. The soil $NH_4^+$ content showed no significant effect on the $CH_4$ uptake.

The stepwise multiple linear regressions indicated soil temperature and soil moisture as the two key factors controlling $CH_4$ uptake, which together explained 35.5–49.3 % ($P < 0.05$) of the variation of the treatments in Exp. 1 and

**Table 2** The mean, median, and range of soil temperature, WFPS, and soil $NO_3^-$ and $NH_4^+$ content for different mulching treatments (Exp. 1) and N application rates (Exp. 2) in 2011–2012 and 2012–2013

| Treatment | | T[a] | | | W | | | N | | | A | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Median | Range | Mean | Median | Range | Mean | Median | Range | Mean | Median | Range |
| 2011–2012 | | | | | | | | | | | | | |
| Exp. 1 | NM[b] | 14.9b[c] | 17.8 | −3.9 to 22.3 | 45.1b | 43.7 | 20.1–70.6 | 25.5a | 25.1 | 5.4–51.2 | 10.8a | 9.2 | 1.2–60.1 |
| | GM | 15.8a | 18.9 | −3.6 to 23.9 | 47.6a | 47.4 | 25.4–67.8 | 23.2a | 19.4 | 5.9–55.1 | 10.4a | 8.9 | 1.3–62.4 |
| | FM | – | – | – | – | – | – | – | – | – | – | – | – |
| Exp. 2 | N0 | 15.7a | 18.5 | −3.3 to 23.8 | 52.6a | 54.8 | 31.2–68.5 | 6.6c | 5.9 | 2.2–18.0 | 9.0b | 8.2 | 1.3–39.8 |
| | N250 | 15.6a | 18.4 | −3.2 to 24.1 | 52.4a | 53.8 | 29.5–71.3 | 26.2b | 24.8 | 6.8–56.6 | 11.4a | 10.5 | 1.4–64.7 |
| | N380 | 15.7a | 18.4 | −3.3 to 24.0 | 50.5b | 53.2 | 28.7–67.5 | 35.8a | 34.6 | 6.9–78.0 | 11.4a | 9.5 | 1.2–83.9 |
| 2012–2013 | | | | | | | | | | | | | |
| Exp. 1 | NM | 15.4b | 17.9 | −4.5 to 22.8 | 47.0b | 47.0 | 24.2–67.4 | 30.8a | 29.2 | 5.6–79.9 | 11.1a | 9.4 | 0.6–30.8 |
| | GM | 16.5a | 18.9 | −4.0 to 23.9 | 47.6b | 47.8 | 26.6–63.6 | 26.5a | 19.4 | 5.5–85.3 | 10.7a | 8.4 | 0.9–32.5 |
| | FM | 16.9a | 19.4 | −4.3 to 25.2 | 50.6a | 50.9 | 28.3–64.9 | 27.9a | 18.2 | 4.8–84.9 | 10.8a | 8.9 | 0.6–35.8 |
| Exp. 2 | N0 | 16.8a | 19.2 | −3.8 to 24.6 | 56.6a | 57.1 | 40.0–67.8 | 7.9c | 7.1 | 2.0–17.7 | 10.4a | 8.8 | 0.6–33.1 |
| | N250 | 16.7a | 19.1 | −3.8 to 24.3 | 53.7b | 55.7 | 31.5–68.8 | 34.7b | 31.3 | 9.1–91.0 | 11.4a | 10.2 | 0.7–33.9 |
| | N380 | 16.5a | 19.0 | −3.8 to 24.2 | 51.9c | 53.9 | 30.2–65.2 | 49.7a | 47.5 | 11.1–120.7 | 11.4a | 9.9 | 0.6–34.0 |

[a] *T* the mean soil temperature of surface and 10-cm depth (°C), *W* soil water-filled pore space (WFPS) in the top 20 cm (%), *N* soil $NO_3^-$ content in the top 20 cm (mg N $kg^{-1}$), *A* soil $NH_4^+$ content in the top 20 cm (mg N $kg^{-1}$)

[b] Definitions of codes for the treatments are shown in the footnotes of Table 1

[c] The values within the columns for each experiment (Exp.) followed by different lowercase letters are significantly different at $P < 0.05$ level

42.6–50.9 % ($P < 0.05$) of the variation of the treatments in Exp. 2 (Table 3). The contribution of the factors in variation of $CH_4$ uptake could be ranked as WFPS > soil temperature > soil $NO_3^-$ content for all treatments in Exp. 1, and WFPS > soil temperature for all treatments in Exp. 2.

