INFLUENCE OF N SPLIT APPLICATION ON NH₃ VOLATILIZATION LOSSES AND N RECOVERY EFFICIENCY FROM PLASTIC MULCHING MAIZE IN LOESS PLATEAU, CHINA

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Abstract. Ammonia (NH₃) volatilization is one of the main reasons of applied-N loss from agricultural cropping systems. Adjusting the application timing of N fertilizer to improve temporal synchronicity between crop-N demand and soil-N availability could result in higher nitrogen (N) recovery efficiency (NRE) and lower N losses. A two-year experiment was conducted to investigate the effect of split fertilizer N application on NH₃ volatilization, grain yield, and NRE. Four treatments were included according to the N application ratio: (i) a single application of total N fertilizer at sowing (N1), (ii) N applied with two splits at a ratio of 4:6 (N2), (iii) N applied with three splits at a ratio of 4:3:3 (N3), and (iv) no N applied as a control (N0). The results show that NH₃ fluxes peaked at 3-5 days after fertilization and then dropped sharply within the next week. NH₃ fluxes increased significantly with N application rate and were significantly and positively correlated with soil NH₄⁺-N content. Slight precipitation (< 10 mm) promoted NH₃ volatilization, while heavy precipitation (> 10 mm) restrained it. Applying N with two or three splits significantly increased the grain yield, total N uptake, and NRE of maize and significantly reduced NH₃ volatilization losses.

Keywords: Dräger-tube method, N application time, N application rate, N loss, grain yield

Introduction

Ammonia (NH₃) volatilization is a major pathway of nitrogen (N) losses in agricultural systems worldwide, which results in low fertilizer N recovery efficiency (NRE) and many other environmental issues, such as soil acidification and surface water eutrophication through N deposition (Behera et al., 2013). In addition, NH₃ is considered a dominant air pollution source, accounting for 25-60% of the total PM2.5 mass (Sutton et al., 2013), and could become a secondary source of N₂O (Sutton et al., 2008). Agricultural activities reportedly contribute up to 90% of the total NH₃ emissions to the atmosphere (Boyer et al., 2002), with the majority originating from livestock production and approximately 12% resulting from N fertilizer application (Ferm, 1998). An average of 18% of applied synthetic fertilizer N is estimated to be lost as NH₃ globally (Pan et al., 2016). China is the world’s largest NH₃ emitter with annual emissions that are 2.7 and 3.0 times higher than those of the European Union and the
United States, respectively (Paulot et al., 2014). The total NH\textsubscript{3} emission of China was estimated to be 3.55 Tg N in 2005, with an estimated 13.2\% of N from fertilizer NH\textsubscript{3} volatilizing (Zhang et al., 2011). The factors influencing NH\textsubscript{3} volatilization include environmental parameters, such as soil pH, moisture, and temperature as well as precipitation (Ma et al., 2010; Yang et al., 2015; Pan et al., 2016) and N fertilizer management practices, such as the use of different types of N fertilizer, N rate and application methods (Liu et al., 2015; Yang et al., 2019).

Urea is one of the most widely used N fertilizers worldwide because of its high N concentration, and its hydrolysis is known as a key process in inducing NH\textsubscript{3} volatilization by producing highly concentrated NH\textsubscript{4}\textsuperscript{+}-N with sharply increased pH (Black et al., 1987). NH\textsubscript{3} volatilization from urea accounts for approximately 10-35\% of the N applied in field crop planting (Soares et al., 2012). Due to the different demand of plants for N at different growth stages, surplus nitrogen is a great environmental risk in that it can leach into groundwater or be lost to the atmosphere through NH\textsubscript{3} volatilization and denitrification. Thus, adjusting the application timing of N fertilizer and improving temporal synchronicity between crop-N demand and soil-N availability are key strategies for improving the NRE (Ribaudo et al., 2011). Field experimental data have shown that grain yields, plant N uptake, and NRE increase with increases in topdressed N fertilizer (López-Bellido et al., 2005; Cui et al., 2008). Scharf et al. (2002) found that crop yields were still responsive to N application until the silking (R1) stage but that the potential yields were not achieved when N applications were delayed until that stage. Applying N with three splits could produce higher grain yields and higher cumulative N\textsubscript{2}O emissions than a single application of N (Wang et al., 2016). Previous studies have shown that high rates of N lead to much higher NH\textsubscript{3} losses, and the emissions response to increasing N input is exponential rather than linear (Ma et al., 2010). Therefore, we hypothesize that maintaining a low rate of N application by using a split application should reduce NH\textsubscript{3} volatilization losses.

