

# AMMONIA VOLATILIZATION IN NO-TILL SYSTEM IN THE SOUTH-CENTRAL REGION OF THE STATE OF PARANÁ, BRAZIL<sup>(1)</sup>

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## SUMMARY

Ammonia (NH<sub>3</sub>) volatilization can reduce the efficiency of urea applied to the surface of no-till (NT) soils. Thus, the objectives of this study were to evaluate the magnitude of NH<sub>3</sub> losses from surface-applied urea and to determine if this loss justifies the urea incorporation in soil or its substitution for other N sources under the subtropical climatic conditions of South-Central region of Paraná State, Brazil. The experiment, performed over four harvesting seasons in a clayey Hapludox followed a randomized block design with four replicates. A single dose of N (150 kg ha<sup>-1</sup>) to V5 growth stage of corn cultivated under NT system was applied and seven treatments were evaluated, including surface-applied urea, ammonium sulfate, ammonium nitrate, urea with urease inhibitor, controlled-release N source, a liquid N source, incorporated urea, and a control treatment with no N application. Ammonia volatilization was evaluated for 20 days after N application using a semi-open static system. The average cumulative NH<sub>3</sub> loss due to the superficial application of urea was low (12.5 % of the applied N) compared to the losses observed in warmer regions of Southeastern Brazil (greater than 50 %). The greatest NH<sub>3</sub> losses were observed in dry years (up to 25.4 % of the applied N), and losses decreased exponentially as the amount of rainfall after N application increased. Incorporated urea and alternative N sources, with the exception of controlled-release N source, decreased NH<sub>3</sub> volatilization in comparison with surface-applied urea. Urea incorporation is advantageous for the reduction of NH<sub>3</sub> volatilization; however, other aspects as its low operating efficiency should be considered before this practice is adopted. In the South-Central region of Paraná, the low NH<sub>3</sub> losses from the surface-applied urea in NT system due to wet springs and mild temperatures do not justify its replacement for other N sources.

**Index terms:** nitrogen fertilizer, urea, corn, urease.

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**RESUMO:** *VOLATILIZAÇÃO DE AMÔNIA EM PLANTIO DIRETO NA REGIÃO CENTRO-SUL DO PARANÁ*

*A volatilização de amônia (NH<sub>3</sub>) pode resultar em baixa eficiência da ureia aplicada na superfície de solos sob plantio direto (PD). Os objetivos deste estudo foram avaliar a magnitude da perda de NH<sub>3</sub> proveniente da ureia e verificar se essa perda justifica a incorporação do fertilizante ou a sua substituição por outras fontes de N nas condições climáticas da região centro-sul do Paraná. O experimento, conduzido por quatro safras num Latossolo Bruno argiloso, consistiu da aplicação em dose única de 150 kg ha<sup>-1</sup> de N em cobertura na cultura do milho (estádio V5) em PD, em sete tratamentos (ureia superficial, ureia incorporada, sulfato de amônio, nitrato de amônio, ureia com inibidor de urease, fonte de N de liberação gradual e uma fonte líquida de N), além de um tratamento controle (sem adubação nitrogenada). Utilizou-se o delineamento de blocos casualizados, com quatro repetições. A volatilização de NH<sub>3</sub> foi avaliada por meio do sistema semiaberto estático, durante 20 dias após a aplicação dos fertilizantes. A perda acumulada de NH<sub>3</sub> com a aplicação superficial de ureia, na média dos quatro anos, foi baixa (12,5 % do N aplicado) em comparação a perdas superiores a 50 % determinadas em regiões mais quentes do Sudeste do Brasil. As maiores perdas de NH<sub>3</sub> da ureia foram verificadas em anos secos (até 25,4 % do N aplicado), as quais reduziram exponencialmente com o aumento do volume de chuva posterior à aplicação do N. A incorporação da ureia e as demais fontes de N, com exceção da fonte de N de liberação gradual, reduziram a volatilização de NH<sub>3</sub> em comparação à ureia superficial. A incorporação da ureia é tecnicamente vantajosa quanto à redução da volatilização de NH<sub>3</sub>, porém a adoção dessa prática deverá levar em consideração outros aspectos, como o seu baixo rendimento operacional. Por sua vez, a baixa perda de NH<sub>3</sub> proveniente da ureia superficial nas condições regionais de primavera chuvosa e com temperatura amena não justifica economicamente sua substituição por outras fontes de N na região centro-sul do Paraná.*