## Discussion

### Semiarid farmlands as a non-negligible $CH_4$ sink

The rain-fed maize fields in the semiarid region of our research area were found to be a sink for atmospheric $CH_4$ irrespective of mulching method or N application rate (Fig. 2). This result was consistent with other researches performed in aerobic upland soils (Barton et al. 2013; Galbally et al. 2008; Wang et al. 2015). The mean annual $CH_4$ uptake rates for the treatments ranged from 21.3 to 40.8 μg $CH_4$-C $m^{-2}$ $h^{-1}$ (Fig. 2), which were higher than the values of 5.4–16.9 μg $CH_4$-C $m^{-2}$ $h^{-1}$ summarized by Galbally et al. (2008) for croplands in semiarid regions. This was probably because the data they cited were almost all gained in areas with low rainfall (275–320 mm per year) and limited moisture in those regions resulted in suppression on methanotrophs (Jacinthe et al. 2014). Our values were also higher than the results (average 15 μg $CH_4$-C $m^{-2}$ $h^{-1}$) obtained by Gao et al. (2014) from a wheat-maize/soybean system in a region with similar precipitation (556 mm) to our study site, probably because the irrigation during crop seasons in their study increased soil moisture and subsequently restricted $CH_4$ diffusion and oxidation (Le Mer and Roger 2001). Since forest soils are regarded as the most active biotic sink for $CH_4$, followed by grassland soils and cropped soils (Le Mer and Roger 2001), most of the researches regarding $CH_4$ uptake were performed in forestry and/or grassland (Dutaur and Verchot 2007; Wang et al. 2014). However, this study found $CH_4$ uptake rates (ranging 21.3 to 40.8 μg $CH_4$-C $m^{-2}$ $h^{-1}$) were comparable to the values reported in the forest (averaged 48.2 μg $CH_4$-C $m^{-2}$ $h^{-1}$) and grassland (averaged 26.5 μg $CH_4$-C $m^{-2}$ $h^{-1}$) (Dutaur and Verchot 2007), suggesting that the cultivated soils, especially the rain-fed cropped soils in the arid and semiarid regions, are not a negligible $CH_4$ sink and should be given much more attention in future studies on the $CH_4$ balance.

### Effect of mulching and N fertilization on soil $CH_4$ uptake

In agreement with previous studies for agriculture (Gao et al. 2014) and forest ecosystem (Ueyama et al. 2015), our results showed that 35.5–50.9 % of the variation in $CH_4$ uptake was explained by soil temperature and soil moisture (Table 3), suggesting them as the key factors controlling $CH_4$ uptake.

We found the $CH_4$ uptake positively and linearly correlated with soil temperature (Fig. 3). The same relationship was also observed by Hu et al. (2013) and Wang et al. (2015) in

