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ORIGINAL ARTICLE

Combined application of organic and inorganic fertilizers mitigates ammonia and nitrous oxide emissions in a maize field

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Abstract This long-term study used a lysimeter platform to monitor the NH_3 and N_2O emissions of summer maize resulting from various fertilization treatments in the Huanghuaihai area, with the goal to assess the efficiency of fertilization measures aimed at reducing NH_3 and N_2O losses during the production of summer maize; the results provide a theoretical basis for synergistically improving maize yield and fertilizer utilization efficiency. A 2-year field trial was conducted. The trial included a no-N-fertilizer treatment as a control to study the following three fertilizer treatments: the exclusive application of urea, the exclusive application of cattle manure, and the combined application of organic and inorganic fertilizers. The results show that during the two maize growth seasons included in the trial, the average N_2O losses associated with exclusively applying urea, exclusively applying cattle manure, and the combined application of organic and inorganic fertilizers were 273%, 542%, and 376% higher than those associated with the control treatment, respectively. During the same period, the average accumulative ammonia volatilization losses were 311%, 542% and 376% higher than those for the control treatment, respectively. The average nitrogen accumulation resulting from the combined application of organic and inorganic fertilizers was 82% higher than that for the control treatment, 12% higher than that for the exclusive application of cattle manure, and 6% higher than that for the exclusive application of urea. The average grain yield for the combined application of organic and inorganic fertilizers, the exclusive application of urea and the exclusive application of cattle manure were 76%, 68% and 61% higher than that for the control treatment, respectively. Overall, the combined application of organic and inorganic fertilizers showed a lower ammonia volatilization loss than the exclusive application of urea, which resulted in a higher ammonium nitrogen and nitrate nitrogen content in the soil, an increased nitrogen uptake, an increased dry matter accumulation of maize, and a high grain yield and nitrogen recovery efficiency.

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Keywords Summer maize · Combined application of organic and inorganic fertilizers · Nitrogen gas loss · Nitrogen recovery efficiency

Introduction

Maize is an important crop, and its planting area and yield has increased rapidly in recent years. In China, the total maize planting area reached 35 million hectares in 2016, achieving a production of 216 million tons (Zhu et al. 2016). In recent years, crop production methods overused nitrogen fertilizer, the application of which reached 59.8 million tons in 2016 (Ju et al. 2007; NBSPRC 2017). In China, the nitrogen use efficiency of 28.7% is lower than the global average of 40–50% (Huang and Tang 2010). Each year, about 15 million tons of nitrogen either enters the water body through leaching, or is released to the atmosphere through ammonia volatilization losses and N_2O emissions, which wastes fertilizer and energy, and seriously pollutes the environment (Liu et al. 2012). NH_3 volatilization is the main pathway for nitrogen gas loss and N_2O is a potential way of nitrogen loss (Harrison and Webb 2001). Additionally, N_2O, which is one of the most potent greenhouse gases, negatively affects the global climate. About 30–50% of the nitrogen fertilizer that is added to the soil is lost by soil leaching (Diez et al. 1997), and 47% is released into the atmosphere by the combined effects of NH_3 volatilization and N_2O emissions (Erisman et al. 2008). Nitrogen fertilizer is the most important contributor to an increased N_2O concentration in the atmosphere (Mehnaz and Dijkstra 2016). The long-term application of chemical fertilizer was also reported to negatively affect the stability and porosity of the soil structure, the growth of crop roots and the nutrient balance of the fertilizer–soil–crop nutrient system (Ding et al. 2016).

The use of organic fertilizers involves the use of complicated composting technology, is very labor intensive, and lacks an immediate response to crop production, and therefore farmers in China generally prefer inorganic fertilizers. A lot of organic fertilizers were underutilized, which gave rise to various types of environmental pollution (Gao et al. 2012). Due to the accelerated transformation of China's livestock husbandry from family-run free-range farming to large-scale industrial farming, the availability of cattle manure has increased rapidly. At present, the total amount of livestock and poultry produced each year is close to 4 billion tons. About 74 million tons of China's various types of organic fertilizer resources are converted into nutrients, which is less than 40% of the total available amount organic fertilizer resources (Gao et al. 2012). In China, the fraction of fertilizer application in the form of organic fertilizers has dropped from 37% in 1990 to 25% in 2003 (Bin et al. 2007). In Western countries, however, bio-fertilizers account for about 50% of the total fertilizer use (Van der Stelt et al. 2007). A return of organic fertilizers could solve the problem of organic fertilizer stacking and reduce its polluting effect on the environment (Ni et al. 2010). In addition, organic fertilizer can continuously supply various nutrients needed for crop growth and development, thereby improving the soil structure, as well as its physical and chemical properties (Chauhan and Bhatnagar 2014). It can also create favorable conditions for soil microbial growth and development, enabling smooth humification, enhanced water retention and fertility, and an improved soil fertility (Liu et al. 2016).

Combining organic and inorganic fertilizers has the advantage of achieving a quick-acting and long-lasting effect that can promote the growth and reproduction of soil microbes, stimulate the formation of diversity, and facilitate the supply capacity of water and fertilizer (Pan et al. 2009; Zhao et al. 2016). In recent years, fertilizer application research has seen a lot of activity in the area of combining organic and inorganic fertilizers, and it has now become the field with the fastest progress. However, studies of the major pathways by which nitrogen gas is lost from the soil, notably ammonia volatilization and nitrous oxide emissions, are relatively rare. Using a permanent lysimeter test platform, we studied the effects of various long-term fertilization treatments (exclusive application of urea, exclusive application of cattle manure, and combined application of organic and inorganic fertilizers) on soil ammonia volatilization and N_2O emission in summer maize, aiming to provide a theoretical basis for improving nitrogen recovery efficiency.