*Termos de indexação: adubação nitrogenada, ureia, milho, urease.*

## INTRODUCTION

In Brazil, the no-till (NT) system has been adopted on approximately 25 million ha and more than 12 million ha are located in the South Region (FEBRAPDP, 2008). Particularly, in the South-Central region of Paraná, NT farming occupies more than 90 % of agricultural area. Corn plays a significant role in the success of the NT system due to the significant input of straw to the soil. Furthermore, the usual corn-soybean rotation in a one-third proportion also reduces diseases and pests, and facilitates weed control (Fontoura & Bayer, 2009).

High corn yields can be achieved with an adequate N supply. For no-till soils, N amendments are often applied by surface coverage fertilization, and urea is the main used source of N. Upon addition to the soil, urea undergoes enzymatic hydrolysis (Cantarella, 2007), and NH<sub>2</sub> is converted to NH<sub>4</sub><sup>+</sup>. As a result, the pH of the soil surrounding the granules increases due to H<sup>+</sup> consumption, which increases NH<sub>3</sub> volatilization (Kissel et al., 1988). Thus, N volatilization is favored by high urease activity in the surface layer of no-tilled soils (Barreto & Westerman, 1989) and the presence of straw on the soil surface, which limits contact between the soil and the fertilizer (Menguel, 1996). However, high soil moisture, organic matter content and CEC levels in the surface layer of

NT soils are important factors increasing the buffer capacity of soil pH variation (Vieira et al., 2008) with possible effects decreasing NH<sub>3</sub> volatilization (Ferguson et al., 1984).

In Southeastern Brazil, N-NH<sub>3</sub> losses from surface-applied urea in NT soils range from 38 to 78 % of the total N applied (Lara Cabezas et al., 1997a, b; Lara Cabezas et al., 2000; Costa et al., 2003). As a result, farmers and researchers question the efficiency of the surface-applied urea as a N source for corn in NT system. However, N losses due to volatilization are highly dependent on the climate and soil type (Al-Kanani et al., 1991; Sangoi et al., 2003). For instance, temperature affects the rate of the enzymatic hydrolysis of urea, and rainfall affects the dilution of alkalinity generated by urea hydrolysis in soil. Moreover, rainfall influences soil moisture, which favors the diffusion of NH<sub>4</sub><sup>+</sup> into soil and its adsorption to soil colloids (Rodrigues & Kiehl, 1986). Soil type affects the pH and the retention of NH<sub>4</sub><sup>+</sup> in the soil (Sangoi et al., 2003). Due to the aforementioned factors, average NH<sub>3</sub> losses below 20 % of the total N applied as urea or manure are observed in subtropical regions of Southern Brazil (Port et al., 2003; Basso et al., 2004; Da Ros et al., 2005). Thus, these lower N volatilization losses than in tropical regions of Southeast Brazil evidenced that regional studies are necessary to determine the most appropriate N fertilization management strategy (Da Ros et al., 2005).

Urea incorporation has been shown to significantly reduce  $\text{NH}_3$  volatilization (Silva et al., 1995). Among alternative N sources, applications of ammonium sulfate and ammonium nitrate to the soil surface can reduce  $\text{NH}_3$  volatilization (Lara Cabezas et al., 1997a) due to acid-base reactions and the presence of  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$  anions, which favor vertical  $\text{NH}_4^+$  soil displacement (Lara Cabezas et al., 1997a, b; Kiehl, 1989). Controlled-release sources of N and fertilizers containing urease inhibitors can be used to increase N efficiency; however, the results obtained from these fertilizers are highly variable and range from null or negative (Rozas et al., 1999) to positive (Clay et al., 1990).