Plastic mulching is used worldwide in vegetable and grain production, especially in arid, semiarid and subhumid areas (Chen et al., 2014), due to its ability to increase soil temperature and moisture, reduce water evaporation, and improve soil nutrient availability (Li et al., 2004). In addition, as a physical barrier, plastic mulching restricts gas exchange between the soil and atmosphere, thus affecting NH\textsubscript{3} volatilization. However, there is little information concerning NH\textsubscript{3} volatilization losses from maize under plastic mulching. The objective of this study was to quantify the effect of N split application on NH\textsubscript{3} volatilization, crop yields, and NRE in a plastic mulching maize cropping system on the Loess Plateau of China.

Materials and methods

Site description

The field experiment was conducted at Changwu Agricultural and Ecological Experimental Station of Chinese Academy of Sciences (35.28°N, 107.88°E, 1200 m altitude) in 2014 and 2015, 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\(^{-1}\).

**Experimental design**

The experimental design consisted of a completely randomized block with three replicates and an area of 5 m × 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 (V8) stages in a ratio of 4:6 (N2), and (iv) N applied at the sowing, V8 and R1 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 row spacing of 0.5 m. For basal N, N fertilizer in the form of urea (N 46%) was manually distributed over the soil surface prior to sowing and then mixed with the soil of the 0-15 cm layer; for topdressed N, N fertilizer was applied in a band 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\(^{-1}\).

**NH\(_3\) volatilization measurements**

The calibrated Dräger-Tube method (DTM) was used to quantify NH\(_3\) volatilization (Pacholski et al., 2006) as this method has been shown to be well suited for NH\(_3\) measurements in multiplot field trials (Ni et al., 2014; Wolf et al., 2014). During the measurement, four stainless steel rings were installed in the upper soil of one plot for each treatment directly after fertilization, 2 on the edge of the mulch, and 2 on the bare land, then they were connected to an NH\(_3\) indicator tube and an automatic pump to ensure a defined flow rate. Air was simultaneously sucked through four connected chambers and led through a NH\(_3\) tube (Fig. 1). Damaged tubes were exchanged by new tubing. Using Drägertubes for different NH\(_3\) concentration ranges allowed measurements of NH\(_3\) concentrations ranging from 0.1 to 70 ppm. In conjunction with all NH\(_3\) measurements, wind speeds at heights of 2.0 m and 0.2 m were recorded every 10 min for the duration of every measuring period (approximately 10-14 days after N fertilizer application until NH\(_3\) volatilization losses were no longer detected), which were used for calculating the calibrated NH\(_3\) fluxes.

**Soil property measurements**

Soil samples at a 20 cm depth were taken from each plot for the moisture and NH\(_4^+\)-N determinations, while NH\(_3\) volatilization was measured using a 4-cm-diameter gauge auger. Each sample was a composite of two subsamples, of which one was taken from the no-mulch bands and the other was taken from film mulched bands, 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 Equation 1. To determine the soil
NH$_4^+$-N content, representative fresh subsamples (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). The soil temperatures at the surface and at a depth of 10 cm were measured using portable digital thermometers (JM624, Jinming Instrument Ltd., Tianjin, China). Precipitation data were obtained from an automatic weather station near the experimental site.

\[
WFPS = \frac{\text{Soil water content} \times \text{Soil bulk density}}{1 - \frac{\text{Soil bulk density}}{\text{Soil density}}} \times 100\% 
\]  
(Eq.1)

**Grain yield and N recovery efficiency**

At harvest, 8 m$^2$ (4 rows each 4 m long) in the middle of each plot was manually harvested to determine the grain yield, and the grain yield was expressed at 15.5% moisture.

