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Reducing Nitrogen Losses in Winter Wheat Grown in the North China Plain by Top-dressing with different Nitrogen Fertilizers

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ABSTRACT

Ammonia-volatilization loss is a common problem for the cropping fields in the North China Plain. A two-year field experiment was conducted to study nitrogen losses and the resultant wheat (*Triticum aestivum* L.) grain yield responses to four types of nitrogen fertilizers that were top-dressed on winter-wheat in Dongbeiwang Town, Beijing. Ammonium Bicarbonate (AC), Urea (U), Calcium Ammonium Nitrate (CAN) or Ammonium Sulphate-Nitrate (ASN) were applied at 190 kg N ha^{-1}. A control (CK) that received no N was included. Soil nitrate (NO_3-N) dynamics were measured and N balance was calculated for the period of the two winter-wheat seasons. The results showed that the apparent nitrogen losses from the AC, U, CAN or ASN treatments were 79, 42, 12, or 33 kg ha^{-1} in 2005 and 64, 45, -15 or -5 kg ha^{-1} in 2006, respectively. The grain yields from the U, CAN or ASN treatments ranged from 3932 to 5012 kg ha^{-1} during the two wheat seasons, much greater than those from the AC or the CK treatments. The nitrogen use efficiency for the AC, U, CAN, or ASN treatments was 43, 52, 59, or 56% in 2005 and 35, 46, 51 or 53% in 2006, respectively. Soil NO_3-N accumulation mainly occurred in the 0-60 cm profile and very small amounts of NO_3-N were detected in the 60-90 cm profile after harvest in the N fertilization treatments. These results suggested that in the North China Plain, which is characterized by a shortage of water resources and high soil pH, CAN is a better nitrogen fertilizer because of its lower nitrogen losses, higher nitrogen use efficiency and higher grain yield than the traditional nitrogen fertilizers, urea or ammonium bicarbonate.

Key words: Calcium ammonium nitrate, ammonium sulphate-nitrate, ammonium bicarbonate, urea, winter-wheat

INTRODUCTION

China is the largest chemical Nitrogen (N) fertilizer consumer in the world accounting for 34.4% of the total global consumption, with 26.1 million tons applied in 2005 (Li *et al.*, 2009). However, the recovery of chemical N fertilizers in crops was only about 30% for agricultural production in China (Zhang *et al.*, 2008). This low recovery has great negative impacts on the environment, such as large emission of gaseous.

Nitrogen and increases of the N concentration in water (Ebid *et al.*, 2007; Chen *et al.*, 2009; Alemi *et al.*, 2010). One of the important reasons for the lower N use efficiency is the heavy ammonia (NH_3) volatilization loss from farmland in China. The use of N fertilizers prone to loss by NH_3 volatilization is the main problem in the N fertilizer management. Different N fertilizers resulted in different rates of ammonia volatilization (Sommer and Jensen, 1994; Guixin *et al.*, 1998; Wagan *et al.*, 2003). The global mean amount of ammonia volatilization from urea (broadcast application) was 15-20%, whereas only 6% was lost from ammonium nitrate and only 3% was from calcium ammonium nitrate (FAO and IFA, 2001). Therefore, it is possible to decrease the N losses associated with fertilization by choosing an optimized N product.

In developed countries, a balanced N fertilizer structure was facilitated to meet the needs of different agricultural environments. Calcium Ammonium Nitrate (CAN), Ammonium Nitrate (AN), urea and liquid N fertilizers compromises 28.9, 25.9, 20.5 and 15.9% of total N fertilizer consumption, respectively, in Western Europe. The direct application of ammonia accounted for 33.2%, N solutions for 28.6% and Urea for 25.4% of N fertilization in USA (IFA, 2006). In China, however, urea and Ammonium Bicarbonate (AC) accounted for 58 and 22% of total N fertilizer consumption in 2003, respectively. As ammonium bicarbonate application is declining and the application of AN was prohibited to crop land in 2002, urea has become the dominant N fertilizer type used, which has lead to a singular N fertilizer structure. There is a substantial risk of ammonia loss through volatilization with urea-based fertilizers if they are not incorporated shortly after application (Isherwood, 2001). This was also occurred in Indian soils (Singh *et al.*, 2011). A potentially effective control mechanism for N losses would, therefore, be the use of alternative N fertilizers with smaller NH_3 emissions (ECETOC, 1994). In China, surface-broadcasting traditionally has been used for the application of N fertilizers because of reduced labour and time requirements. Developing a series of new N fertilizer types may be a practical way for farmers to improve nitrogen-use efficiency. The objectives of this study were to determine the effect of different N fertilizers on the growth and the yield of winter wheat and to identify an N fertilizer that can be used to optimize N retention in top-dressing applications in the North China Plain.