Materials and methods

Experimental site

The experiments were carried out during the maize growth seasons in 2016 and 2017 using the large free draining lysimeters (2.5 m long × 2.5 m wide × 2 m deep) (Gu et al. 2014) at the Huanghuaihai Corn Science and Technology Innovation Center of Shandong Agricultural University (36° 09′ N, 117° 09′ E). The site has a total of 12 lysimeters, and has been in use since 2008. In the Huang Huai-Hai Plains (HHP), which are located in northern China, a winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) cropping system is common practice. According to the meteorological data from 2008 to 2017, which are shown in Supplementary Fig. 1, 2016 and 2017 were representative of the regional climate (as indicated by the meteorological data for maize growth periods being between the two red lines). The maize growing seasons in 2016 and 2017 (June 12 to October 6, 2016 and June 12 to September 26, 2017) had a total precipitation of 443.4 mm and 357.5 mm, a daily average temperature of 25.9 °C and 26.7 °C (the average maximum temperature was 31.6 °C and 32.1 °C; the average minimum temperature was 20.7 °C and 21.7 °C), and an effective accumulated temperature of 1557.92 °C and 1858.73 °C, respectively. Soil samples were collected from a nearby site at 0.10 m depth increments and packed in the same order and to the same bulk density as found at site. The walls and floors of the lysimeters are constructed from 0.255 m-thick concrete, which eliminates the possibility of lateral nutrient and water losses from the lysimeters, as well as exchanges with groundwater. Effectively, the lysimeters are isolated from the surrounding soil environment but have an identical temperature regime. To prevent runoff or run-on from surrounding areas, the edge of the lysimeters is raised above the soil surface by 50 mm. The rotation was winter wheat–maize, with maize sowed immediately after wheat harvesting. The soil taxonomy is loam soil. The physical and chemical properties of the soil layer between 0 and 200 mm in the lysimeter before sowing are pH 7.2, bulk density 1.2 g cm^{-3}, organic matter 13.6 g kg^{-1}, total nitrogen 1.4 g kg^{-1}, available P 26.9 mg kg^{-1}, available K 92.8 mg kg^{-1}.

Experimental design

The experiment was conducted using the maize variety Zhengdan 958 (ZD958). The following four fertilization treatments were applied: the application of no-N-fertilizer (CK), the exclusive application of urea (U), the exclusive application of cattle manure (M), and the combined application of organic and inorganic fertilizers (UM; at a ratio of 1:1). For U, M, and UM, the application rate of N was 200 kg N ha^{-1}, as calculated from the total N content of dry manure. Each treatment was composed of three replicate plots with an area of 6.25 m^2 (2.5 m × 2.5 m). Before fertilization, the water and nutrient content of the decomposed cattle manure was determined at 10 randomly selected sampling points, the results of which are shown in Supplementary Table 1. The amount of cattle manure was calculated from its nitrogen and water content after decomposition. The application rates of phosphorus and potassium fertilizers for all treatments were 110.7 kg P ha^{-1} and 168.0 kg K ha^{-1}. For the cattle manure treatment, in case the P content was less than 110.7 kg ha^{-1} or the K content was less 168.0 kg ha^{-1}, calcium phosphate and potassium sulfate were added to make up for any difference. The nitrogen content of the urea used in the test was 46%, the P content of the calcium phosphate was 5%, and the K content of the potassium sulfate was 42%. Each treatment that used phosphorus and potassium fertilizers was used as a basal fertilizer and was applied before seeding. Fertilization and seeding were carried out on the same day. Manure was incorporated into the top 200 mm soil manually before each crop was planted, whereas for maize, 50% of the urea was incorporated into soil at the time of seeding, and the other 50% was applied at the beginning of the 12-leaf stage.

Sample collection and measurements

Soil samples

In each lysimeter, the soil layer between 0 and 200 mm was sampled before sowing, and again at the maturity stage with a 50-mm-diameter soil auger. For each treatment, sampling was repeated three times to form a mixed soil sample, which was subjected to the quartering method. To determine its moisture content, the soil was dried at 80 °C to a constant weight. 100 g of dried soil sample was put into a 1000 ml wide-mouth plastic bottle. Then, 500 ml deionized water were added, the bottle mouth was sealed, the bottle was shaken for 30 min, and then left to sit for 24 h. Next, the content was filtered with a Buchner funnel until a clear leachate was obtained, the pH of which was immediately measured with a pH meter (Sartorius PB-10) (Zaman et al. 2009). Subsequently, the soil sample was mixed thoroughly, and representative sub-samples were extracted immediately using a 1 mol l^{-1} KCl solution (using a soil to solution ratio of 1:5). The sub-samples were shaken for 1 h on a rotary shaker (180 rev min^{-1}), after which they were filtered and directly analyzed for their NH_4^+-N and NO_3^--N content using a continuous flow auto-analyzer (AAIII, SEAL Analytical, Germany). The organic matter content of the soil was determined by hydration with the potassium dichromate oxidation-colorimetric method (China Soil Science Association Agricultural Chemistry Committee 1983). The total nitrogen content of the soil was determined with the Hanon K9860 Kjeldahl method (Lu 2000). Phosphorus was extracted from the soil using the sodium bicarbonate and molybdenum antimony anti-colorimetric method (Gu et al. 2016). Potassium was extracted from the soil with a 1 mol l^{-1} ammonium acetate solution and measured with a FP6410 flame photometer (Lu 2000).

Plant dry matter accumulation and plant nitrogen content

Maize plants were sampled at the tasseling (VT) and maturity (R6) stages (Han et al. 2014; Jia et al. 2018). The plants were separated into stalks (including leaf sheaths), leaves, tassels, cobs and grains, and each treatment was repeated three times. The dry matter was determined after drying the plant parts at 80 °C to a constant weight. The dried plant samples were ground with a pulverizer, and then treated with H_2SO_4-H_2O_2. The nitrogen content of the samples was determined with an AAIII continuous flow analyzer (Gu et al. 2016).