N recovery efficiency (NRE) was calculated by difference method using Equation 2.

\[
\text{NRE} (\%) = \frac{\text{N uptake in fertilized plot (kg ha}^{-1}\text{)} - \text{N uptake in unfertilized plot (kg ha}^{-1}\text{)}}{\text{N application rate (kg ha}^{-1}\text{)}}
\]  
(Eq.2)

**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 NH$_3$ volatilization flux and soil variables.

**Results**

**Soil WFPS, temperature and NH$_4^+$-N content**

The soil WFPS and temperature during NH$_3$ volatilization measurements over two years are shown in Figure 2. The mean soil temperature during the application of basal N, topdressed N at the V8 stage (T$_{V8}$-N) and topdressed N at the R1 stage (T$_{R1}$-N) were 15.5 °C, 21.3 °C and 21.7 °C, respectively, in 2014 and were 15.6 °C, 18.3 °C and 18.4 °C, respectively, in 2015. Soil WFPS fluctuated with precipitation events, varying.
from 20.6 to 59.4% in 2014 and from 36.7 to 64.4% in 2015, and there was no difference among the four treatments.

The soil NH$_4^+$-N content increased sharply after the application of N fertilizer and then returned to normal within approximately one week (Fig. 3). The mean soil NH$_4^+$-N content during the basal N application in the N1 treatment was 66.1 mg kg$^{-1}$, which was significantly higher than that in the N2 (20.7 mg kg$^{-1}$) and N3 (17.9 mg kg$^{-1}$) treatments in 2014. Relatively low soil NH$_4^+$-N content was measured during basal N application in 2015, with mean values of 21.6, 5.1 and 4.2 mg kg$^{-1}$ in the N1, N2 and N3 treatments, respectively. After the TV8-N application, the mean soil NH$_4^+$-N content was 55.9 mg kg$^{-1}$ and 26.1 mg kg$^{-1}$ in treatments N2 and N3, respectively, in 2014 and 163.1 mg kg$^{-1}$ and 77.7 mg kg$^{-1}$, respectively, in 2015, respectively. After the TR1-N application in the N3 treatment, the mean soil NH$_4^+$-N content reached 33.2 mg kg$^{-1}$ and 59.1 mg kg$^{-1}$ in 2014 and 2015, respectively. Overall, the mean soil NH$_4^+$-N contents across the whole growth period were 4.2, 28.5, 30.3 and 24.6 mg kg$^{-1}$ in the N0, N1, N2 and N3 treatments, respectively, in 2014 and were 1.5, 7.4, 59.1 and 49.1 mg kg$^{-1}$, respectively, in 2015.

**Figure 2.** Soil moisture and temperature dynamics during NH$_3$ volatilization measurements in 2014 and 2015.
**NH₃ volatilization flux**

The dynamics of NH₃ volatilization fluxes with different N split applications are shown in Figure 4. Since NH₃ volatilization mainly occurred after fertilization, it was only determined within two weeks after fertilization in this study. Under different N application periods, the rate of NH₃ volatilization usually peaked at 3-5 days after fertilization and then dropped sharply within the next week. After the basal N application, the mean NH₃ volatilization rate in the two years was 71 g ha⁻¹ h⁻¹ in the N1 treatment, which was significantly higher than the 5, 24, 27 g ha⁻¹ h⁻¹ in the N0, N2 and N3 treatments, respectively, due to its higher N application rate. The highest volatilization rates from N1 were 193 and 234 g ha⁻¹ h⁻¹ after the basal N applications in 2014 and 2015, respectively, while only 100-130 g ha⁻¹ h⁻¹ were observed in the N2 and N3 treatments. After the Tᵥ₈-N application, the mean rates of NH₃ volatilization from the N2 treatment were 18.8 and 26.5 g ha⁻¹ h⁻¹ in 2014 and 2015, respectively, which were significantly higher than those from the N3 treatment (10.4 g ha⁻¹ h⁻¹ in 2014 and 11.8 g ha⁻¹ h⁻¹ in 2015). A small emissions peak emerged in the N3 treatment when Tᵣᵢ₁-N was applied, with the highest volatilization rates of 37.5 g ha⁻¹ h⁻¹ in 2014 and 77.5 g ha⁻¹ h⁻¹ in 2015.

*Figure 3. Soil NH₄⁺-N dynamics after the application of basal and topdressed N in 2014 and 2015. Bars denote standard deviations of soil NH₄⁺-N content on three replicate plots.*
Figure 4. NH₃ volatilization fluxes after the application of basal and topdressed N in 2014 and 2015. Bars denote standard deviations of NH₃ fluxes on three replicate plots.