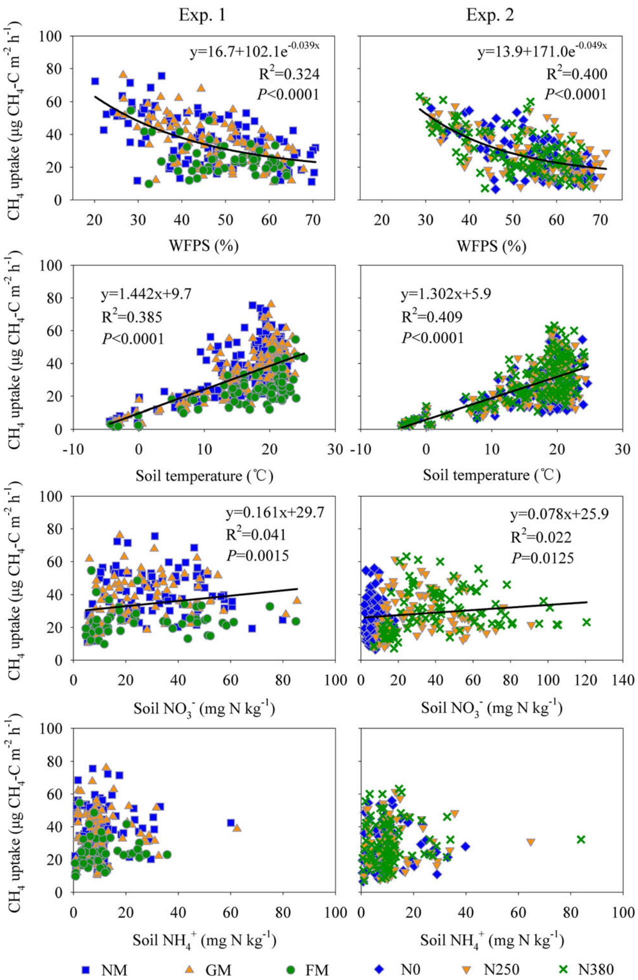


**Fig. 3** The $CH_4$ uptake rate response to soil water-filled pore space (*WFPS*) in the top 20 cm, mean soil temperature of surface and 10-cm depth, and soil $NO_3^-$ and $NH_4^+$ content in the top 20 cm for different mulching treatments (*Exp. 1*) and N application rates (*Exp. 2*). *NM*, bare plot with no 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 $ha^{-1}$

croplands. Castro et al. (1995) indicated that soil $CH_4$ uptake clearly increased from 0 to 0.12 mg $CH_4$-C $m^{-2}$ $h^{-1}$ as soil temperature increased from −5 to 10 °C. The optimum temperature for $CH_4$ consumption was about 25 °C in the temperate and subarctic environment (Dunfield et al. 1993). Either lower or higher soil temperature would decrease the activity of methanotrophs and enzymes (Liu et al. 2016; Menichetti et al. 2015). The soil temperature in our experiments (ranging −4.5 to 25.2 °C, Table 2) remained in the range that increases soil $CH_4$ oxidation capacity. However, the $CH_4$ uptake rates were maintained at a relatively low level during the fallow season (Fig. 2), probably because the low soil temperature during this period suppressed $CH_4$ oxidation.

The $CH_4$ uptake rate was found to exponentially decrease with the soil moisture (Fig. 3). Similar result was reported by Ueyama et al. (2015) in temperate forest soils and by Hu et al. (2013) in croplands. It is generally recognized that $CH_4$ is oxidized under aerobic environment. High soil moisture would reduce the activity of methanotrophs and restrict the diffusions of $CH_4$ and $O_2$ (Le Mer and Roger 2001; Smith et al. 2003). On the other hand, soil $CH_4$ uptake would also be inhibited under very low soil moisture conditions (Jacinthe et al. 2014). The optimal soil WFPS for $CH_4$ oxidation was approximately 25–49 % (Wang et al. 2015), which was exceeded in this research for most of the time, particularly for the mulching treatments (Table 2). Frequent and heavy precipitation could reduce $CH_4$ uptake (Figs. 1 and 2; Gao et al. 2014). Despite the higher soil temperature in 2012–2013, the soil $CH_4$ uptake for the treatments in this year was lower than that in 2011–2012 (Fig. 2 and Table 1). This was probably because the high rainfall (642 mm) in 2011–2012 exceeded the water demand of maize, leaving the excess rain water reserved in soil, which resulted in higher soil water contents in 2012–2013 (Table 2) and subsequently limited $CH_4$ uptake.

