Effect of split application of nitrogen on nitrous oxide emissions from plastic mulching maize in the semiarid Loess Plateau

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\textbf{A R T I C L E H I S T O R Y}

Article history:
Received 18 October 2015
Received in revised form 23 December 2015
Accepted 24 December 2015
Available online xxx

\textbf{Keywords:}
N management
Yield-scaled \( \text{N}_2\text{O} \) emissions
Emission factor
Dry land

\textbf{A B S T R A C T}

Applying nitrogen (N) using split application to improve temporal synchronicity between crop-N demand and soil-N availability is a key strategy for improving nitrogen use efficiency (NUE). Its effect on nitrous oxide \( (\text{N}_2\text{O}) \) emissions has not been well evaluated, especially from plastic mulching maize (\textit{Zea mays} L.) in semiarid farmland. We conducted a two-year experiment to investigate the effect of split fertilizer N application on \( \text{N}_2\text{O} \) emissions. Three approaches each applying a total of 225 kg N ha\textsuperscript{-1} were tested either as a single application at sowing (N1), N applied with two splits at a ratio of 4:6 (N2), and N applied with three splits at a ratio of 4:3:3 (N3), a no-N application treatment was also included as a control (N0). Compared with the single application, split application of N significantly increased the grain yields by 4.7–9.1%. The cumulative \( \text{N}_2\text{O} \) emissions significantly increased by 18.1% under the three splits application in the 2014–2015 season compared with the single application but not in the growing season of 2015, which followed the same pattern with yield-scaled \( \text{N}_2\text{O} \) emissions. Fertilizer application combined with precipitation was the main driving factor for \( \text{N}_2\text{O} \) emissions. Therefore, the higher frequency (three times) of fertilizer application had a high risk for increasing \( \text{N}_2\text{O} \) emissions due to the relatively strong and frequent precipitation in maize mid and late growth period in this region; applying N with two splits is more suitable for this region which could produce higher grain yields, and lower risk of \( \text{N}_2\text{O} \) emissions.

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\section{1. Introduction}

Nitrous oxide \( (\text{N}_2\text{O}) \) is a potent greenhouse gas, with a 298 times higher global warming potential than carbon dioxide \( (\text{CO}_2) \) on a 100-year time scale; moreover, it contributes to the destruction of stratospheric ozone \((\text{O}_3)\) (IPCC, 2013). Due to human activities, the atmospheric concentration of \( \text{N}_2\text{O} \) has increased dramatically from approximately 270 ppbv in the pre-industrial era to 319 ppbv at present (Flückiger et al., 1999; Sowers, 2001). Agricultural soils are major sources of \( \text{N}_2\text{O} \), contributing approximately 60% of the global anthropogenic \( \text{N}_2\text{O} \) emissions (Forster et al., 2007). Increasing \( \text{N}_2\text{O} \) emissions from agriculture are heavily linked with the application of mineral nitrogen (N) fertilizer (Bouwman et al., 2002; Rochette et al., 2008), which has supporting the rapidly expanding population of the world in the last few decades (Tilman et al., 2011).

Most of N management practices to produce higher grain yields and nitrogen use efficiency (NUE) have been found to generate higher \( \text{N}_2\text{O} \) emissions (Fujinuma et al., 2011; Gagnon et al., 2011). Due to the different demand of plants for N at different growing stages, surplus nitrogen has a great environmental risk for leaching into groundwater or being lost to the atmosphere through ammonia volatilization and denitrification. Thus, adjusting the application timing of N fertilizer and improving temporal synchronicity between crop-N demand and soil-N availability is a key strategy for improving the NUE (Ribaudo et al., 2011). Previous studies have reported the effect of split N application and N application timing on \( \text{N}_2\text{O} \) emissions, but there were no consistent results. Ventera and Coulter (2015) found that applying granular urea using split applications to better coincide with crop N demand does not necessarily decrease and may actually increase \( \text{N}_2\text{O} \) emissions. A study on rain-fed potato (\textit{Solanum tuberosum} L.)