The nitrogen recovery efficiency (NRE) was calculated using the following formula (Han et al. 2011):

$$\mathrm{NRE} = \Big(\text{total nitrogen uptake by plants in nitrogen application area } \left(\mathrm{kg\,ha^{-1}}\right) - \text{total nitrogen uptake by plants without nitrogen application area } \left(\mathrm{kg\,ha^{-1}}\right)\Big) / \text{nitrogen application rate } \left(\mathrm{kg\,ha^{-1}}\right) \times 100\%$$

Grain yield

Plants were harvested and measured at the maturity stage (R6), and each pool that was used to determine the grain yield and yield components was harvested from the middle three rows.

The partial factor productivity (PFP, kg kg^{-1}) was calculated using the following formula:

$$\mathrm{PFP} = \text{grain yield } \left(\mathrm{kg\,ha^{-1}}\right) / \text{pure N amount } \left(\mathrm{kg\,ha^{-1}}\right)$$

Soil N_2O emission rate and soil ammonia volatilization rate

N_2O sample collection and analysis were performed using static chamber-gas chromatography (Hutchinson and Livingston 1993). The static term chamber base (0.60 × 0.50 × 0.25 m) was driven into the soil between the maize rows. The upper part of the base was equipped with a water sink (a 50 mm sink on top of the base while the bottom was sunk 0.15 m into the soil. To take measurements, the water sink was filled and placed on the sampling chamber, and the upper chamber (0.60 × 0.50 × 0.50 m) was stuck on the base. The chamber's built-in fan was used to mix the gas in the chamber. The gas collection time lasted from 9:00 to 11:00. A syringe was used to draw 30 ml samples from the three-way valve at 0, 15, 30, 45 min, and inject them into the vacuum bottle while recording the temperature inside the chamber. After the application of nitrogen fertilizer, a measurement was taken every 7 days for a total of 14 measurements. The gas sample taken was analyzed using a gas chromatograph (Shimadzu GC2010) (Tian et al. 2012), using a 4 m long PorpakQ packed column, and N_2 as the carrier gas. The detector was an Electron Capture Detector (ECD) with an ECD detection temperature of 300 °C, an item temperature of 45 °C and a total carrier gas flow of 40 ml min^{-1}. The makeup flow was 40 ml min^{-1}.

To calculate the N_2O flux, the following formula was used:

$$F = \frac{273}{273 + t} \times \frac{28}{22.4} \times 60 \times 10^{-3} \times H \times \frac{dc}{dt}$$

In this formula, F is the N_2O emission flux (mg m^{-2} h^{-1}), t is the temperature in the tank, 28 is the mass of N per mol of N_2O molecule, 22. 4 is the molar volume of N_2O at a temperature of 273 K, H is the height of the sampling chamber (m), c is the N_2O gas concentration (μl l^{-1} min^{-1}), t is the closing time (min), and dc/dt is the rate of change of the N_2O gas concentration in the sampling chamber (μl l^{-1} min^{-1}).

Cumulative emissions were estimated using linear interpolation and trapezoidal integration between N_2O fluxes measured on consecutive sampling dates (Xu et al. 2016; Li et al. 2016).

The ammonia volatilization was measured using the ventilation method (Wang et al. 2004; Gu et al. 2016). The aeration device deployed by this method was made of a rigid polyvinyl chloride ring with an inner diameter of 150 mm and a height of 120 mm. Two sponges with a thickness of 20 mm and a diameter of 160 mm were uniformly immersed in a 20 ml solution of glycerol phosphate (40 ml of glycerol + 50 ml of phosphoric acid, with a volume adjustment to 1000 ml). Next, the two sponge layers were placed inside the ring in such a way that the lower sponge was 50 mm from the ground and the upper sponge was level with the top of the tube. Three gas collection devices were placed in each plot. The soil ammonia volatilization process started on the day of fertilization. To take measurements, the lower sponge was removed from the aeration device, and placed into a 800 ml plastic bottle, after which 500 ml of 1 mol l^{-1} KCl solution was added, and it was shaken for 1 h. Finally, the ammonium nitrogen content in the extract was determined. The aeration device at the test plot was furnished with a new sponge. During the first week after sowing, one sample per day was taken, During the second and third week, a sample was taken every 2–3 days, after which the sampling interval was extended to 7 days until the ammonia volatilization became undetectable. The NH_3 concentration was determined using the Hanon K9860 Kjeldahl method (Lu 2000).

The ammonia volatilization rate (AVR) was calculated as AVR = M/(A × D)/100, where AVR is the rate of AV (kg N ha^{-1} day^{-1}), M is the NH_3-N collected by the PVC collector (mg), A is the cross-sectional area of the PVC collector (m^2), and D is the sampling interval for AV collection (days). Cumulative ammonia volatilization (CAV) was calculated as CAV = $AVR_1 + AVR_2 + \cdots$.

Data statistics and analysis

Statistically significant differences in the total N_2O emission, the amount of ammonia volatilization, the grain yield, and so on between the treatments were analyzed using the analyses of variation (ANOVA) method, using the DPS 15.10 software package. For the inter-annual data difference, a two-way ANOVA was used, and for each year, the data difference was a one-way ANOVA. For the emission rate of nitrous oxide and ammonia volatilization over time, we used the repeated measures ANOVA, using the SAS software package. Graphs were produced with Sigma Plot 10.0 software. Mean values (n = 3) between treatments were compared using Least Significant Difference (LSD) calculations at a 5% significance level.