MATERIALS AND METHODS

Experimental site: A field experiment was conducted from 2004 to 2006 in Donbeiwang Town, Beijing (40.0° N, 116.2° E). The soil at the experimental site is a calcareous alluvial soil (calcareous Cambisol, FAO classification), which is typical for the North China Plain. Soil texture was loamy (Sedimentation method, Taubner *et al.*, 2009), with a bulk density of 1.33 g cm^{-3} in the 0-30 cm layer and 1.45 g cm^{-3} in the 30-60 cm and 60-90 cm layers. A list of selected soil properties is shown in Table 1. The topsoil layer (0-30 cm) was collected for measuring soil organic matter (Pereira *et al.*, 2006), total N (Kjedahl method, Bremner, 1996), extractable phosphorus (the molybdate-ascorbic acid method (Zhao *et al.*, 2006) and extractable potassium contents (the ammonium acetate Baker method (Chen, 2003). The rainfall during the experimental period was concentrated between June and August. The average annual amount of rainfall during the winter-wheat season in this region in recent years was 134 mm. The total rainfall amounts in the wheat seasons of 2005 and 2006 were 111 and 53 mm, respectively. Prior to this experiment, the field had been in a typical 1-year winter wheat-summer maize rotation. The experiment here focused only on the winter wheat season.

Table 1: Soil selected properties in the 0-30 cm layer at the experimental site in Donbeiwang Town, Beijing

Depth (cm)	Soil texture	pH (H_2O)	Organic matter (g kg^{-1})	Total N (g kg^{-1})	Olsen P (mg kg^{-1})	NH_4OAc-K (mg kg^{-1})
0-30	Loamy	8.0	2.3	1.02	17.4	157.5

Experimental design: The experiment started in mid-October 2004 and ran through to June 2005 in the first cropping year. The winter-wheat cultivar was Jingdong-8. Five treatments were tested; four of the treatments were top-dressed with four different N fertilizers and the remaining treatment was used as a control without any N application. All treatments were arranged in a randomized complete block design with four replicates. The plot size was 4.0×5.0 m^2. The N fertilizers used were: U (urea), AC (ammonium bicarbonate), CAN (calcium ammonium nitrate) and ASN (ammonium sulphate-nitrate). The total N application rate was 190 kg ha^{-1}, which was split into two applications of 120 kg ha^{-1} top-dressed on March 30 and 70 kg ha^{-1} top-dressed on April 26. Three sprinkler irrigations were applied during the cropping season. The first two applications occurred immediately after the two N applications, where 80 and 60 mm of water were applied, respectively. The last irrigation occurred on June 2, where 70 mm of water were applied. The experiment was repeated the following year at another site on the same farm. In the second year, the two N fertilizer applications occurred on March 30 and April 20.

Methods: Soil samples were obtained five times: before the first N application (March 30, 2005 and March 20, 2006), about 15 days after the first N application (April 15, 2005 and April 6, 2006), before the second N application (April 26, 2005 and April 20, 2006), about 15 days after the second N application (May 12, 2005 and May 10, 2006) and post-harvest in the middle of June. Each sampling included five cores per plot taken to a depth of 90 cm at a 30 cm increment. All of the samples were taken back to the school laboratory in an icebox. Once at the laboratory, the samples were passed through a 5 mm screen. A 12 g sample was extracted with 100 mL of 0.01 mol L^{-1} $CaCL_2$, followed by shaking for 1 h on a rotary shaker (180 rev min^{-1}). Following filtration, the extracts were analyzed directly for NH_4-N and NO_3-N using an automated continuous flow analyzer (TRAACS 2000 system, Bran and Luebbe, Norderstedt, Germany). The soil water content also was determined at the time of the extraction using a drying method.