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http://dx.doi.org/10.1016/j.agee.2015.12.030
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production on a medium-textured soil indicated that N split application significantly reduced nitrate intensity but did not reduce N$_2$O emissions (Zebath et al., 2012). Burton et al. (2008) found that N split application decreased N$_2$O emissions within one of two growing seasons. These inconsistent results may be attributed to the potentially sensitive soil N$_2$O emissions due to a wide range of management, environmental, and soil factors that can affect N$_2$O-producing processes (Venterea et al., 2012).

In the maize production of Loess Plateau of China, N fertilizer was always applied with two splits at sowing and jointing stages or a single application at sowing by farmers. Previous studies found that consistent improvements in dry matter and N accumulation during the post-silking stage are essential for obtaining high yields from film-mulched maize (Liu et al., 2014b). Scharf et al. (2002) found that yield was still responsive to N application until silking, but that the potential yields was not achieved when N applications were delayed until that stage. So we hypothesized that splitting moderate quantities of topdressed N fertilizer to the silking stage could further increase grain yields. Previous studies have shown that high rates of N lead to much higher N$_2$O losses, and the emissions response to increasing N input is exponential rather than linear (Hoben et al., 2011; Shcherbak et al., 2014). So our hypothesis was that keeping the rate low by split application should reduce N$_2$O fluxes.

Plastic mulch is used worldwide in vegetable and grain production, especially in arid, semiarid and sub-humid areas (Zhou et al., 2012), which has been demonstrated to increase soil temperature and moisture, reducing water evaporation, and improve the soil nutrient availability (Li et al., 2004). Improvements of the soil microenvironment change the processes of nitrification and denitrification, thus affecting N$_2$O emissions. However, there was little information concerning N$_2$O emissions from maize under plastic mulch. The objective of this study was to quantify the effect of N split application on N$_2$O emissions, crop yields, and yield-scaled N$_2$O emissions in a plastic mulching maize cropping system in semiarid region.

2. Materials and methods

2.1. Site description

A two-year (2014 and 2015) experiment was conducted at Changwu Agricultural and Ecological Experimental Station of Chinese Academy of Sciences (35.28°N, 107.88°E, 1200 m altitude), which has a semiarid climate on the Loess Plateau of China. From 2009 to 2013, the mean annual air temperature is 9.7 °C, and the average annual precipitation is 555 mm, 73% of this falls during the maize growth season (MS), whereas the average potential evaporation is 1560 mm. Total precipitation during MS was 375 mm in 2014, and 361 mm in 2015, respectively. The main cropping system in this area includes harvesting one crop of maize or wheat per year. The soil at the experiment site is classified as Cumuli-Ustic Isohumosols according to the Chinese Soil Taxonomy (Gong et al., 2007). The soil properties at the top 20 cm were: bulk density 1.3 g cm$^{-3}$, pH 8.3, organic C 8.1 g kg$^{-1}$, total N 1.0 g kg$^{-1}$, available phosphorus (Olsen-P) 21.5 mg kg$^{-1}$, and available potassium (NH$_4$OAc–K) 135.2 mg kg$^{-1}$, and mineral N (NO$_3$–N + NH$_4$–N) 28.3 mg kg$^{-1}$.

2.2. Field experiments and crop management

The experimental design consisted of a completely randomized block with three replicates, with an area of 5 m $\times$ 6 m for each plot. The split application of N at the same rate of 225 kg ha$^{-1}$ was the major factor that was investigated. The four treatments were (i) no N as a control (N0), (ii) 100% N applied at sowing (N1), (iii) N applied at the sowing and jointing stages in a ratio of 4:6 (N2), and (iv) N applied at the sowing, jointing and silking stages in a ratio of 4:3:3 (N3). Half-film mulching was performed for all of the plots; the width of the plastic film and the interval of two films were both 0.5 m, and maize was seeded on both sides of the film, with a 0.5-meter row spacing. For base N, N fertilizer in the form of urea (N 46%) was manually distributed over the soil surface prior to sowing and then plowed into the soil; for topdressed N, N fertilizer was band applied in the middle of the no-film rows at a depth of 5 cm. Each plot was supplied with 40 kg P ha$^{-1}$ (calcium superphosphate, P$_2$O$_5$, 12%) and 80 kg K ha$^{-1}$ (potassium sulfate, K$_2$O, 45%) at sowing with the base N fertilizer. A high-yielding maize hybrid (Pioneer 335) was used in this study; the plant density was 65,000 plants ha$^{-1}$.