Results

Soil total and inorganic N content

In 2016, the total nitrogen concentration in the soil after the exclusive application of cattle manure (1.65 g kg^{-1}) and after the combined application of organic and inorganic fertilizers (1.61 g kg^{-1}) was significantly higher than the concentration after the exclusive application of urea (1.22 g kg^{-1}) or the application of no-N-fertilizer (0.95 g kg^{-1}) before seeding (Table 1). Compared with other treatments, the concentration of nitrate nitrogen was the highest after the combined application of organic and inorganic fertilizers (19.8 mg kg^{-1}). The ammonium nitrogen concentration after the exclusive application of cattle manure (8.08 mg kg^{-1}) and after the combined application of organic and inorganic fertilizers (7.48 mg kg^{-1}) were significantly higher than the concentration after the exclusive application of urea (5.67 mg kg^{-1}) or the application of no-N-fertilizer (4.27 mg kg^{-1}), but the difference between them was not (Table 1). At maturity, the exclusive application of

Table 1 Effects of different fertilization treatments on soil properties in 2016 (0–200 mm)

Treatments	Before seeding			Maturity stage			Difference		
	TN (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	TN (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	TN (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})
CK	0.95c	7.02d	4.27b	0.21c	5.18c	1.75ab	0.74	1.84	2.52
U	1.22b	11.06c	5.67b	0.22c	11.55b	1.69ab	1.00	− 0.49	3.98
M	1.65a	14.39b	8.08a	0.41a	16.92a	1.43b	1.24	− 2.53	6.65
UM	1.61a	19.76a	7.48a	0.25b	16.56a	1.87a	1.36	3.20	5.61

Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year

TN, total nitrogen; NO_3^--N, nitrate nitrogen, NH_4^+-N, ammonium nitrogen

cattle manure (0.41 g kg^{-1}) resulted in the highest nitrogen content as compared with the other treatments. The concentration of nitrate nitrogen after the exclusive application of cattle manure (16.9 mg kg^{-1}) and after the combined application of organic and inorganic fertilizers (16.6 mg kg^{-1}) was significantly higher than the concentration after the single application of urea (11.6 mg kg^{-1}) or the concentration after the application of no-N-fertilizer (5.18 mg kg^{-1}). There was no significant difference between the ammonium nitrogen concentration after any of the treatments (Table 1). Whether the fertilizer treatment was carried out before seeding or at maturity did give rise to differences in nitrogen content. When changing the fertilization date, the largest difference in total nitrogen content (1.36 g kg^{-1}) and nitrate nitrogen content (320 mg kg^{-1}) was measured after the combined application of organic and inorganic fertilizers, while the largest difference in ammonium nitrogen (6.65 mg kg^{-1}) was measured after the exclusive application of cattle manure (Table 1).

N_2O emission rate and cumulative emissions, ammonia volatilization rate and cumulative ammonia volatilization

An analysis of variance shows significant differences in N_2O emission depending on the year during which the measurement was made, as well as on the fertilizer treatments that were used ($P < 0.05$). In 2017, the cumulative emission of nitrous oxide was reduced by 33% compared to 2016 (Table 2). The N_2O emission rates for the various treatments immediately following basal fertilizer application at sowing and topdressing in 2016 and 2017 are shown in Fig. 1. The N_2O emissions resulting from the different fertilization treatments show significant differences, and can be ranked as follows: emissions from the exclusive application of cattle manure > emissions from the combined application of organic and inorganic fertilizers > emissions from single application of urea > emissions from the application of no-N-fertilizer. After the exclusive application of cattle manure, the N_2O emission peaked after the first day of fertilization at 4.64 mg N m^{-2} day^{-1} in 2016 and 3.76 mg N m^{-2} day^{-1} in 2017. From the 15th to 20th day, the 2-year N_2O emission gradually increased, and, for the exclusive application of urea, it peaked on the 46th day at 6.11 mg N m^{-2} day^{-1} in 2016 and at 12.6 mg N m^{-2} d^{-1} in 2017. After that, the N_2O emissions from each fertilization treatment gradually decreased until they were close to those from the no-N-fertilizer treatment (Fig. 1). The cumulative loss varied between 1.96 and 4.25 kg ha^{-1} in 2016, and between 1.87 and 2.35 kg ha^{-1} in 2017. The 2-year average N_2O loss for the exclusive application of urea, the exclusive application of cattle manure, and the combined application of organic and inorganic fertilizers during the maize growth season was 273%, 542% and 376% higher than that for the control treatment, respectively. (Table 2).

An analysis of variance shows significant differences in ammonia volatilization between the years during which the study was carried out, as well as between the fertilizer treatments that were used ($P < 0.05$). In 2017, the accumulated ammonia emission loss was reduced by 14% compared to 2016 (Table 2). The ammonia volatilization rate for the

Table 2 The amount of ammonia volatilization and N_2O emission in different fertilizer treatments in 2016–2017 and analysis of variance for the interaction of year and fertilizer type on cumulative ammonia volatilization and N_2O loss

Year	Treatments	NH_3-N loss (kg ha^{-1})	N_2O-N loss (kg ha^{-1})	Sum of the two losses (kg ha^{-1})	Leaching (kg ha^{-1})	Total N loss (kg ha^{-1})	Sum of the two losses/Total N loss (%)
2016	CK	11.1d	0.77d	11.9d	10.5c	22.3d	53.1
	U	40.0a	1.96c	41.9a	58.9a	101a	41.6
	M	22.1c	4.25a	26.4c	18.6b	45.0c	58.6
	UM	32.4b	2.81b	35.2b	21.9b	57.1b	61.6
2017	CK	7.50d	0.31d	7.81d	11.8c	19.6d	39.4
	U	36.4a	1.87c	37.4a	76.7a	114a	32.8
	M	16.1c	2.35a	17.3c	35.6b	52.9c	32.6
	UM	31.2b	2.08b	32.1b	37.0b	69.1b	46.5

Origin of variance	F value	*p* value	Origin of variance	F value	*p* value
Year (A)	30.61	0.0003	Year (A)	615.94	0.0000
Fertilizer type (B)	292.48	0.0000	Fertilizer type (B)	485.74	0.0000
A × B	4.51	0.0401	A × B	209.84	0.0000

Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year. Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year. The first part of the *p* and F value represent the interaction of year and fertilizer type on cumulative ammonia volatilization loss; The second part of the *p* and F value represent the interaction of year and fertilizer type on N_2O loss

CK, no-N-fertilizer treatment; U, exclusive application of urea; M, exclusive application of cattle manure; UM, combined application of organic and inorganic fertilizers

various treatments immediately increased after basal fertilizer application at sowing and topdressing stage, as shown in Fig. 2 for 2016 and 2017. The ammonia volatilization rate followed the same pattern in both 2016 and 2017. After applying the basal fertilizer, the ammonia volatilization for each fertilization treatment increased significantly, and then gradually decreased over time. After the exclusive application of cattle manure and the combined application of organic and inorganic fertilizers, the volatilization rate peaked on the first day after fertilization, but after the exclusive application of urea the peak appeared on the second day. The exclusive application of urea resulted in the highest ammonia volatilization rate in both 2016 and 2017, measured at 4.93 kg N ha^{-1} day^{-1} and 3.94 kg N ha^{-1} day^{-1}, respectively. For the exclusive application of urea, the ammonia volatilization peaked on the second day after fertilization, at 2.95 kg N ha^{-1} day^{-1} in 2016 and at 4.39 kg N ha^{-1} day^{-1} in 2017. After 15 days of topdressing, the ammonia volatilization rate dropped to an extremely low level. The rate of ammonia volatilization for the exclusive application of cattle manure was extremely low, with no significant change over time (Fig. 2). The cumulative ammonia volatilization followed essentially the same pattern in both 2016 and 2017 (Fig. 3). The cumulative ammonia volatilization rate increased rapidly during the first 10 days of basal fertilization. After 15 days of basal fertilization, however, the cumulative ammonia volatilization growth trend slowed down. The amount of cumulative ammonia volatilization after the exclusive application of urea > the amount after the combined application of organic and inorganic fertilizers > amount after the exclusive application of cattle manure > amount after the application of no-N-fertilizer (Fig. 3). The cumulative ammonia volatilization rate increased rapidly during the first 7 days of topdressing, and after 10 days, the growth trend slowed down. The cumulative ammonia volatilization for the exclusive application of urea > cumulative volatilization for the combined application of organic and inorganic fertilizers > cumulative volatilization for the exclusive application of cattle manure > cumulative volatilization for the application of no-N-fertilizer (Fig. 3). The range of

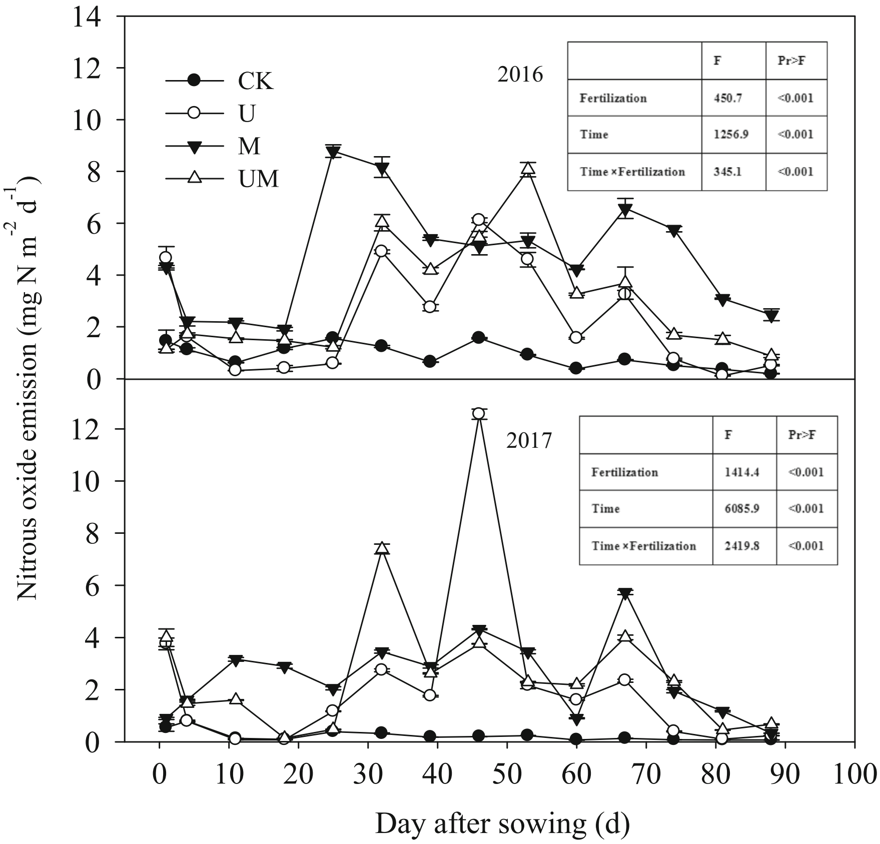

Fig. 1 Changes in N_2O emission flux in response to different N treatments in 2016 and 2017. Error bars represent 95% confidence limits

cumulative ammonia volatilization loss for the different fertilization treatments was 22.1–40.0 kg ha^{-1} in 2016 and 16.1–36.4 kg ha^{-1} in 2017. The 2-year average of the accumulative ammonia volatilization losses during the maize growth season for the exclusive application of urea, the exclusive application of cattle manure, and the combined application of organic and inorganic fertilizers were 311%, 542% and 376% higher than those for the control treatment, respectively (Table 2). The total nitrogen leaching after the exclusive application of urea was significantly higher than that for the other treatments, as measured at 58.9 kg ha^{-1} in 2016 and at 76.7 kg ha^{-1} in 2017, which is 462% and 551% higher than the leaching after the application of no-N-fertilizer, respectively. The amount of nitrogen leaching after the combined application of organic and inorganic fertilizers and after the exclusive application of cattle manure were relatively small: on average they were 140% and 161% higher than after the application of no-N-fertilizer, respectively (Table 2).