Plant samples were taken at the stage of about 15 days after the first N application, about 15 and 30 days after the second N application and after harvest. Two subsamples (one row, 1-meter length) were taken from each plot before the harvest. For winter wheat final harvest, areas (3 m^2) in the middle of each plot were harvested to determine fresh grain yield. The straw and grain samples were for oven-dried at 65 degrees centigrade till weight constancy for the determination of dry matter. Subsamples of the grain and the straw were analyzed for N content by the Kjedahl method (Bremner, 1996).

The nitrogen budget sheets were calculated from the re-greening stage to the harvesting stage during the two growing seasons. For each season, the inputs of the N budget consisted of the inorganic N in the 0-90 cm soil profile before re-greening (initial N_{min}), the N mineralization and the top-dressed fertilizer N. The outputs consisted of the plant N accumulation and residual inorganic N in the 0-90 cm soil profile. The N mineralization was estimated using the balance of the inputs and the outputs in the control treatment. The nitrogen-use efficiency was expressed as the N recovery efficiency. The formulas used are given below and are expressed in kg ha^{-1}:

- Apparent N loss = N inputs – N outputs
- N input = top-dressed fertilizer N + initial N_{min} + N mineralization
- N output = residual N_{min} + plant N accumulation
- N mineralization = crop N accumulation from the control + residual N_{min} in the control – initial N_{min} in the control

- N recovery = (N accumulation from the N applied plot – N accumulation in the control plot) / the amount of N fertilizer

The data were subjected to Analysis of Variance (ANOVA) and significant differences among the five treatments were calculated using the Tukey test. Statistical analyses were performed using DUNCAN procedures of the SAS software package (SAS Institute, 1996).

RESULTS

Wheat yield: The wheat grain yields from the U, CAN and ASN treatments ranged from 3932 to 5012 kg ha^{-1} and were significantly higher than those from the CK or AC treatment at $p<0.05$. There was no significant difference ($p<0.05$) among the U, CAN or ASN treatments (Table 2). The yields from the ASN treatment were the highest in both of the experimental years. In the first year, the yield increased by 19 and 2% and in the second year by 25 and 8%, compared with the AC and U treatments, respectively. The yields in the second year were affected by the drought and were lower than those recorded in the first year. The head number and the kernel count per head increased during the two growing seasons in the treatments with U, CAN or ASN, compared to the AC treatments, which accounted for the yield increase in these treatments.

Total N concentration in growth stages and N recovery: The N concentrations of the wheat plants at different growth stages in 2005 and 2006 are shown in Fig.1. In the 2005, 15 days after the first N fertilizer application, the N concentrations of the CK, AC, U, CAN and ASN treatment were 2.30, 3.49, 4.06, 4.10 and 4.16%, respectively. The N concentration of the AC treatment was significantly less than that of the U, CAN or ASN treatments and there was no significant difference among the U, CAN and ASN treatments. The same trend occurred in the two subsequent N concentration tests conducted before the second N fertilizer dressing and at about 15 days after the second fertilization. In 2006, the N concentrations of the CK, AC, U, CAN and ASN treatments were 2.39, 2.68, 3.36, 3.56 and 3.52% at 15 days after the first N fertilization, respectively. There was no significant difference between the CK and AC treatments, but significant differences occurred between the AC treatment and the treatments with CAN or ASN. The results were similar for the second N dressing. In the data from the two seasons, there is a low value in the CK or AC treatments compared with those given in the study of Reuter *et al.* (1997). These results imply that the N supply provided in the AC treatment was not sufficient for full winter wheat plant

Table 2: Grain yield and its components of winter wheat from CK, AC, U, CAN and ASN treatments in two growing seasons

Parameters	Year	CK [a)]	AC	U	CAN	ASN
Yield (kg ha^{-1})	2005	1373[c)]	4038[b]	4890[a]	4935[a]	5012[a]
Head number (m^{-1} row)		67.8[b]	88.3[a]	88.0[a]	89.3[a]	90.9[a]
Kernels $head^{-1}$		13.8[c]	23.1[b]	28.5[a]	28.5[a]	28.7[a]
1000-grain weight		34.8[b]	36.5[a]	37.9[a]	38.1[a]	37.9[a]
Yield (kg ha^{-1})	2006	2019[c]	3689[b]	3932[a]	4118[a]	4449[a]
Head number (m^{-1} row)		87.5[b]	86.9[b]	95.8[a]	95.3[a]	98.9[a]
Kernels $head^{-1}$		15.6[b]	23.3[a]	22.9[a]	24.2[a]	23.7[a]
1000-grain weight		35.2[b]	36.9[ab]	38.2[a]	38.4[a]	38.2[a]