In this study, the soil $NH_4^+$ displayed no effect on $CH_4$ uptake, whereas a positive correlation was observed between $CH_4$ uptake and soil $NO_3^-$ content (Fig. 3). These results were in line with that reported by Gao et al. (2014) for cropped soils. However, the interactions between the N and $CH_4$ cycle are complex therefore with uncertainties (Bodelier 2011). Some studies demonstrated that the ammonium and nitrate could reduce $CH_4$ uptake while the others reported opposite results (Aronson and Helliker 2010; Bodelier et al. 2000; Bodelier and Laanbroek 2004; Yonemura et al. 2014). Our result of no relationship between soil $NH_4^+$ and $CH_4$ uptake (Fig. 3) was probably because that in the upland soils the $NH_4^+$ would be quickly oxidized by nitrifying bacteria in a short period of time after N application (Hu et al. 2013), since our previous study also observed that the soil $NH_4^+$ first increased and then rapidly decreased within a short time after fertilization (Liu et al. 2014c). Different from the effect of soil $NH_4^+$, the soil $NO_3^-$ content stimulated the $CH_4$ uptake (Fig. 3). N deficiency is a major nutritional constraint in the arable dryland soils (Li et al. 2009), which probably inhibit the activity and growth of microbial population (Ho et al. 2015). Increased soil $NO_3^-$ content resulted from N fertilization most likely relieved the N limitation on methanotrophic bacteria (Bodelier and Laanbroek 2004). In addition, higher soil $NO_3^-$ content could promote the synthesis of enzymes involved in the process of $CH_4$ oxidation (Bodelier and Laanbroek 2004). And the increased nitrifying population after fertilization also played a certain role in $CH_4$ oxidation (Bodelier and Laanbroek 2004).

Both mulching treatments, GM and FM, significantly increased the soil temperature and soil moisture (Table 2), which was in agreement with previous studies (Cuello et al. 2015; Wang et al. 2011). Being conciliated by the contrary effects of soil temperature and soil moisture on $CH_4$ uptake, the two mulching practices in our study ultimately decreased soil

**Table 3** Multiple linear regression models for $CH_4$ uptake of different mulching treatments (Exp. 1) and N application rates (Exp. 2)

| Treatment | | Regression equation ($P < 0.0001$) | Standardized estimated regression coefficient ($P < 0.05$) | | | | Number of observations | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | T[a] | W | A | N | | |
| Exp. 1 | All | $F = 39.652 + 1.056T - 0.537W + 0.086N$ | 0.362 | −0.434 | ns | 0.108 | 243 | 0.433 |
| | NM[b] | $F = 33.628 + 1.483T - 0.430W$ | 0.481 | −0.337 | ns | ns | 96 | 0.486 |
| | GM | $F = 40.449 + 1.187T - 0.527W$ | 0.429 | −0.407 | ns | ns | 96 | 0.493 |
| | FM | $F = 24.032 + 1.014T - 0.347W$ | 0.527 | −0.365 | ns | ns | 51 | 0.355 |
| Exp. 2 | All | $F = 41.675 + 0.967T - 0.566W$ | 0.364 | −0.455 | ns | ns | 288 | 0.475 |
| | N0 | $F = 47.957 + 0.928T - 0.684W$ | 0.379 | −0.506 | ns | ns | 96 | 0.509 |
| | N250 | $F = 38.052 + 0.936T - 0.486W$ | 0.341 | −0.422 | ns | ns | 96 | 0.426 |
| | N380 | $F = 38.196 + 1.103T - 0.527W$ | 0.403 | −0.416 | ns | ns | 96 | 0.477 |

*ns*, not significant at $P < 0.05$ level

[a] Definitions of codes for the soil variables are shown in the footnotes of Table 2

[b] Definitions of codes for the treatments are shown in the footnotes of Table 1

$CH_4$ uptake (Fig. 2 and Table 1). The result indicated that under mulching conditions the increase in soil moisture outran that increase in soil temperature in the effect on $CH_4$ uptake. Similar findings were also reported by Cuello et al. (2015), that film mulching reduced $CH_4$ uptake and caused higher $CH_4$ emission compared to that of the non-mulched soil because of the improved soil moisture underneath the film. Due to the higher soil water content (Table 2), the FM treatment further decreased $CH_4$ uptake by 22.3 % compared to that of the GM treatment (Table 1). Of course, the mulching film would to some degree impede the $CH_4$ diffusion, though certain gas molecules were found to be able to permeate the film (Nishimura et al. 2012). The application of mulching film reached nearly $1.4 \times 10^6$ Mg in 2013 with mulching areas of almost $1.8 \times 10^7$ ha in China (China Rural Statistical Yearbook 2014). This seems disadvantageous for reducing the agricultural greenhouse gas emissions in terms of $CH_4$ flux. However, the increase in food demand and changes in climate require management practices that should maximize crop productivity as well as minimize the negative environmental effects (Tilman et al. 2011). Our previous work reported that GM and FM increased maize grain yield from 8.4 to 11.7 and 13.4 Mg ha$^{-1}$, respectively, but did not stimulate nitrous oxide ($N_2O$) emission, and even decreased the yield-scaled $N_2O$ emission (Liu et al. 2014c). This present study pointed out that though the $CH_4$ uptake was reduced under mulching conditions, the mulched soil was still a sink for $CH_4$. These results suggest that soil mulching is an advisable technique to improve agriculture production in arid and semiarid regions.