2.3. Gas sampling and measurements

N$_2$O emissions were measured manually using the closed static chamber method as described by Zheng et al. (2008). Each chamber was composed of a 50 × 50 × 50 cm top chamber and a stainless steel base frame (50 × 50 × 20 cm) with a water-filled groove to seal the top chamber airtight during the sampling period. The frames were inserted 20 cm into the soil prior to planting and remained there until planting the next year, each covered half of the plastic mulched and no mulched spacing. To avoid the sharp increase of air temperature inside the chamber in summer during the sampling period, each side of the top chamber was covered with Styrofoam coating. And two small fans were installed at opposite positions at the top of each chamber to ensure complete mixing of air inside the chamber. Two maize plants were placed in each chamber, and were cut 50 cm above the soil surface when their main stalks became too high at the beginning of July, but this cutting would not significantly affect the total seasonal N$_2$O emissions (Gao et al., 2014).

The gas samples were collected between 09:00 a.m. and 11:00 a.m. at intervals of 3–4 days in the MS, and half a month in the fallow season (FS), using 60 ml plastic syringes through a three-way stopcock and a Teflon tube connected to the chamber at 0, 10, 20 and 30 min after the chambers were closed. After the fertilization and precipitation events, gas samples were collected at an interval of 1–2 days for about 10 and 5 days, respectively, depending on when the gas fluxes decreased to the normal level.

The N$_2$O concentrations were analyzed on the sampling day using gas chromatography (Agilent 7890A, Shanghai, China) equipped with an electronic capture detector (ECD). High-purity di-nitrogen (N$_2$) (99.999%) was used as carrier gas at a flow rate of 21 ml min$^{-1}$. ECD detector and column oven were 300 and 60 °C, respectively. The N$_2$O fluxes 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.

2.4. Soil and weather measurements

Soil samples at a 20 cm depth for moisture and mineral N (NH$_4$+–N + NO$_3$–N) determinations were taken from each plot every 7 days and 15 days during the MS and FS using a 4-cm-diameter gage auger. Following fertilization and precipitation events samples were taken every other day for about 10 days and 5 days, respectively. However, no soil sample was collected during the period of soil freezing (December to early March next year). Each sample was a composite of two subsamples, of which one was taken from the no mulched bands, and the other one was taken from film mulched bands, in order to represent the aggregate condition. 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 using Eq. (1). To determine the soil NO$_3^-$–N and NH$_4^+$–N 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).

$$\text{WFPS} = \frac{\text{Soil water content}\% \times \text{Soil bulk density}}{2.65} \times 100\%$$ (1)

The soil temperatures at the surface and at a depth of 10 cm and the air temperature in the headspace of the chambers were measured at the start and end of gas sampling using portable digital thermometers (JM624, Jinming Instrument Ltd., Tianjin, China). The mean values of the two readings represented the temperature of during gas sampling. We used the mean temperature of the two soil layers as the soil temperature for each treatment in the following analysis. Precipitation data were obtained from an automatic weather station near the experimental site.

2.5. Grain yield and yield-scaled N$_2$O emissions

At harvest, 8 m$^2$ (4 rows each 4 m long) in the middle of each plot were manually harvested to determine the grain yield, the grain yield was expressed at 15.5% moisture. Yield-scaled N$_2$O emissions were calculated by dividing cumulative area-scaled emissions by grain yield.

2.6. Statistical analysis

Statistical analysis was conducted using the SPSS 20.0 software package for one-way analysis of variance (ANOVA); the statistically significant differences between different treatments were tested by the least significant difference (LSD) at the 5% level. The Pearson correlation analysis was performed to investigate the correlations between the N$_2$O emissions and soil variables.

3. Results

3.1. Environmental and soil conditions

Soil moisture (WFPS) and temperature, as well as daily precipitation, are graphed in Fig. 1. Strong precipitations occurred in the mid and late growth period in both years. The monthly mean air temperatures during the experimental period were well within the long-term observations. The soil temperature ranged from 11.8 to 24.0°C, with an average of 18.6°C during the MS in two years, and from 1.5 to 14.8°C, with an average of 4.2°C during the FS in 2014–2015. The WFPS in the top 20-cm soil layer markedly increased after heavy precipitation and then rapidly decreased due to soil evaporation and/or plant transpiration (Fig. 1). The WFPS varied from 19.4 to 71.7%, with an average of 47.1% during the experimental period; no significant difference in soil moisture was observed between different treatments. A persistent drought period (WFPS < 30%) emerged from July to August 2014 due to the high temperature and less rainfall.