The total NH₃ volatilization and fertilizer-induced emission (FIE) are shown in Table 1. The total NH₃ volatilizations under different N split applications were 13.5-20.4 kg ha⁻¹ and 14.2-21.5 kg ha⁻¹ in 2014 and 2015, respectively, accounting for 6.0%-9.1% and 6.3%-9.6% of the total N application rates, respectively. The amount of NH₃ volatilization increased with increasing N levels applied after the basal or topdressed N applications. Compared to the single N application (N1), N applications with two or three splits significantly reduced the NH₃ volatilization losses by 30.5%. The FIE of NH₃ from basal N was 7.6% (averaged over two years), which was significantly higher than that from topdressed N (5.2%) in the N2 treatment. For the N3 treatment, a higher FIE of NH₃ was measured from basal N (8.4%) than from topdressed N (5.7%).

The NH₃ volatilization flux was significantly and positively correlated with the soil NH₄⁺-N content, while no significant correlation was observed among the NH₃ volatilization flux, soil WFPS and temperature (Table 2).

Grain yield and N recovery efficiency

Compared with the N0 treatment, the N fertilizer application treatments significantly increased the grain yield of maize, varying from 12.4 to 13.3 t ha⁻¹ under different N.
split applications over two years. The mean yields in the two years were 13.2 and 13.4 t ha$^{-1}$ in the N2 and N3 treatments, respectively, which were significantly higher than that of in the treatment N1 of 12.4 t ha$^{-1}$. The total N uptake varied from 193.9 to 238.5 kg ha$^{-1}$ in the fertilized treatments, and split N application significantly increased the total N uptake. The average NRE across two years was 47.3%, 58.8% and 67.1% in the N1, N2 and N3 treatments, respectively. In comparison to N1, applying N with two or three splits increased the NRE significantly.

**Table 1. Accumulated NH$_3$ volatilization and fertilizer induced emission (FIE) from basal and topdressed N fertilizer**

| Treatments | N rate (kg ha$^{-1}$) | Total NH$_3$ volatilization (kg ha$^{-1}$) | Fertilizer-induced emission (%) |
|------------|------------------------|---------------------------------------------|-------------------------------|
|            |                        | 2014                                       | 2015                          | 2014                          | 2015                          |
| N1         | 225                    | 20.4 aA                                   | 21.5 aA                       | 9.1 aA                       | 9.6 aA                       |
| N2         | B 90                   | 7.1 b                                      | 6.5 b                         | 7.9 a                        | 7.2 b                        |
|            | TV$_8$ 135             | 6.4 b                                      | 7.7 b                         | 4.7 b                        | 5.7 c                        |
|            | Total 225              | 13.5 B                                    | 14.2 B                        | 6.0 B                        | 6.3 B                        |
| N3         | B 90                   | 7.8 b                                      | 7.3 b                         | 8.6 a                        | 8.1 b                        |
|            | TV$_8$ 67.5            | 3.4 c                                      | 3.5 c                         | 5.0 b                        | 5.2 c                        |
|            | TK$_1$ 67.5            | 3.6 c                                      | 4.9 c                         | 5.4 b                        | 7.3 b                        |
|            | Total 225              | 14.8 B                                    | 15.7 B                        | 6.6 B                        | 7.0 B                        |

Different lowercase letters within a column indicate significant differences (p < 0.05). Different capital letters within a column indicate significant differences (p < 0.05). B denotes basal N; TV$_8$ and TK$_1$ denote topdressed N at the eight-leaf stage and the silking stage, respectively.

**Table 2. The relationship between NH$_3$ volatilization flux and soil properties**

|                  | Soil NH$_4^+$-N | WFPS | Soil temperature |
|------------------|-----------------|------|------------------|
| NH$_3$ flux      | 0.288***        | 0.021| -0.089           |