[a)] CK: treatment received no N, AC: Treatment received ammonium bicarbonate at 190 kg N ha^{-1}, U: Treatment received urea at 190 kg N ha^{-1}, CAN: Treatment received calcium ammonium nitrate at 190 kg N ha^{-1}, ASN: Treatment received ammonium sulphate nitrate treatment at 190 kg N ha^{-1}. The different letters in the same list represent significant differences among treatments at $p<0.05$

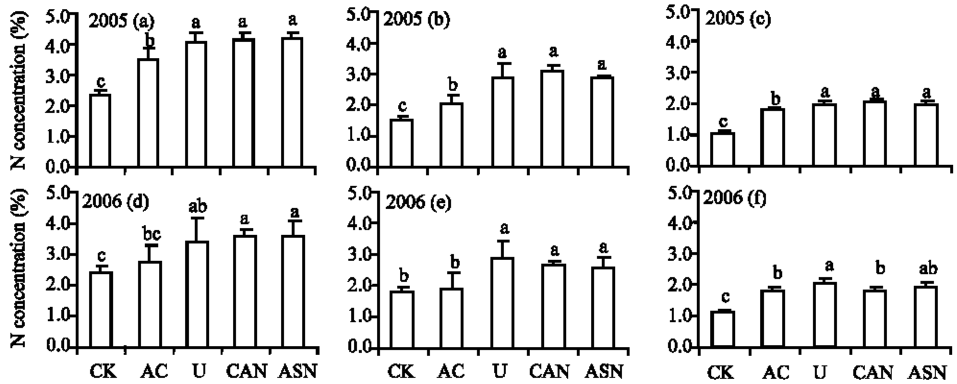

Fig. 1 (a-f): N concentration of winter wheat plant during times of 15th day after the first N dressing in 2005 (a), 15th day after the second N dressing in 2005 (b), 30th day after the second N dressing in 2005 (c) and 15th day after the first N dressing in 2006 (d), 15th day after the second N dressing in 2006 (e), 30th day after the second N dressing in 2006 (f), respectively. CK: Treatment received no N, AC: Treatment received ammonium bicarbonate at 190 kg N ha^{-1}; U: Treatment received urea at 190 kg N ha^{-1}; CAN: Treatment received calcium ammonium nitrate at 190 kg N ha^{-1}; ASN: Treatment received ammonium sulphate nitrate at 190 kg N ha^{-1}. The different small letters above each column represent significant differences at $p<0.05$

Table 3: Crop N accumulation and N recovery of winter wheat of CK, AC, U, CAN, ASN treatments in two growing seasons

		CK [a)]	AC	U	CAN	ASN
Crop N accumulation (kg ha^{-1})	2005	50.2^{c}	132.0^{b}	148.4^{a}	162.0^{a}	157.2^{a}
N recovery (%) [c)]		0	43	52	59	56
Crop N accumulation (kg ha^{-1})	2006	46.8^{c}	113.3^{b}	133.8^{ab}	144.1^{a}	148.3^{a}
N recovery (%)		0	35	46	51	53

[a)] CK: Treatment received no N, AC, U, CAN, ASN: Treatments received ammonium bicarbonate, urea, calcium ammonium nitrate, ammonium sulphate nitrate at 190 kg N ha-1, respectively. The different letters in the same row represent significant differences among treatments at $p<0.05$; [c)] N recovery = (N accumulation in N fertilization plot – N accumulation in no N fertilization plot)/the amount of N fertilizer ×100

development. The N concentration in 2006 was lower than that of the 2005 season for the same growing period due to poor rainfall in 2006; only 53 mm of precipitation fell during the winter wheat growth season in that year.

The different plant N concentrations recorded during the growth seasons resulted in significant differences in the N accumulation in response to the U, CAN or ASN treatments compared to the AC or CK treatments. The N use efficiency of the U, CAN or ASN treatments was between 56% in 2005 and 46-53% in 2006, much higher than the treatment with AC (43% in 2005 and 35% in 2006) (Table 3).