The soil NO$_3^-$–N and NH$_4^+$–N contents in the top 20-cm profile showed a high response to N fertilization that sharply increased after fertilization. Thereafter, the NH$_4^+$–N content rapidly decreased to the baseline level, but the NO$_3^-$–N content was constant at a high level for a relatively long period of time (Fig. 2). The application of N fertilizer significantly increased the soil NO$_3^-$–N and NH$_4^+$–N contents, compared with the N0 treatment, especially in the MS. The averaged soil mineral N contents (NO$_3^-$–N + NH$_4^+$–N) were 18, 71, 106, and 95 mg N kg$^{-1}$ dry soil for the N0, N1, N2, and N3 treatments during the MS in 2014–2015, respectively, and 10, 46, 100, and 102 mg N kg$^{-1}$ dry soil for the N0, N1, N2, and N3 treatments during the MS in 2015, respectively. The soil mineral N contents were lower during the FS, varying from 7 to 9 mg N kg$^{-1}$ dry soil.

3.2. N$_2$O emissions

The N$_2$O emissions fluctuated with the fertilization and precipitation events at a high level during the MS and were maintained at a relatively low level during the FS (Fig. 3). Fertilization with N markedly increased N$_2$O emissions, especially after fertilization and precipitation, compared with the N0 treatment. The mean values of N$_2$O fluxes ranged from 16 to 23 μg N$_2$O–N m$^{-2}$ h$^{-1}$ during the MS in 2014–2015 and from 16 to 20 μg N$_2$O–N m$^{-2}$ h$^{-1}$ during the MS in 2015 among different N-fertilized treatments, compared with only approximately 4 μg N$_2$O–N m$^{-2}$ h$^{-1}$ during the FS in 2014–2015. For the N0 treatment, the N$_2$O fluxes was maintained at a low level of 3 μg N$_2$O–N m$^{-2}$ h$^{-1}$ in the 2014–2015 season and 4 μg N$_2$O–N m$^{-2}$ h$^{-1}$ during the MS of 2015, except for some small spikes after some precipitation events. The N$_2$O emissions peaked approximately 3 to 5 days after fertilization and precipitation events (Fig. 3). The largest peaks occurred in treatment N3 at 138 μg N$_2$O–N m$^{-2}$ h$^{-1}$ after a precipitation event following fertilizer topdressed with N at the silking stage in the MS of 2014–2015, and this may be attributed to the coordination effect of N fertilization and heavy precipitation. Due to almost no precipitation at a higher temperature, a dry period (WFPS < 30%) persisted from several days before being topdressed at the silking stage until early August in the MS of 2014–2015 (Fig. 1); thus, only a relatively small peak occurred after being topdressed at the silking stage in treatment N3, and the heavy precipitation (91 mm)

![Fig. 1. Soil temperature (°C), soil water filled pore space (WFPS,% in the top 20 cm of the soil profile, and precipitation (mm) during the field experiment. The soil temperature was the mean value at the surface and at a depth of 10 cm.](image)
following that immediately stimulated the nitrification and denitrification, thus generating a large sum of N₂O. Peaks of N₂O emissions persisted for approximately 2 weeks after base N fertilization in the N2 and N3 treatments in both growing seasons, while the high-intensive N₂O emissions that were induced by N fertilization persisted until almost one month later in the N1 treatment. This result may be attributed to a single application of total N in the N1 treatment, which supplied an adequate substrate for nitrification and denitrification.

Cumulative N₂O emissions increased significantly in N-fertilized treatments compared with the N0 treatment, ranging from 659 to 778 g N₂O-N ha⁻¹ in the 2014–2015 season and from 442 to 467 g N₂O-N ha⁻¹ in the MS of 2015 (Table 1). The cumulative N₂O emissions significantly increased with N three splits application compared with a single N application in the 2014–2015 season, while no difference was observed between different N split applications during the MS in 2015. The cumulative N₂O emissions showed no difference between different N split applications during the FS in 2014–2015, ranging from 197 to 211 g N₂O-N ha⁻¹ and accounting for 25.3–32.1% of the annual emissions. The N₂O emission factors for all of the N-fertilized treatments showed the same pattern as did the cumulative N₂O emissions, ranging from 0.18 to 0.23% in the 2014–2015 season and from 0.14 to 0.15% in the MS of 2015.