In general, this study found soil $CH_4$ uptake was stimulated by N fertilizer application (Fig. 2 and Table 1), which was consistent with other researches (Bodelier and Laanbroek 2004). Liu et al. (2012b) reported that $CH_4$ uptake dramatically increased by an average of 16.3 and 44.9 % when the N fertilizer rate increased from 0 to 135 and 650 kg N ha$^{-1}$, respectively, in a maize field. However, some studies also indicated that $CH_4$ uptake was inhibited by N fertilization (Gao et al. 2014). Aronson and Helliker (2010) performed a meta-analysis and found that soil $CH_4$ uptake tended to decrease at N rates of higher than 100 kg ha$^{-1}$. We speculate that three reasons may have been responsible for the increased $CH_4$ uptake with N application rate in this study. First, N application promoted crop growth, which subsequently resulted in higher plant transpiration and then decreased soil water content (Table 2). Second, N fertilization markedly increased soil $NO_3^-$ content (Table 2). Third, improved crop growth with N fertilization indirectly created better conditions for microbial growth, such as higher carbon and N availability (Bodelier and Laanbroek 2004). Compared to the N250 treatment, N380 further increased the $CH_4$ uptake by 4.4–7.9 % (Table 1). However, such high N rate is not profitable for crop production because it could not produce higher grain yield (15.4 Mg ha$^{-1}$ for N250 and 14.4 Mg ha$^{-1}$ for N380), but significantly increased N losses (Liu et al. 2013, 2014c). These results indicated that rational N application is essential to minimize the negative environmental effects while maintain or increase crop yield.

## Conclusions

With the annual uptake of 1.31–2.38 kg $CH_4$-C ha$^{-1}$, the semi-arid cropped soils are not a negligible sink for atmospheric $CH_4$. The $CH_4$ uptake linearly increased with the soil temperature, but exponentially decreased with the soil moisture, with the two factors together explaining 35.5–50.9 % of the variation in $CH_4$ uptake. Both mulching practices of GM and FM significantly reduced $CH_4$ uptake, probably due to the improved soil water content. N fertilization decreased soil moisture and increased soil $NO_3^-$ content and therefore stimulated $CH_4$ uptake. These results contribute to our understanding of the effects of agriculture management regimes on the $CH_4$ uptake in dryland regions and are helpful to accurately estimate the regional and global $CH_4$ budget.

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## References

An T, Schaeffer S, Li S, Fu S, Pei J, Li H, Zhuang J, Radosevich M, Wang J (2015) Carbon fluxes from plants to soil and dynamics of microbial immobilization under plastic film mulching and fertilizer application using $^{13}C$ pulse-labeling. Soil Biol Biochem 80:53–61

Aronson EL, Helliker BR (2010) Methane flux in non-wetland soils in response to nitrogen addition: a meta-analysis. Ecology 91:3242–3251

Barton L, Murphy DV, Butterbach-Bahl K (2013) Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil. Agric Ecosyst Environ 167:23–32

Bodelier PLE (2011) Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils. Curr Opin Environ Sustain 3:379–388

Bodelier PLE, Laanbroek HJ (2004) Nitrogen as a regulatory factor of methane oxidation in soils and sediments. FEMS Microbiol Ecol 47:265–277

Bodelier PLE, Roslev P, Henckel T, Frenzel P (2000) Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. Nature 403:421–424

Castro MS, Steudler PA, Melillo JM, Aber JD, Bowden RD (1995) Factors controlling atmospheric methane consumption by temperate forest soils. Global Biogeochem Cycles 9:1–10

China Rural Statistical Yearbook (2014) China Statistical Press, Beijing (in Chinese)

Cuello JP, Hwang HY, Gutierrez J, Kim SY, Kim PJ (2015) Impact of plastic film mulching on increasing greenhouse gas emissions in temperate upland soil during maize cultivation. App Soil Ecol 91:48–57