The present study, performed over four harvest seasons, aimed to evaluate the magnitude of  $\text{NH}_3$  volatilization from surface-applied urea to a no-till clayey Hapludox under the mild subtropical conditions of the South-Central region of the State of Paraná, Brazil. Furthermore, we aimed to determine whether the incorporation of urea or the application of an alternative N source should be recommended in substitution of surface-applied urea in this region.

## MATERIAL AND METHODS

The present study was conducted between 2004/05 and 2007/08 at the experimental area of Agraria Foundation of Agricultural Research, located in the Entre Rios district of the county of Guarapuava, State of Paraná, Brazil. According to Köppen classification, the climate is humid subtropical, and a dry season does not occur in the study region. According to the meteorological station of Agraria Foundation, the annual precipitation and average temperature are 1,956 mm and 16.9 °C, respectively. The soil is a Hapludox (Latossolo Bruno aluminico by the Brazilian Soil Classification System – Embrapa, 2006). The chemical attributes of the 0–10 and 10–20 cm soil layers in the different years of the study are provided in table 1.

The experiment consisted in a single dose of 150 kg ha<sup>-1</sup> of N applied by broadcasting at the V5 growth stage of corn under a no-till system. The following fertilizers were evaluated: urea, ammonium sulfate, ammonium nitrate, urea with urease inhibitor, controlled-release N source and a liquid N source, which was only evaluated during the last two harvests. In each year, a control treatment without N application and a treatment with incorporated urea were also evaluated. The urea was incorporated manually in a groove 15–20 cm from the corn row. The experiment was conducted according to a randomized block design, and treatments were applied to 24.0 m<sup>2</sup> plots (six corn rows at 0.8 m spacing and 5 m long) in four replications.

In each trial, corn was preceded by wild radish (*Raphanus raphanistrum* L.), which was managed with glyphosate herbicide applied, at 1,000 g ha<sup>-1</sup> a.e., approximately 10 days prior to corn sowing. Pioneer 30F53 hybrid corn was sown on 10/01/2004, 10/03/2005, 9/26/2006 and 9/28/2007 using a seed drill with a chisel-type furrow opener at a density of 65,000 plants ha<sup>-1</sup>. Seeds were treated yearly with thiodicarb (700 g a.i. per 100 kg of seeds). Fertilization was performed according to the results of chemical soil analyses (Table 1), and the application of 350, 390, 400 and 350 kg ha<sup>-1</sup> of 10–20–20 (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) was applied in 2004/05, 2005/06, 2006/07 and 2007/08, respectively. Post-emergence weed control was achieved with a mixture of atrazine, simazine and a mesotrione herbicides at a rate of 750, 750 and 120 g ha<sup>-1</sup> a.e., respectively.

To evaluate  $\text{NH}_3$  volatilization, five polyvinyl chloride (PVC) bases per plot were fixed between corn rows at a depth of 2.5 cm prior to N application. The bases were isolated with a plastic film during fertilizer application. Immediately after application, the plastic was removed and fertilizer was added to each PVC base. The objective of the plastic film and the posterior application of N in the PVC base was to reduce the variability of  $\text{NH}_3$  volatilization.

**Table 1. Soil chemical attributes of the experimental areas during the four growing seasons**

Year	Depth	pH <sup>(1)</sup>	H + Al	Al <sup>3+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	P	MO	V
	cm				cm ol <sub>c</sub> dm <sup>-3</sup>			mg dm <sup>-3</sup>	g dm <sup>-3</sup>	%
2004/05	0–10	4.80	7.76	0.08	7.05	1.62	0.44	16.0	60.30	54.0
	10–20	4.60	9.01	0.27	4.76	1.54	0.26	5.7	53.61	42.1
2005/06	0–10	4.80	9.01	0.04	3.64	1.25	0.50	14.5	56.28	35.6
	10–20	4.70	9.70	0.08	3.71	1.05	0.49	5.8	53.66	35.1
2006/07	0–10	5.00	6.69	0.00	6.56	2.16	0.43	11.5	57.77	57.8
	10–20	4.50	8.36	0.34	3.87	0.91	0.28	8.0	67.08	37.7
2007/08	0–10	5.20	5.76	0.00	6.12	2.99	0.47	12.8	69.13	62.4
	10–20	4.80	8.36	0.04	4.61	1.74	0.38	6.1	63.67	44.6