**Correlation is significant at the 0.01 level**

**Discussion**

Urea applied to soil will be rapidly hydrolyzed into ammonium nitrogen at appropriate temperature and humidity and then easily converted into NH$_3$ volatilization loss (Li et al., 2018). The total cumulative NH$_3$ loss under different N split applications ranged from 6.2 to 9.4% of the applied N in this study (Table 1), which were slightly lower than the emissions factor of 10% of applied N advocated by the IPCC (2007). A lower FIE of less than 2.5% has also been reported by another study on the Loess Plateau in rain-fed winter wheat field (Yang et al., 2015). Cai et al. (2002) found that the NH$_3$ volatilization losses range from 11 to 48% of the applied N to maize. The lower NH$_3$ losses in the present study than in Cai et al. (2002) may be attributed to the application method of N fertilizer. In this study, basal N was broadcast on the surface and then was mixed into soil; for topdressed N, N fertilizer was applied in a band in the middle of the no-film rows at a depth of 5 cm. NH$_3$ volatilization losses of N fertilizer are closely related to the application technique and N rate (Sommer et al., 2003; Zhao et al., 2009). In comparison to surface application, deep placement of N fertilizer could
reduce NH$_3$ losses substantially (Zeng et al., 2016). Rochette et al. (2013) reported that NH$_3$ volatilization losses were 50% of applied N when urea was banded at the surface and incorporation of the band decreased emissions by an average of 7% cm$^{-1}$. Pan et al. (2016) also found that in comparison to surface application, deep placement significantly decreased NH$_3$ volatilization through the incorporation of fertilizer at 54.7%.

A previous study reported that a split applications of N fertilizer did not affect NH$_3$ volatilization, regardless of splitting frequency (Pan et al., 2016). In our study, applying N with two or three splits significantly decreased NH$_3$ volatilization by 30.5% over two years, and the FIE from topdressed N was significantly lower than that from basal N (Table 1). One possible reason for this discrepancy is the different application method with basal and topdressed N, as described above. Basal N was broadcast on the surface and then mixed with the 0-15 cm soil; however, some of the N fertilizer was still exposed on the soil surface, increasing the risk of NH$_3$ losses compared to that with topdressed N. In addition, N losses through NH$_3$ volatilization increase with an increasing rate of N application in soils (Tian et al., 2001; Zhao et al., 2009), and previous studies have shown that the NH$_3$ emissions response to increasing N input is exponential rather than linear (Ma et al., 2010). In the present study, all N fertilizer was applied as basal dressing in treatment N1, which led to large amounts of NH$_3$ volatilization.

NH$_3$ volatilization is a physical process that is mainly influenced by the concentration of NH$_4^+$-N in the soil solution and by the resistance to NH$_3$ movement from the soil matrix (Sommer et al., 2004). Rochette et al. (2013) found cumulative losses increased exponentially with increasing maximum NH$_4^+$-N measured in the surface soil during the experiment. Consistent with previous reports, significant and positive correlations were observed between NH$_3$ volatilization flux and soil NH$_4^+$-N contents in this study (Table 2). Soil temperature and moisture are two other important factors affecting NH$_3$ volatilization. Fan et al. (2011) reported that the cumulative NH$_3$ volatilization loss increased by 1.6 fold in sandy soil when the temperature increased from 20 to 30°C. A study in the wheat growing season showed that soil temperature has positive effects on NH$_3$ fluxes during Oct-Dec but has negative effects during Feb.-May (Yang et al., 2015). However, no significant correlations were observed between NH$_3$ flux and soil temperature in the present study. This difference could be explained by the influence of precipitation events on the soil temperature and NH$_3$ volatilization flux. In some cases, high NH$_3$ emissions occurred following precipitation events when the soil temperature was relatively low. Soil moisture had significant positive effects on NH$_3$ fluxes, which could explain 7.3-19.7% of the variation in the NH$_3$ fluxes (Yang et al., 2015). Bosch-Serra et al. (2014) found that NH$_3$ volatilization was significantly reduced when the WFPS in the 0-30 cm soil layer was less than 56%. In this study, no significant correlations were observed between the NH$_3$ flux and soil WFPS. This result may be attributed to the different effects of precipitation amount on NH$_3$ fluxes. Previous studies have reported that the magnitude of NH$_3$ losses was largely influenced by small temporal differences in the weather and initial soil moisture content (Engel et al., 2011; Turner et al., 2012). The largest losses (30-44% of applied N) occurred after urea was applied to high-water content soil surfaces, followed by a period of slow drying with little or no precipitation (Engel et al., 2011). Light precipitation and high soil moisture would increase NH$_3$ volatilization risk by promoting urea hydrolysis, while heavy precipitation may effectively mitigate NH$_3$ losses by leaching.
unhydrolyzed urea into the soil profile (Holcomb et al., 2011). In this study, the NH$_3$ flux increased sharply following slight precipitation events of 3 mm and 5 mm after topdressed N was applied at the V8 and R1 stages, respectively, in 2015. We also observed that the NH$_3$ flux was restrained rapidly by heavy precipitation of 20 mm after the application of topdressed N at the V8 stage in 2014 (Fig. 4).