Dynamics of Ammonium-N and Nitrate-N in 0-90 cm Soils: The topsoil (0-30 cm layer) NH_4-N in the fertilizer treatments ranged from 5.5 to 41.6 in 2005 and 3.6 to 40.8 in 2006, reached peaks after the first N dressing and then declined to its original level. Little change was observed in the lower soil layers (30-90 cm) throughout the entire cropping season. The NH_4-N in the profile of these upland soils indicates a strong capacity for soil nitrification and low NH_4-N accumulation.

During the period from 15 days after the first N dressing to the wheat harvest, the NO_3-N in the 0-90 cm soil profiles changed from 5.80 to 96.4 kg N ha^{-1} in 2005 and from 10.8 to 113 kg N ha^{-1} in 2006 (Fig. 2). In the top-soil layer, the NO_3-N accumulation increased after the first N dressing. In the 30-60 cm layer, the NO_3-N accumulation in the U, CAN or ASN treatments increased after the second N dressing in the first year, whereas no increase occurred from the AC treatment comparing with the CK treatment. In 2006, there were no NO_3-N increases from the N applied treatments in the 30-60 cm soil layers after the second N dressing, then the increases occurred after harvest. In the bottom-soil layers (60-90 cm), the NO_3-N accumulations in the AC, U, CAN or ASN treatments did not change compared with the CK treatments within the two growth periods. The residual NO_3-N was less than 20 kg N ha^{-1} in the bottom-soil layer following harvest, so it is impossible to move NO_3-N out of the 90 cm soil profile in the wheat seasons. The total soil residual NO_3-N in 0-90 cm profiles in the ASN, CAN or U treatments (45.3 to 113 kg N ha^{-1}) was greater than those in the AC or CK treatments (5.8 to 96.4 kg N ha^{-1}). Higher accumulation of soil residue NO_3-N (>100 kg N ha^{-1} in 0-90 cm soil layer (Chen, 2003) in the CAN treatment suggested that the amount of CAN was excessive and that the application rate of this particular fertilizer can be reduced to increase the N use efficiency.

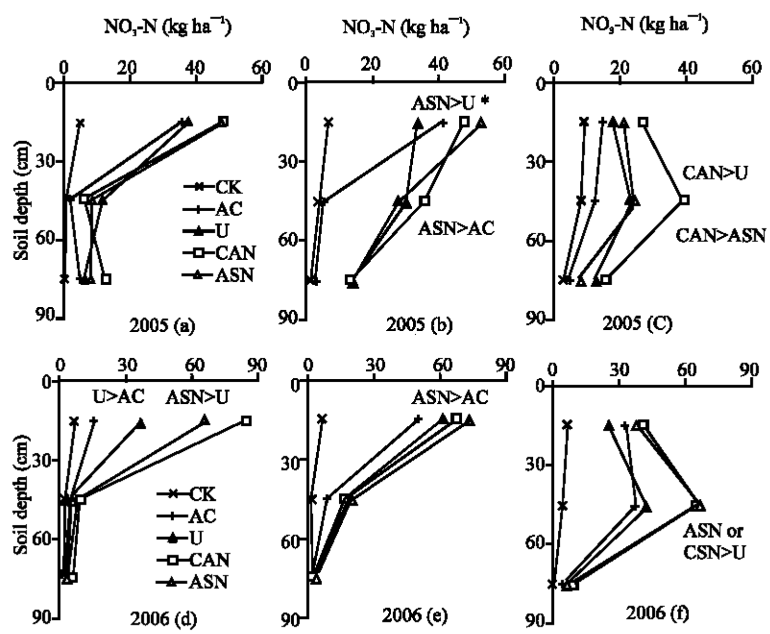

Fig. 2 (a-f): NO_3-N accumulation in the 0 to 90 cm soil profile at a 30-cm increment in the five treatments during times of 15th day after the first N dressing in 2005 (a), 15th day after the second N dressing in 2005 (b), after wheat harvest in 2005 (c) and 15th day after the first N dressing in 2006 (d), 15th day after the second N dressing in 2006 (e), after wheat harvest in 2006 (f), respectively. CK: Treatment received no N; AC, U, CAN, ASN: Treatments received ammonium bicarbonate, urea, calcium ammonium nitrate, ammonium sulphate nitrate at 190 kg N ha^{-1}, respectively. *- Significant differences at $p<0.05$