Plant dry matter accumulation, grain yield and nitrogen recovery efficiency

An analysis of variance shows significant differences in ammonia volatilization between the years during which the study was carried out, as well as between the fertilizer treatments that were used ($P < 0.05$). In 2017, the dry matter accumulation of plants increased by 11% compared with 2016 (Table 3). The combined application of organic and inorganic fertilizers significantly affected the dry matter accumulation and its proportion in pre-anthesis and post-anthesis stages (Table 3). In 2016, the combined application of organic and inorganic fertilizers had the highest dry matter quality at maturity. The total amount of dry matter for the combined application of organic and inorganic fertilizers > amount for the exclusive application of urea > amount for the exclusive application of cattle manure > amount for the application of no-N-fertilizer. The total amount of dry matter resulting from the combined application of organic and inorganic fertilizers was 3.75%, 11.0%, and 45.2% higher

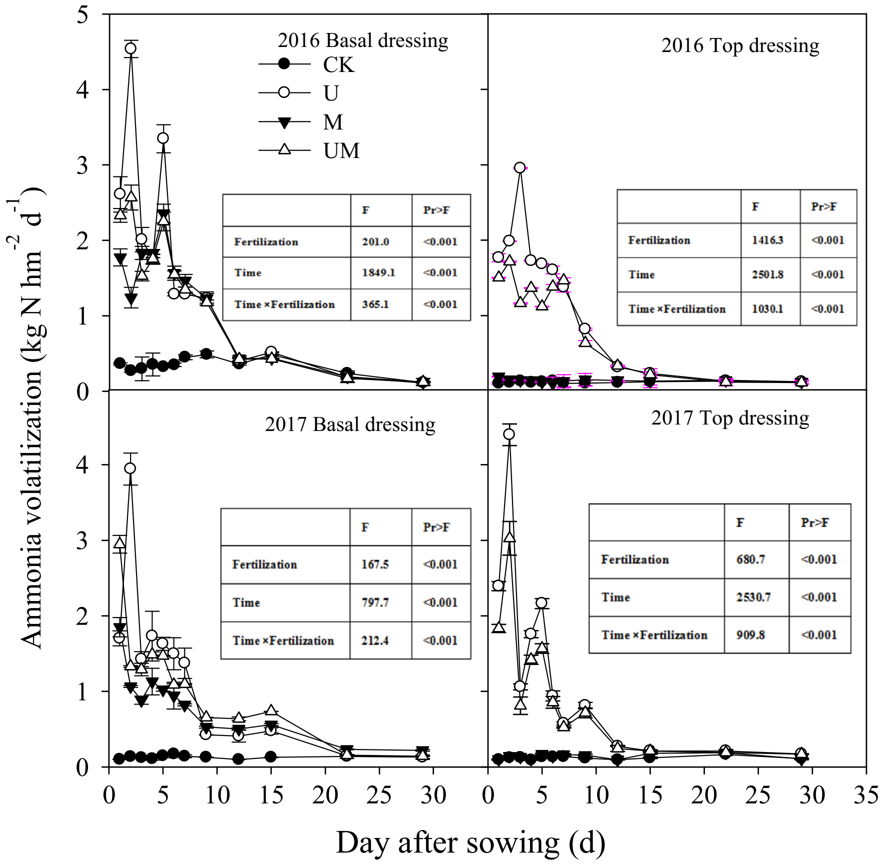

Fig. 2 Ammonia volatilization rate after basal dressing and top dressing stage (2016–2017). Error bars represent 95% confidence limits

than the amount for the exclusive application of urea, the amount for the exclusive application of cattle manure, and the application of no-N-fertilizer, respectively. In 2016, the exclusive application of urea resulted in a higher dry matter accumulation at pre-anthesis, and the combined application of organic and inorganic fertilizers resulted in a higher dry matter accumulation at post-anthesis than the exclusive application of urea. In 2017, the dry matter accumulation resulting from the exclusive application of urea, the exclusive application of cattle manure, and the combined application of organic and inorganic fertilizers were significantly higher than the accumulation resulting from the application of no-N-fertilizer. The differences between the accumulation values resulting from the exclusive single application of urea, the exclusive application of cattle manure, and the combined application of organic and inorganic fertilizers were not significant, which is probably due to extreme high-temperature weather (Table 3). An analysis of variance shows not significant differences in grain yield between the years during which the study was carried out ($P > 0.05$). There were significant differences between the summer maize grain yield for the different fertilization treatments (Table 4). The summer maize grain yield for the combined application of organic and inorganic fertilizers > yield for the exclusive application of urea > yield for the exclusive application of cattle manure > yield for the application of no-N-fertilizer (Table 4). In 2016, the grain yield for the combined application of organic and inorganic fertilizers, the exclusive application of urea and the exclusive application of cattle manure were 60.6%, 55.2% and 52.5% higher than that for the application of no-N-fertilizer. In 2017, the grain yield for the combined application of organic and inorganic fertilizers, the exclusive application of urea, and the single application of cattle manure were 91.0%, 80.5% and 69.8% higher than that for the application of no-N-fertilizer. The grain yield for each fertilization treatment was significantly higher than that for the no-N-fertilizer treatment (Table 4). An analysis of variance