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 NRE (Ribaudo et al., 2011). In the present study, higher grain yields, total N uptake, and NRE were observed from the plots under N split applications than in the other plots (Table 3). Similar to our results, Shi et al. (2012) also found that the grain yield and NRE increased significantly when N fertilizer application was divided into an appropriate ratio of basal and topdressed N. Yi et al. (2008) reported that the NRE increased by more than 2 fold when N was applied with splits of 1:1 compared with a split of 2:1 of basal to topdressed N. This result may be attributed to the lower N demand in the early growth stage of maize and the increased risk of leaching from a large amount of N fertilizer input. Kettering et al. (2013) indicated that applying fertilizer N with 3-4 splits according to a plant’s N needs could reduce N leaching and increase the NRE.

### Table 3. Grain yield, total N uptake and N recovery efficiency

| Treatments | Grain Yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | NRE (%) |
|------------|--------------------------|-------------------------------|---------|
|            | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 |
| N0         | 8.6 b | 3.6 c | 125.2 d | 50.1 d |
| N1         | 12.7 a | 12.1 b | 218.7 c | 169.1 c | 41.6 b | 52.9 c |
| N2         | 13.3 a | 13.0 a | 242.8 b | 197.0 b | 52.3 b | 65.3 b |
| N3         | 13.5 a | 13.2 a | 255.0 a | 221.9 a | 57.7 a | 76.4 a |

Different lowercase letters within a column indicate significant differences (p < 0.05)

### Conclusions

NH$_3$ flux was positively correlated with soil NH$_4^+$-N content and was greatly affected by precipitation events. Applying N with two or three splits significantly increased the grain yield, total N uptake, and NRE of maize and significantly reduced NH$_3$ volatilization losses. The coupling effect of N fertilizer application and precipitation on NH$_3$ volatilization should be further investigated in the future.

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### REFERENCES

[1] Behera, S. N., Sharma, M., Aneja, V. P., Balasubramanian, R. (2013): Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. – Environmental Science and Pollution Research 20(11): 8092-8131.

[2] Black, A., Sherlock, R., Smith, N. (1987): Effect of urea granule size on ammonia volatilization from surface-applied urea. – Fertilizer Research 11(1): 87-96.
[3] Bosch-Serra, À. D., Yagüe, M. R., Teira-Esmatges, M. R. (2014): Ammonia emissions from different fertilizing strategies in Mediterranean rainfed winter cereals. – Atmospheric Environment 84: 204-212.

[4] Boyer, E. W., Goodale, C. L., Jaworski, N. A., Howarth, R. W. (2002): Anthropogenic Nitrogen Sources and Relationships to Riverine Nitrogen Export in the Northeastern U.S.A. – In: Boyer, E. W., Howarth, R. W. (eds.) The Nitrogen Cycle at Regional to Global Scales. Springer, Dordrecht, pp. 137-169.

[5] Cai, G. X., Chen, D. L., Ding, H., Pacholski, A., Fan, X. H., Zhu, Z. L. (2002): Nitrogen losses from fertilizers applied to maize, wheat and rice in the North China Plain. – Nutrient Cycling in Agroecosystems 63(2): 187-195.

[6] Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F. (2014): Producing more grain with lower environmental costs. – Nature 514(7523): 486-489.

[7] Cui, Z. L., Zhang, F. S., Chen, X. P., Miao, Y. X., Li, J. L., Shi, L. W., Xu, J. F., Youliang, Y. L., Liu, C. S., Yang, Z. P., Qiang, Z., Huang, S. M., Bao, D. J. (2008): On-farm evaluation of an in-season nitrogen management strategy based on soil N-min test. – Field Crops Research 105(1-2): 48-55.

[8] Engel, R., Jones, C., Wallander, R. (2011): Ammonia volatilization from urea and mitigation by NBPT following surface application to cold soils. – Soil Science Society of America Journal 75: 2348-2357.

[9] Fan, X. H., Li, Y. C., Alva, A. K. (2011): Effects of temperature and soil type on ammonia volatilization from slow-release nitrogen fertilizers. – Communications in Soil Science and Plant Analysis 42(10): 1111-1122.