<sup>(1)</sup> CaCl<sub>2</sub> 0.05 mol L<sup>-1</sup>. The analysis was carried out according to the procedures described in Tedesco et al. (1995).

N-NH<sub>3</sub> volatilization was evaluated with a semi-open static collector (Lara Cabezas & Trivelin, 1990) made of a transparent acrylic chamber ( $\varnothing = 0.15$  m and  $h = 0.35$  m). The collector was installed over the bases, and the evaluation performed at 0, 1, 3, 5, 9 and 20 days after N application. During the evaluation period, the chamber was transferred to an adjacent base to ensure that the measured period reflected the environmental conditions (rain, wind, temperature) of the previous period and to prevent interferences caused by the chamber (Cantarela et al., 1999). A plastic support was installed on the top of the chamber in order to avoid rain (Da Ros et al., 2005).

Two absorbing sponge disks were placed inside the chamber (2.0 cm thick and soaked in 0.05 mol L<sup>-1</sup> sulfuric acid and 2 % glycerin). The first disk was placed 14 cm from the bottom of the chamber to capture volatilized NH<sub>3</sub> from the soil, and the second disk was placed 8 cm below the top of the cylinder to prevent NH<sub>3</sub> from the atmosphere from entering the chamber and contaminating the lower sponge. Ammonium was extracted from the lower disk by five successive washes with 1.0 mol L<sup>-1</sup> KCl. The washings were collected in a volumetric flask, and the final volume of the solution was increased to 200 mL. To a 20 mL aliquot of the solution, 0.2 g of MgO was added, and the mixture was steam distilled in a semi-micro Kjeldahl. NH<sub>3</sub><sup>+</sup> was converted to NH<sub>4</sub> in a H<sub>3</sub>BO<sub>3</sub> solution, which was quantified by titration with a standard sulfuric acid solution (Tedesco et al., 1995). The amount of volatilized N-NH<sub>3</sub> was calculated based on the total volume (200 mL) of the washings, and the results were expressed in daily rates (kg ha<sup>-1</sup> day<sup>-1</sup>) of N-NH<sub>3</sub>. Volatilization rates from the control treatment (without N fertilizer) were subtracted, and cumulative N-NH<sub>3</sub> losses from each N source were calculated (kg ha<sup>-1</sup>) and expressed as a percent of the applied N.

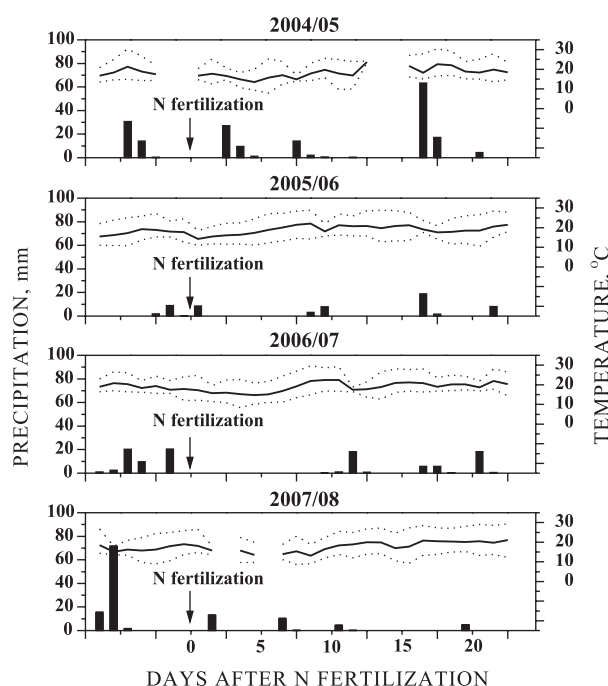
The yield of corn grain was evaluated by manually harvesting a 12.8 m<sup>2</sup> area (four central corn rows), and the data was expressed at 13% humidity. Rainfall and air temperature data was obtained from the meteorological station of Agraria Fundation, which is located 500 to 1,000 m from the experimental area.