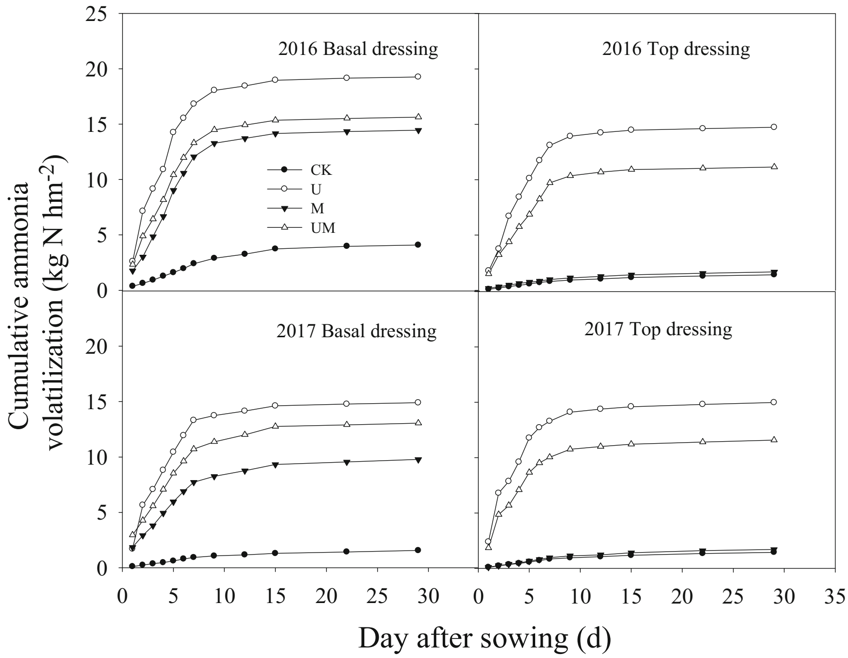

Fig. 3 Cumulative ammonia volatilization after basal dressing and top dressing stage (2016–2017)

Table 3 Accumulation amounts and ratios of dry matter accumulation in pre-anthesis and post-anthesis stages in 2016–2017 and analysis of variance for the interaction of year and fertilizer type on dry matter accumulation

Year	Treatments	Dry matter accumulation (Mg hm^{-2})			Proportion of pre-anthesis (%)	Proportion of post-anthesis (%)
		Maturity stage	Pre-anthesis	Post-anthesis		
2016	CK	15.4c	4.92b	10.5d	31.9	68.1
	U	21.6a	7.40a	14.2b	34.3	65.7
	M	20.2b	6.96ab	13.2c	34.5	65.5
	UM	22.4a	7.04a	15.4a	31.4	68.6
2017	CK	18.4b	4.03b	14.3c	21.9	78.1
	U	23.4a	6.17a	17.2b	26.4	73.6
	M	23.7a	4.85b	18.8a	20.5	79.5
	UM	23.0a	5.24b	17.8b	22.7	77.3

Origin of variance	F value	*p* value
Year (A)	117.76	0.000
Fertilizer type (B)	6.57	0.015
A × B	21.57	0.000

Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year

shows not significant differences in nitrogen accumulation between the years during which the study was carried out ($P > 0.05$). There were significant differences between the nitrogen accumulation for the different fertilization treatments (Table 5). The two-year average nitrogen accumulation for the

Table 4 Effects of different treatments on grain yields and composing factors to yield of summer maize in 2016–2017 and analysis of variance for the interaction of year and fertilizer type on grain yields

Year	Treatments	Grain yield (Mg ha^{-1})	Ears per unit area ($\times$ 10^4 ear ha^{-1})	Grains in a ear	1000-kernels weight (g)
2016	CK	8.63c	6.24c	497c	364a
	U	13.39b	8.00b	569a	376a
	M	13.17b	8.24b	543b	365a
	UM	13.86a	8.56a	565ab	384a
2017	CK	7.28d	5.51c	473c	341b
	U	13.15b	8.53a	522b	369a
	M	12.36c	7.60b	537b	373a
	UM	13.91a	8.64a	570a	364a

Origin of variance	F value	*p* value
Year (A)	3.11	0.108
Fertilizer type (B)	11.81	0.002
A $\times$ B	1.82	0.212

Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year

combined application of organic and inorganic fertilizers was 82.15%, 12.37% and 6.07% higher than that for the application of no-N-fertilizer, the exclusive application of cattle manure and the exclusive application of urea, respectively (Table 5). The nitrogen recovery efficiency for the combined application of organic and inorganic fertilizers was 33.2% higher than that for the exclusive application of cattle manure, and 15.6% higher than that for the exclusive application of urea (Table 5). The partial factor productivities for the exclusive application of urea, the exclusive application of cattle manure and the combined application of organic and inorganic fertilizers were higher than for the application of no-N-fertilizer in 2016, but the differences between the exclusive application of urea, the exclusive, and the combined application of organic and inorganic fertilizers were not significant. In 2017, the combined application of organic and inorganic fertilizers had the highest partial factor productivity, which was 91.0%, 12.5% and 5.83% higher than that for the application of no-N-fertilizer, the exclusive application of cattle manure, and the exclusive application of urea, respectively (Table 5).

Table 5 Nitrogen recovery efficiency and partial factor productivity of summer maize in 2016–2017 and analysis of variance for the interaction of year and fertilizer type on N uptake

Year	Treatments	N uptake (Mg ha^{-1})	NRE (%)	PFP (Mg Mg^{-1})
2016	CK	0.15d	–	43.2b
	U	0.24b	46.2b	67.0a
	M	0.23c	39.2c	65.9a
	UM	0.26a	55.9a	69.3a
2017	CK	0.14d	–	36.4d
	U	0.25b	54.9b	65.7b
	M	0.23c	48.9c	61.8c
	UM	0.26a	60.5a	69.6a

Origin of variance	F value	*p* value
Year (A)	0.01	0.915
Fertilizer type (B)	11.66	0.013
A $\times$ B	0.29	0.757

Values followed by different small letters in the same column are significantly different at 0.05 probability level among the treatments for the same year

NRE, nitrogen recovery efficiency; PFP, partial factor productivity

Discussion

Combined application of organic and inorganic fertilizers reduced N_2O loss and increased soil nitrogen accumulation