Table 4: Apparent N balance sheet for the CK, AC, U, CAN, ASN treatments from re-greening to harvest stage in 2005 and 2006

Parameters	CK[a]	AC	U	CAN	ASN
The wheat growing season in 2005					
(N input N, kg ha^{-1})					
0-90 cm Soil N_{min} before re-greening	43[a]	37[ab]	29[b]	48[a]	28[b]
N fertilizer	0	190	190	190	190
Soil N mineralization[c]	39	39	39	39	39
(N output N, kg ha^{-1})					
0-90 cm Soil N_{min} after harvest	32[c]	55[b]	68[b]	100[a]	67[b]
Crop N accumulation	50[c]	132[b]	148[a]	165[a]	157[a]
Apparent N losses (N input–N output)	0	79	42	12	33
The wheat growing season in 2006					
(N input N, kg ha^{-1})					
0-90 cm Soil N_{min} before re-greening	23[a]	29[a]	23[a]	18[a]	24[a]
N fertilizer	0	190	190	190	190
Soil N mineralization	51	51	51	51	51
(N output N, kg ha^{-1})					
0-90 cm Soil N_{min} after harvest	27[b]	93[b]	85[b]	130[a]	122[a]
Crop N accumulation	47[c]	113[b]	134[ab]	144[a]	148[a]
Apparent N losses (N input–N output)	0	64	45	-15	-5

[a] CK: treatment received no N, AC, U, CAN, ASN: treatments received ammonium bicarbonate, urea, calcium ammonium nitrate, ammonium sulphate nitrate at 190 kg N ha^{-1}, respectively. Different letters indicate significant difference at $p<0.05$ in the same row.
[c] N mineralization = crop N accumulation from the control + residual N_{min} in the control – initial N_{min} in the control

Nitrogen budgets: From the re-greening to the post-harvesting stage, the apparent N losses from the N fertilization treatments in 2005 ranged from 12 to 79 kg N ha^{-1} and the N losses from the AC treatments were the highest among them (Table 4). The loss rates in the AC, U, CAN and ASN treatments were 41, 22, 6 and 17%, respectively. The N application significantly increased the N_{min} in the 0-90 cm soil profile at harvesting. The crop N accumulation ranged from 50 to 165 kg N ha^{-1}, this value was a result of 39 kg N ha^{-1} soil N mineralization. There were significant differences in the N accumulation between the CK and AC treatments and the U, CAN or ASN treatments but no significant differences occurred among the U, CAN or ASN treatments. During the 2006 season, the apparent N losses were similar to those of the 2005 season. The losses were 64, 45, -15 and -5 kg N ha^{-1} for the AC, U, CAN and ASN treatments, respectively and 0-34% of applied N was lost to the environment. The soil N mineralization (51 kg N ha^{-1}) was higher in the 2006 season, whereas the crop N accumulation (47-148 kg N ha^{-1}) was less in the 2005 season. These differences were likely due to different weather conditions between two growing seasons. However, the trend of losses from different N fertilizers was similar in two years.

DISCUSSION

Studies conducted two decades ago in China showed that the yield effects of Ammonium Bicarbonate (AC), urea or Ammonium Nitrate (AN) were similar when these N fertilizers were applied deeply into the soil (Zhenbang *et al*., 1985). When these fertilizers were top-dressed, the N losses by ammonia volatilization in the AC application were significantly higher than those of the urea application (Zhenbang *et al*., 1985; Guixin *et al*., 1998). In the experiment presented here, the yield in the AC treatment was significantly lower than that of the U, CAN, or ASN treatments, whereas the N loss from the AC treatment was higher than in the other treatments, an effect that may explain why the yield of the AC treatment was not as high as with other treatments. Present yield results are in contrast to other experiments using the same N fertilizer application methods to summer maize in the North China Plain (Ding *et al.*, 2004), which may be due to the different weather condition such as temperature and rain fall, between the winter and summer growth seasons.