The corn yield and cumulative N-NH<sub>3</sub> volatilization (as a percentage of applied N) results were subjected to an analysis of variance. The differences between the treatment means were evaluated by Tukey test at 5 %.

## RESULTS AND DISCUSSION

Average monthly temperatures in November, month that N fertilizers were applied each year, showed a very little variation among years, varying from 18.1 to 18.9 °C (Figure 1). A few higher

temperature was observed in the second (2005/06) and third years (2006/07). On the other hand, significant variations were observed in the volume of precipitation, which varied from 58.6 to 185.0 mm. As shown in Figure 1, the driest years coincided with the highest temperatures (2005/06 and 2006/07). Theoretically, the second and third years had the greatest potential for nitrogen loss due to NH<sub>3</sub> volatilization because high temperatures accelerate the enzymatic hydrolysis of urea due to an increase in urease activity, and low volumes of precipitation result in low soil moisture, which reduces NH<sub>4</sub><sup>+</sup> diffusion into the soil (Rodrigues & Kiehl, 1986).

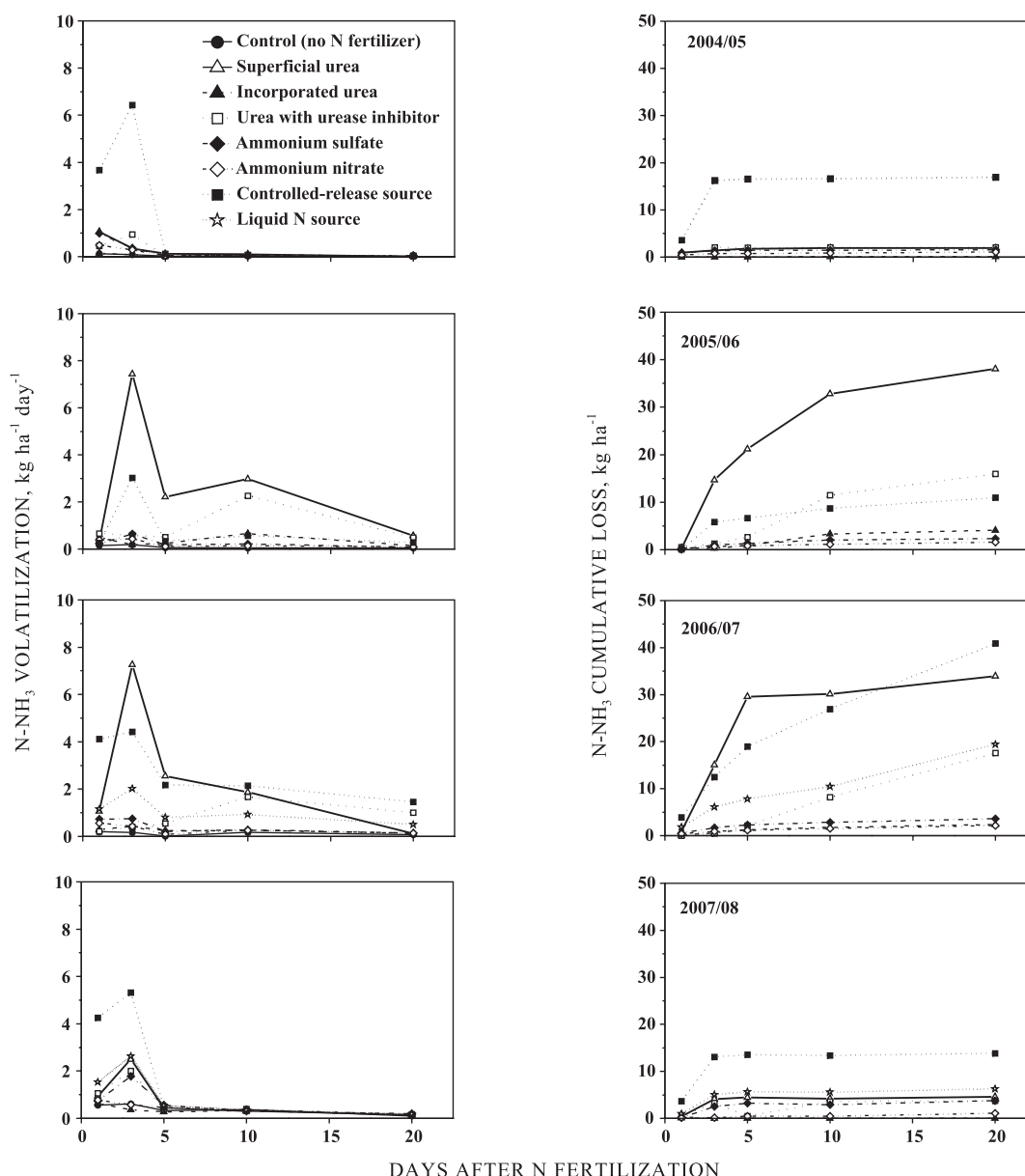


**Figure 1. Pluviometric precipitation (vertical bars) and air temperature (minimum, average and maximum) for the month of November during four growing seasons in Guarapuava, PR.**

### Daily rates and cumulative losses of N-NH<sub>3</sub> due to the surface application of urea

The volatilization rate and cumulative losses of N-NH<sub>3</sub> due to the surface application of urea varied among years (Figure 2). The greatest volatilization rates and cumulative N-NH<sub>3</sub> losses were observed in the second and third years due to low volumes of precipitation and high average temperatures (Figure 2, Table 2). Three days after N application, the volatilization rates were approximately 8 kg ha<sup>-1</sup> day<sup>-1</sup> in both the second and third years, and cumulative losses of N-NH<sub>3</sub> in 2005/06 and 2006/07 were 25.4 and 20.1 % of the total applied N, respectively (Table 2). In 2004/05 and 2007/08, cumulative NH<sub>3</sub> losses were equal to 1.3 and 3.0% of the total applied N, respectively (Table 2).