The NO_3^--N and NH_4^+-N concentrations in the soil directly affect the potential N_2O emissions (Cui et al. 2016). Adding a nitrification inhibitor increases the NH_4^+-N concentration, which in turn reduces the rate of nitrification (Wu et al. 2017). The study presented in this paper shows that the NO_3^--N and NH_4^+-N concentrations in the soil after the combined application of organic and inorganic fertilizers are higher than those for other treatments, resulting in the accumulation of NO_3^--N and NH_4^+-N in the soil, thereby reducing N_2O and N_2 emissions. The combined application of organic and inorganic fertilizers weakened the N_2O emission process, resulting in the accumulation of nitrate nitrogen and ammonia nitrogen in the soil, which was beneficial to crop nitrogen absorption and utilization and achieved a higher nitrogen use efficiency than that achieved with other treatments. With respect to the average cumulative N_2O emission resulting from each treatment, the study shows that the cumulative N_2O emission for the exclusive application of cattle manure > emission for the combined application of organic and inorganic fertilizers > emission for the exclusive application of urea > emission for the application of no-N-fertilizer. The exclusive application of cattle manure can provide abundant carbon and nitrogen sources for soil microorganisms, promote soil microbial activities, and increase the emission of N_2O. Organic fertilizer has long-lasting properties (Ni et al. 2010). Although the nitrogen supply capacity in the early stage was not as good as that for the exclusive application of fertilizer, it can provide abundant nitrogen for microbial denitrification in later stages (Liu et al. 2009). The emissions resulting from the combined application of organic and inorganic fertilizers were higher than those for the exclusive application of urea, because the excessive supply of inorganic nitrogen in chemical fertilizers and the continuous mineralization of organic fertilizers in the early stage of combined application of organic and inorganic fertilizers result in a higher N_2O emission rate than that for the exclusive application of urea.

Combined application of organic and inorganic fertilizers reduced ammonia volatilization loss

Ammonia volatilization is the main route of nitrogen loss, and the volatilization rate is affected by the fertilization method, the nitrogen application rate, and the environmental conditions (Harrison and Webb 2001; Xu et al. 2012). In this experiment, the amount of fertilization was consistent, and therefore the ammonia volatilization depended primarily on the fertilization treatment. The ammonia volatilization peaked 1–3 days after the application of basal fertilizer and topdressing, and then gradually declined. The main reason for this was that the fertilizer is completely hydrolyzed approximately 3 days after fertilization, which causes a steep increase in the NH_4^+ concentration in the soil and greatly accelerates the ammonia volatilization process. Under application of the same amount of nitrogen, the ammonia volatilization loss resulting from the exclusive application of cattle manure and the combined application of organic and inorganic fertilizers were significantly lower than that resulting from the exclusive application of urea. The results of the two-year experiment show that the average amount of ammonia volatilization loss resulting from the exclusive application of urea > loss from the combined application of organic and inorganic fertilizers > loss from the exclusive application of cattle manure > loss from the application of no-N-fertilizer. The combined application of organic and inorganic fertilizers can produce organic acids, which reduces the soil pH during decomposition of organic fertilizers and limits the alkalinity to a level below the level that is required for urea ammonia volatilization to start (Dong et al. 2009), thereby reducing the ammonia volatilization loss. Compared with the exclusive application of urea, the combination of organic and inorganic fertilizers and the exclusive application of organic fertilizer can significantly reduce ammonia volatilization.

Combined application of organic and inorganic fertilizers improved nitrogen recovery efficiency and increased grain yield

Using the same nitrogen application rate, the combined application of organic and inorganic fertilizers can regulate nitrogen accumulation and transport in maize and achieve a higher nitrogen use efficiency than other treatments (Wen et al. 2016; Zhao et al. 2016). In the study presented in this paper, the average nitrogen recovery efficiency for the combined application of organic and inorganic fertilizers was 33.2% and 15.6%, which was higher than that for the exclusive application of cattle manure and the exclusive application of urea in 2016 and 2017, respectively. The combined application of organic and inorganic fertilizers increased the nitrogen recovery efficiency, because microorganisms can easily utilize organic fertilizer, thereby fixing more nitrogen and reducing the loss of inorganic nitrogen. When crops require large amounts of nutrition, the soil is unable to provide sufficient nutrients to sustain the microorganisms, and many of them die and release the nitrogen they fixed in the soil, making it available for crop absorption and utilization (Jalilian et al. 2012). The combined application of organic and inorganic fertilizers resulted in a grain yield that was 75.8%, 4.64% and 8.89% higher than the yield for the application of no-N-fertilizer, the exclusive application of urea, and the exclusive application of cattle manure, respectively. The higher yield is mainly due to the combined application of organic and inorganic fertilizers, which guarantees the long-term nitrogen supply of the soil and the short-term nutrient demands of the crop, and reduces the nitrogen loss due to ammonia volatilization, N_2O emission and nitrogen leaching. In addition, the combined application of organic and inorganic fertilizers is more efficient with respect to satisfying the demand for nitrogen nutrients for the growth and development of maize, the improvement of the nitrogen utilization efficiency, the increase of dry matter accumulation, and the improvement of the grain yield.

Conclusions

The purpose of this study was to find an effective way to reduce nitrogen loss and increase crop nitrogen accumulation. The study found that the combined application of organic and inorganic fertilizers resulted in several improvements: The ammonia volatilization loss was 17% lower than for the exclusive application of urea, and nitrous oxide emissions were 26% lower than for the exclusive application of cattle manure. Additionally, the average nitrogen recovery efficiency was improved, being 15% and 32% higher than for the exclusive application of urea and the exclusive application of cattle manure, respectively. Finally, dry matter accumulation was increased, and the yield was high. All in all, the combined application of organic and inorganic fertilizers proved to be an effective fertilization method for realizing high yield, high efficiency and improved sustainability for the production of summer maize.

In this study, we only studied the effects of different fertilization methods on nitrogen loss, crop yield and dry matter accumulation, and did not delve into the causes of this phenomenon. Therefore, in future research, we will further analyze the causes of this phenomenon by taking soil microbial diversity, relative abundance, soil microbial biomass carbon and soil microbial biomass nitrogen as areas of study.

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