The daily N₂O emissions were significantly and positively correlated with the WFPS and the soil NO₃⁻–N and NH₄⁺–N content in the MS, while a significant negative correlation was observed between N₂O fluxes and soil temperature in the MS in both years (Table 2). No significant correlation was observed between N₂O fluxes and soil variables in the FS, except for the soil temperature.

### 3.3. Grain yields and yield-scaled N₂O emissions

The N application significantly increased the grain yields by 47.7–57.0% in 2014 and by 236.2–266.3% in 2015 (Table 1). The grain yields with two or three splits application of N were significantly higher than a single application of N in both years, but there was no difference between the two and three splits applications.
Table 1  Cumulative N₂O emissions, N₂O emissions factor (EF), grain yields, and yield-scaled N₂O emissions as affected by N application timing.

<table>
<thead>
<tr>
<th></th>
<th>N0</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Grain yields (tha⁻¹)</td>
<td>Cumulative N₂O emission (g N₂O–N ha⁻¹)</td>
<td>Emission factor (%)</td>
<td>Yield-scaled N₂O emission (g N₂O–N⁻¹)</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>2014</td>
<td>8.6 ± 0.4₄c</td>
<td>12.7 ± 0.1b₀</td>
<td>13.3 ± 0.1a</td>
<td>13.5 ± 0.2a</td>
</tr>
<tr>
<td></td>
<td>3.6 ± 0.4 c</td>
<td>12.1 ± 0.4 b</td>
<td>13.0 ± 0.6 a</td>
<td>13.2 ± 0.4 a</td>
</tr>
<tr>
<td>2014</td>
<td>MS</td>
<td>124 ± 12 d</td>
<td>448 ± 33 c</td>
<td>505 ± 25 b</td>
</tr>
<tr>
<td></td>
<td>FS</td>
<td>139 ± 7 b</td>
<td>211 ± 25 a</td>
<td>202 ± 11 a</td>
</tr>
<tr>
<td>Annual</td>
<td>263 ± 16 c</td>
<td>659 ± 54 b</td>
<td>706 ± 19 ab</td>
<td>778 ± 54 a</td>
</tr>
<tr>
<td>2015</td>
<td>MS</td>
<td>133 ± 12 b</td>
<td>467 ± 27 a</td>
<td>442 ± 36 a</td>
</tr>
<tr>
<td></td>
<td>MS</td>
<td>0.14 ± 0.01 c</td>
<td>0.17 ± 0.01 b</td>
<td>0.20 ± 0.02 a</td>
</tr>
<tr>
<td></td>
<td>FS</td>
<td>0.01 ± 0.01 a</td>
<td>0.03 ± 0.01 a</td>
<td>0.03 ± 0.01 a</td>
</tr>
<tr>
<td>Annual</td>
<td>0.18 ± 0.02 b</td>
<td>0.20 ± 0.01 ab</td>
<td>0.23 ± 0.03 a</td>
<td>0.14 ± 0.01 a</td>
</tr>
<tr>
<td>2015</td>
<td>MS</td>
<td>0.15 ± 0.02 a</td>
<td>0.14 ± 0.01 a</td>
<td>0.14 ± 0.01 a</td>
</tr>
</tbody>
</table>

₄ The type of error is standard deviation.
₀ Means within a row followed by the same letter are not significantly different at the 0.05 probability level.
₅ MS and FS denote the maize growing season and fallow season, respectively.

N application significantly increased yield-scaled N₂O emissions in the 2014–2015 season. There were no significant differences among different N splits application, except for N three splits and a single application in the 2014–2015 season. No significant differences were observed between different N treatments in yield-scaled N₂O emissions in the MS of 2015.