[10] Ferm, M. (1998): Atmospheric ammonia and ammonium transport in Europe and critical loads: a review. – Nutrient Cycling in Agroecosystems 51(1): 5-17.

[11] Gong, Z., Zhang, G., Chen, Z. (2007): Pedogenesis and Soil Taxonomy (in Chinese). – Science Press Publishing, Beijing.

[12] Holcomb, J. C., Sullivan, D. M., Horneck, D. A., Clough, G. H. (2011): Effect of Irrigation Rate on Ammonia Volatilization. – Soil Science Society of America Journal 75: 2341-2347.

[13] Kettering, J., Ruidisch, M., Gaviria, C., Ok, Y. S., Kuzyakov, Y. (2013): Fate of fertilizer 15N in intensive ridge cultivation with plastic mulching under a monsoon climate. – Nutrient Cycling in Agroecosystems 95(1): 57-72.

[14] López-Bellido, L., López-Bellido, R. J., Redondo, R. (2005): Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. – Field Crops Research 94(1): 86-97.

[15] Li, F.-M., Wang, J., Xu, J.-Z., Xu, H.-L. (2004): Productivity and soil response to plastic film mulching durations for spring wheat on entisols in the semi-arid Loess Plateau of China. – Soil and Tillage Research 78(1): 9-20.

[16] Li, M., Wang, Y., Adeli, A., Yan, H. (2018): Effects of application methods and urea rates on ammonia volatilization, yields and fine root biomass of alfalfa. – Field Crops Research 218: 115-125.

[17] Liu, T. Q., Fan, D. J., Zhang, X. X., Chen, J., Li, C. F., Cao, C. G. (2015): Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. – Field Crops Research 184: 80-90.

[18] Ma, B. L., Wu, T. Y., Tremblay, N., Deen, W., McLaughlin, N. B., Morrison, M. J., Stewart, G. (2010): On-farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. – Agronomy Journal 102: 134-144.
[19] Ni, K., Pacholski, A., Kage, H. (2014): Ammonia volatilization after application of urea to winter wheat over 3 years affected by novel urease and nitrification inhibitors. – Agriculture, Ecosystems & Environment 197: 184-194.

[20] Pacholski, A., Cai, G., Nieder, R., Richter, J., Fan, X., Zhu, Z., Roelcke, M. (2006): Calibration of a simple method for determining ammonia volatilization in the field - comparative measurements in Henan Province, China. – Nutrient Cycling in Agroecosystems 74(3): 259-273.

[21] Pan, B., Lam, S. K., Mosier, A., Luo, Y., Chen, D. (2016): Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. – Agriculture, Ecosystems & Environment 232: 283-289.

[22] Paulot, F., Jacob, D. J., Pinder, R. W., Bash, J. O., Travis, K., Henze, D. K. (2014): Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: interpretation with a new agricultural emissions inventory (MASAGE_NH₃). – Journal of Geophysical Research: Atmospheres 119(7): 4343-4364.

[23] Ribaudo, M., Hansen, L., Livingston, M., Mosheim, R., Williamson, J., Delgado, J. (2011): Nitrogen in agricultural systems: Implications for conservation policy. – USDA-ERS Economic Research Report Number 127, Washington, DC.

[24] Rochette, P., Angers, D. A., Chantigny, M. H., Gasser, M.-O., MacDonald, J. D., Pelster, D. E., Bertrand, N. (2013): Ammonia volatilization and nitrogen retention: how deep to incorporate urea? – Journal of Environmental Quality 42: 1635-1642.

[25] Scharf, P. C., Wiebold, W. J., Lory, J. A. (2002): Corn Yield Response to Nitrogen Fertilizer Timing and Deficiency Level. – Agronomy Journal 94(3): 435-441.

[26] Shi, Z., Jing, Q., Cai, J., Jiang, D., Cao, W., Dai, T. (2012): The fates of 15N fertilizer in relation to root distributions of winter wheat under different N splits. – European Journal of Agronomy 40: 86-93.

[27] Soares, J. R., Cantarella, H., Menegale, M. L. d. C. (2012): Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. – Soil Biology and Biochemistry 52: 82-89.