Dunfield P, Knowles R, Dumont R, Moore TR (1993) Methane production and consumption in temperate and subarctic peat soils: response to temperature and pH. Soil Biol Biochem 25:321–326

Dutaur L, Verchot LV (2007) A global inventory of the soil $CH_4$ sink. Global Biogeochem Cycles 21:GB4013. doi:10.1029/2006GB002734

Espí E, Salmarón A, Fontecha A, García Y, Real AI (2006) Plastic films for agricultural applications. J Plast Film Sheeting 22:85–102

Galbally IE, Kirstine WV, Meyer CP, Wang YP (2008) Soil-atmosphere trace gas exchange in semiarid and arid zones. J Environ Qual 37:599–607

Galbally I, Meyer CP, Wang YP, Kirstine W (2010) Soil-atmosphere exchange of $CH_4$, CO, $N_2O$ and $NO_x$ and the effects of land-use change in the semiarid Mallee system in Southeastern Australia. Global Change Biol 16:2407–2419

Gan Y, Siddique KHM, Turner NC, Li X-G, Niu J-Y, Yang C, Liu L, Chai Q (2013) Ridge-furrow mulching systems—an innovative technique for boosting crop productivity in semiarid rain-fed environments. Adv Agron 118:429–476

Gao B, Ju X, Su F, Meng Q, Oenema O, Christie P, Chen X, Zhang F (2014) Nitrous oxide and methane emissions from optimized and alternative cereal cropping systems on the North China Plain: a two-year field study. Sci Total Environ 472:112–124

Gong ZT, Zhang GL, Chen ZC (eds) (2007) Pedogenesis and soil taxonomy. Beijing Science Press Publishing, Beijing **(in Chinese)**

Hernandez-Ramirez G, Brouder SM, Smith DR, Van Scoyoc GE (2009) Greenhouse gas fluxes in an eastern corn belt soil: weather, nitrogen source, and rotation. J Environ Qual 38:841–854

Ho A, El-Hawwary A, Kim SY, Meima-Franke M, Bodelier P (2015) Manure-associated stimulation of soil-borne methanogenic activity in agricultural soils. Biol Fertil Soils 51:511–516

Hu X-K, Su F, Ju X-T, Gao B, Oenema O, Christie P, Huang B-X, Jiang R-F, Zhang F-S (2013) Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. Environ Pollut 176:198–207

IPCC (2007) Climate change: the physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 539–542

Jacinthe P-A, Dick WA, Lal R, Shresth RK, Bilen S (2014) Effects of no-till duration on the methane oxidation capacity of Alfisols. Biol Fertil Soils 50:477–486

Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: a review. Eur J Soil Biol 37:25–50

Li SX, Wang ZH, Hu TT, Gao YJ, Stewart BA (2009) Nitrogen in dryland soils of China and its management. Adv Agron 101:123–181

Liu C, Wang K, Zheng X (2012a) Responses of $N_2O$ and $CH_4$ fluxes to fertilizer nitrogen addition rates in an irrigated wheat-maize cropping system in northern China. Biogeosciences 9:839–850

Liu Y, Mao L, He X, Cheng G, Ma X, An L, Feng H (2012b) Rapid change of AM fungal community in a rain-fed wheat field with short-term plastic film mulching practice. Mycorrhiza 22:31–39

Liu J, Bu L, Zhu L, Luo S, Chen X, Li S, Hill RL, Zhao Y (2013) Nitrogen fertilization effects on nitrogen balance and use efficiency for film-mulched maize in a semiarid region. Acta Agric Scand Sect B S P 63:612–622

Liu J, Bu L, Zhu L, Luo S, Chen X, Li S (2014a) Optimizing plant density and plastic film mulch to increase maize productivity and water-use efficiency in semiarid areas. Agron J 106:1138–1146

Liu J, Zhan A, Bu L, Zhu L, Luo S, Chen X, Cui Z, Li S, Hill RL, Zhao Y (2014b) Understanding dry matter and nitrogen accumulation for high-yielding film-mulched maize. Agron J 106:390–396