4. Discussion

4.1. N₂O emissions

Accumulating evidence suggests that increases in N₂O fluxes were best described by a nonlinear, exponentially increasing response to increasing N rate (McSwinney and Robertson, 2005; Hoben et al., 2011; Scherbak et al., 2014). So it might be expected that keeping the rate low by split application would decrease cumulative N₂O emissions, as compared to a single application, under the same total N rate. Most previous studies reported reduced or equivalent values of cumulative N₂O emissions under split or delayed N application compared with a single early N application. Yan et al. (2001) found no significant effect of split N application on N₂O emissions from maize under low rainfall conditions. Burton et al. (2008) reported split N application to be an effective strategy for reducing N₂O emissions in years in which there was significant rainfall during the period between planting and hilling. Drury et al. (2012) reported that delayed N application could reduce N₂O emissions when the soil moisture was high in the first month after planting. In contrast to these reports, in our study, the cumulative N₂O emissions with N three splits application was significantly higher than a single N application in the 2014–2015 season, but no significant difference was observed between two splits N application and a single N application. In the MS of 2015, there were no significant differences between different N splits treatments (Table 1). Similar results also were found by Venterea and Coulter (2015), who reported that applying granular urea using split applications to better coincide with crop N demand did not necessarily reduce and could actually increase N₂O emissions. In the present study, the equivalent, or even higher values of cumulative N₂O emissions under split N application in both seasons may be attributed to the combination of fertilization and heavy precipitation events. In the Loess Plateau of China, precipitation mainly distributed in the mid and late growth period of maize (Fig. 1), tended to coincide with topdressed N fertilization (Fig. 3).

In the 2014–2015 season, a 32-mm precipitation occurred within two weeks after topdressed N at the jointing stage (Fig. 1), followed by strong peaks with a peak value of 64 µg N₂O–N m⁻² h⁻¹ from the N2 treatment and 62 µg N₂O–N m⁻² h⁻¹ from the N3 treatment. Thereafter, a prolonged dry period (WFPS < 30%) persisted from several days before topdressed N application at the silking stage in the N3 treatment until early in August, following which only a peak week occurred with a peak value of 23 µg N₂O–N m⁻² h⁻¹. The lower emissions of N₂O after this fertilization may be due to lower soil WFPS. N₂O is produced in soils essentially through the processes of nitrification and denitrification (Vilain et al., 2014), which were closely related with soil moisture. Linn and Doran (1984) reported a linear relationship for N₂O production between WFPS of 30 and 70%. Some previous studies also found that the favorable soil temperature and moisture conditions for N₂O emissions were approximately 25°C and 60% WFPS, respectively (Schmidt et al., 2000; Gao et al., 2014). Because of the prolonged dry period, the mobilization of fertilizer N throughout the soil profile was limited by the lower soil moisture, which may have restricted root N uptake (Venterea and Coulter, 2014). Then, a series of heavy precipitation (total 91 mm) occurred early in August, and the soil WFPS increased sharply to

Table 2  Pearson correlation between daily N₂O emissions and soil variables for the maize growing season (MS) and fallow season (FS).

<table>
<thead>
<tr>
<th></th>
<th>MS</th>
<th>FS</th>
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<tbody>
<tr>
<td>n</td>
<td>r</td>
<td>n</td>
</tr>
<tr>
<td>Tmean⁹</td>
<td>131²</td>
<td>-0.294⁹</td>
</tr>
<tr>
<td>WFPS</td>
<td>97</td>
<td>0.407⁹</td>
</tr>
<tr>
<td>NO₃−N</td>
<td>78</td>
<td>0.421⁹</td>
</tr>
<tr>
<td>NH₄⁺−N</td>
<td>78</td>
<td>0.311⁹</td>
</tr>
</tbody>
</table>

⁹ Tmean, 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 (%); NO₃−N, the soil NO₃−N content in the top 20 cm (mg N kg⁻¹); NH₄⁺−N, the soil NH₄⁺−N content in the top 20 cm (mg N kg⁻¹).
² n, Number of observations.
⁹ Correlation is significant at the 0.01 level.
approximately 70%. In addition to an abundant substrate for nitrification and denitrification remaining in the soil, a vast amount of N2O was immediately emitted with a peak value of 138 μg N2O–N m−2 h−1. It is likely that split or delayed N application had a high risk of N2O emissions accompany with high precipitations.