In general, ammonia volatilization, biological denitrification and nitrogen leaching were the main pathways for N losses (Zhu and Chen, 2002). Ju *et al.* (2002) reported that the denitrification loss in winter wheat was 0.21-0.26% of the applied N in Dongbeiwang Town, Beijing, at the same farm site where our experiment was conducted. Denitrification was not an important process in N loss from the calcareous soil in the North China Plain (Guixin *et al.*, 1998; Liu *et al.*, 2003). The combination of irrigation in excess of the crop requirements, heavy rainfall and a high nitrate concentration in the soil profile resulted in high nitrate leaching losses (Zhu *et al.*, 2005; Zhang *et al.*, 2005; Zhao *et al.*, 2006). During the two growth seasons in this study, the rainfall amounts were very small (111 and 53 mm) and none of the rainfall events exceeding 40 mm of precipitation. The soil water content was always below the field capacity; as a result there was limited water movement into the deeper soil layers (>90 cm), despite the optimized irrigation (3 applications with a total of 210 mm applied). With the low NO_3-N accumulation in the 60-90 cm soil layers, the resultant conditions were not appropriate for NO_3-N leaching. Ammonia volatilization was more likely to be the main pathway of N losses in this study area. Gao *et al.* (2005) and Chen (2003) reported similar results under poor rainfall and appropriate N application.

The type of N fertilizer applied had a great effect on the magnitude of N losses this experiment. The highest N loss was in the AC treatment, followed in order by the U, ASN and CAN treatments. Present results support those of Whitehead and Raistrick (1990), Bian *et al.* (1997), Zia *et al.* (1999), Brentrup *et al.* (2001), Li *et al.* (2001) and Weber *et al.* (2001). Top-dressing with CAN or ASN could increase the nitrogen use efficiency by 5-10%. The CAN or ASN treatments had less N losses to the environment than the urea treatment. Sommer and Jensen (1994) determined that the ammonia loss from U and CAN surface applications to the winter wheat were 25 and <2%, respectively. Data summarized by the FAO and IFA (2001) for major fertilizer types showed that NH_3 loss rates from AC, U and CAN are 21-70, 15-20 and <6%, respectively. The reason for the lower N losses from CAN or ASN fertilizers is not very clear. Wagan *et al.* (2003) reported that volatilization losses from ammonium nitrate or ammonium sulphate to use as a topdressing was less than that from urea under high soil pH or low moisture conditions. In the Northern China Plain, cropland is just under these conditions (Zhao *et al.*, 2006). The CAN and ASN fertilizers were produced from Ammonium Nitrate (AN) with CaO or H_2SO_4 added, respectively. It was reported that adding CaO or H_2SO_4 to AN could reinforce the stability of the AN and reduce ammonia emission when the product is applied in the field (Beyrouty *et al.*, 1988; FAO and IFA, 2001).

The high loss seen in the AC treatment suggests that applying AC, followed by irrigation, is still not a good practice under the experimental conditions. Surface-broadcast urea or AC resulted in more NH_3 volatilization than banded fertilizer application (Cai *et al.*, 2002; Zhang *et al.*, 1992). Although top-dressed urea was followed by irrigation, the NH_3 emission was still not low, accounting for 15.5-25.7% of the applied N (Yu-Ming *et al.*, 2004; Su *et al.*, 2006). However, lower losses came from the ASN or CAN top-dressed treatments of the winter wheat field. The top-dressing application was consistent with traditional farming practices, as few farmers would choose to dress N fertilizer by deep banding since this technique is time-and-labour intensive. Selecting an optimized N fertilizer type as a top-dressing fertilizer with a low ammonia volatilization loss may be an effective and simple way for local farmers to reduce N losses.

CONCLUSIONS

In this study, compared to the use of conventional nitrogen fertilizers, the use of top-dressed CAN in the winter wheat system could maintain higher nitrogen use efficiency, provide an increase in grain yield and reduce N losses by 16 to 35%. While the use of top-dressed ASN also increased the grain yield of the winter wheat by 2 to 25%, the treatment caused smaller losses of N in the second year; this is an interesting finding that will require further research. The challenge is that could the CAN or ASN be introduced to farmers as direct measures to limit N losses from the cropping fields in Northern China. Further work will be required to provide a detailed evaluation on CAN or ASN in other cropping systems.

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