Liu J, Zhu L, Luo S, Bu L, Chen X, Yue S, Li S (2014c) Response of nitrous oxide emission to soil mulching and nitrogen fertilization in semi-arid farmland. Agric Ecosyst Environ 188:20–28

Liu J, Zhan A, Chen H, Luo S, Bu L, Chen X, Li S (2015) Response of nitrogen use efficiency and soil nitrate dynamics to soil mulching in dryland maize (*Zea mays* L.) fields. Nutr Cycl Agroecosyst 101:271–283

Liu W, Allison SD, Xia J, Liu L, Wan S (2016) Precipitation regime drives warming responses of microbial biomass and activity in temperate steppe soils. Biol Fertil Soils 52:469–477

Menichetti L, Ortigoza ALR, García N, Giagnoni L, Nannipieri P, Renella G (2015) Thermal sensitivity of enzyme activity in tropical soils assessed by the $Q_{10}$ and equilibrium model. Biol Fertil Soils 51:299–310

Mosier AR, Halvorson AD, Reule CA, Liu XJ (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. J Environ Qual 35:1584–1598

Nishimura S, Komada M, Takebe M, Yonemura S, Kato N (2012) Nitrous oxide evolved from soil covered with plastic mulch film in horticultural field. Biol Fertil Soils 48:787–795

Rong Y, Ma L, Johnson DA (2015) Methane uptake by four land-use types in the agro-pastoral region of northern China. Atmos Environ 116:12–21

Smith KA, Ball T, Conen F, Dobbie KE, Massheder J, Rey A (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. Eur J Soil Sci 54:779–791

Tellez-Rio A, García-Marco S, Navas M, López-Solanilla E, Rees RM, Tenorio JL, Vallejo A (2015) Nitrous oxide and methane emissions from a vetch cropping season are changed by long-term tillage practices in a Mediterranean agroecosystem. Biol Fertil Soils 51:77–88

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci U S A 108:20260–20264

Ueyama M, Takeuchi R, Takahashi Y, Ide R, Ataka M, Kosugi Y, Takahashi K, Saigusa N (2015) Methane uptake in a temperate forest soil using continuous closed-chamber measurements. Agric For Meteorol 213:1–9

UNEP (2007) Global Environment Outlook GEO-4: environment for development. United Nations Environment Programme, Nairobi

Wang Y, Xie Z, Malhi SS, Vera CL, Zhang Y, Guo Z (2011) Effects of gravel-sand mulch, plastic mulch and ridge and furrow rainfall harvesting system combinations on water use efficiency, soil temperature and watermelon yield in a semi-arid Loess Plateau of northwestern China. Agric Water Manage 101:88–92

Wang Y, Chen H, Zhu Q, Peng C, Wu N, Yang G, Zhu D, Tian J, Tian L, Kang X, He Y, Gao Y, Zhao X (2014) Soil methane uptake by grasslands and forests in China. Soil Biol Biochem 74:70–81

Wang L, Pan Z, Xu H, Wang C, Gao L, Zhao P, Dong Z, Zhang J, Cui G, Wang S, Han G, Zhao H (2015) The influence of nitrogen fertiliser rate and crop rotation on soil methane flux in rain-fed potato fields in Wuchuan County, China. Sci Total Environ 537:93–99

Yamanaka T, Inoue M, Kaihotsu I (2004) Effects of gravel mulch on water vapor transfer above and below the soil surface. Agric Water Manage 67:145–155

Yonemura S, Nouchi I, Nishimura S, Sakurai G, Togami K, Yagi K (2014) Soil respiration, $N_2O$, and $CH_4$ emissions from an Andisol under conventional-tillage and no-tillage cultivation for 4 years. Biol Fertil Soils 50:63–74

Zheng X, Mei B, Wang Y, Xie B, Wang Y, Dong H, Xu H, Chen G, Cai Z, Yue J, Gu J, Su F, Zou J, Zhu J (2008) Quantification of $N_2O$ fluxes from soil-plant systems may be biased by the applied gas chromatograph methodology. Plant Soil 311:211–234

Zhu Q, Schmidt JP, Bryant RB (2015) Maize (*Zea mays* L.) yield response to nitrogen as influenced by spatiotemporal variations of soil-water-topography dynamics. Soil Till Res 146:174–183