The N2O emission factors (EF) in our study ranged from 0.18 to 0.23%, which fall into the range of 0.14–0.42% as reported by Venterea et al. (2011), but is lower than the default values of 1% as reported by the IPCC (2013) as well as other previous studies (Cai et al., 2013; Venterea and Coulter, 2014). Similar results were reported by Maris et al. (2015). The reason for the lower EF in our study might be a low N2O emissions, which may be attributed to the low soil organic carbon content at the experimental site. Soil N2O emissions rates are tightly connected to the soil organic carbon content. Maljanen et al. (2003) found that organic carbon-rich soils emitted very high N2O, which was mainly derived from the N mineralized from SOC rather than the N that was added as inorganic fertilizer. Sehy et al. (2003) and Zhuang et al. (2012) also found higher rates of fertilizer N-induced N2O emissions in organic carbon-rich soil.

Significant and positive correlations were observed between N2O emissions and soil and temperature during the MS and a significant positive correlation between them over the FS, similar to some previous studies (Venterea and Coulter, 2015). In contrast to our results, some other researchers have reported a significant positive correlation between N2O emissions and soil temperature (Ding et al., 2007; Allen et al., 2010; Liu et al., 2014c). Migliorati et al. (2014) found that N2O emissions was positively correlated with soil temperature during the maize growing season, but a negative correlation was observed during the wheat growing season. The negative correlation between N2O emissions and soil temperature in this study may be attributed to the high N2O emissions following the precipitation events, when the soil temperature was relatively lower (Fig. 1).

4.2. Yield-scaled N2O emissions

The yield-scaled N2O emissions reported by few previous studies varied greatly. In the present study, the yield-scaled N2O emissions ranged from 31 to 58 g N2O–N t−1 grain in the 2014–2015 season and from 34 to 39 g N2O–N t−1 grain in the MS of 2015 (Table 1), similar to the values (31–67 g N2O–N t−1) that were reported by Halvorson et al. (2010) in a study of irrigated corn in Colorado. However, a yield-scaled N2O emissions more than 10 times greater than our values was reported by some other studies. Gagnon et al. (2011) found a range of 1.3 to 2.0 kg N2O– N t−1 grain in a clay soil receiving sidedress N applications for rainfed corn in eastern Canada, and a range of 1.0 to 2.5 kg N2O– N t−1 grain was also found in a rainfed wheat system in China (Wei et al., 2010). In the present study, the lower yield-scaled N2O emissions may be attributed to the higher grain yields and the lower annual emissions. Plastic film mulching is an effective strategy for producing high grain yields in arid and semiarid regions (Anikwe et al., 2007). Compared with no mulching, the grain yields was significantly increased by 3.0–6.3 t ha−1 under plastic film mulching (Liu et al., 2014a).

Expressing N2O emissions on a yield-scale basis provides additional information to evaluate agricultural practices. For instance, Liu et al. (2014c) reported that neither gravel mulching nor plastic film mulching increased cumulative N2O emissions, but both treatments dramatically reduced the yield-scaled N2O emissions due to the higher grain yields compared with that of the non-mulched treatment. In the present study, the same grain yields were obtained with two or three splits application of N fertilizer, which were significantly higher than with a single application, while yield-scaled N2O emissions with two splits N application did not increase compared to a single application, but a significant increase was observed from the plots with three splits N application. Similar results were reported by Venterea and Coulter (2015), who found a greater yield-scaled N2O emissions with N splits application. This result shows a greater environmental risk under three splits N application than applied with two splits, on the premise of obtaining high grain yields for this experimental condition.

5. Conclusions

Split application of N could significantly increase the maize grain yields under plastic film mulching compared with a single application. The annual N2O emissions and yield-scaled N2O emissions significantly increased under some weather conditions when the three splits application treatment was employed. Fertilization combined with precipitation was the main driving factor for N2O emissions, which was hard to be controlled and predicted in a rainfed N application. N three splits application had a high risk for increasing N2O emissions due to the relatively strong and frequent precipitation in maize mid and late growth period in this region; applying N with two splits is more suitable for this region which could produce higher grain yields, and relatively lower risk of N2O emissions.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (41401343, 31270553, 51277917), the Ministry of Science and Technology of China (2015CB150402) and the Special Fund for Agricultural Profession (201103003).

References