[28] Sommer, S. G., Génermont, S., Cellier, P., Hutchings, N., Olesen, J. E., Morvan, T. (2003): Processes controlling ammonia emission from livestock slurries in the field. – European Journal of Agronomy 19(4): 465-486.

[29] Sommer, S. G., Schjoerring, J. K., Denmead, O. T. (2004): Ammonia emission from mineral fertilizers and fertilized crops. – Advances in Agronomy 82: 557-622.

[30] Sutton, M. A., Erisman, J. W., Dentener, F., Møller, D. (2008): Ammonia in the environment: From ancient times to the present. – Environmental Pollution 156(3): 583-604.

[31] Sutton, M. A., Reis, S., Riddick Stuart, N., Dragoumits, U., Nemitz, E., Theobald Mark, R., Tang, Y. S., Braban Christine, F., Vieno, M., Dore Anthony, J., Mitchell Robert, F., Wanless, S., Daunt, F., Fowler, D., Blackall Trevor, D., Milford, C., Flechard Chris, R., Loubet, B., Massad, R., Cellier, P., Personne, E., Coheur Pierre, F., Clarisse, L., Van Damme, M., Ngadi, Y., Clerbaux, C., Skjøth Carsten, A., Geels, C., Hertel, O., Wichink Kruit Roy, J., Pinder Robert, W., Bash Jesse, O., Walker John, T., Simpson, D., Horváth, L., Misselbrook Tom, H., Bleeker, A., Dentener, F., de Vries, W. (2013): Towards a climate-dependent paradigm of ammonia emission and deposition. – Philosophical Transactions of the Royal Society B: Biological Sciences 368(1621): 20130166.

[32] Tian, G., Cai, Z., Cao, J., Li, X. (2001): Factors affecting ammonia volatilisation from a rice–wheat rotation system. – Chemosphere 42(2): 123-129.

[33] Turner, D. A., Edis, R. E., Chen, D., Freney, J. R., Denmead, O. T. (2012): Ammonia volatilization from nitrogen fertilizers applied to cereals in two cropping areas of southern Australia. – Nutrient Cycling in Agroecosystems 93(2): 113-126.
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[34] Wang, S., Luo, S., Li, X., Yue, S., Shen, Y., Li, S. (2016): Effect of split application of nitrogen on nitrous oxide emissions from plastic mulching maize in the semiarid Loess Plateau. – Agriculture, Ecosystems & Environment 220: 21-27.

[35] Wolf, U., Fuß, R., Höppner, F., Flessa, H. (2014): Contribution of N$_2$O and NH$_3$ to total greenhouse gas emission from fertilization: results from a sandy soil fertilized with nitrate and biogas digestate with and without nitrification inhibitor. – Nutrient Cycling in Agroecosystems 100(1): 121-134.

[36] Yang, Q., Liu, P., Dong, S., Zhang, J., Zhao, B. (2019): Effects of fertilizer type and rate on summer maize grain yield and ammonia volatilization loss in northern China. – Journal of Soils and Sediments 19(5): 2200-2211.

[37] Yang, Y., Zhou, C., Li, N., Han, K., Meng, Y., Tian, X., Wang, L. (2015): Effects of conservation tillage practices on ammonia emissions from Loess Plateau rain-fed winter wheat fields. – Atmospheric Environment 104: 59-68.

[38] Yi, Z., Wang, P., Hong, B., Lu, L., Yu, G. (2008): Effect of base N to dress N ratio on water and nitrogen utilization, growth of summer maize in North China Plain. II. Nitrogen accumulation and translocation of summer maize and dynamics of soil inorganic N. – Chinese Journal of Eco-Agriculture 16(1): 86-90.

[39] Zeng, J., Liu, X., Song, L., Lin, X., Zhang, H., Shen, C., Chu, H. (2016): Nitrogen fertilization directly affects soil bacterial diversity and indirectly affects bacterial community composition. – Soil Biology and Biochemistry 92: 41-49.

[40] Zhang, Y., Luan, S., Chen, L., Shao, M. (2011): Estimating the volatilization of ammonia from synthetic nitrogenous fertilizers used in China. – Journal of Environmental Management 92(3): 480-493.

[41] Zhao, X., Xie, Y. X., Xiong, Z. Q., Yan, X. Y., Xing, G. X., Zhu, Z. L. (2009): Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu Lake region, China. – Plant and Soil 319(1-2): 225-234.