**Figure 2.** Rate and cumulative loss of  $\text{N-NH}_3$  by volatilization during four harvest seasons (2004/05, 2005/06, 2006/07 and 2007/08) of no-till corn treated with urea (superficial and incorporated) and other N sources in Guarapuava, PR.

Cumulative  $\text{N-NH}_3$  losses from all four years were averaged, and the results indicated that losses from surface-applied urea were equal to 12.5 % (Table 2). This value is similar to the results (13.6 %) obtained by Rozas et al. (1999), who studied  $\text{NH}_3$  volatilization in the Balcarce region of Argentina, which has an annual rainfall and average annual temperature of 870 mm and 13.7 °C, respectively. Moreover, the results of the present study were slightly lower than those (17 %) reported by Da Ros et al. (2005), who evaluated a sandy soil in the Central Depression region of the State of Rio Grande do Sul, Brazil, which has an annual rainfall and average annual temperature of 1,769 mm and 19.3 °C, respectively.

In previous field studies conducted in the Southern region of Brazil, manure was applied as an N source, and cumulative N losses ranging from 6.5 to 26 % of ammoniacal N were observed (Port et al., 2003; Basso et al., 2004). Moreover, N losses in subtropical climates were significantly lower than those obtained in tropical climates (38 to 78 %) (annual average temperature ~22 °C), such as Uberlândia (Lara Cabezas et al., 1997a, b; Lara Cabezas et al., 2000) and Piracicaba (Costa et al., 2003), which is located in Southeast Brazil. The aforementioned results indicated that the magnitude of N loss due to  $\text{NH}_3$  volatilization in no-till soils in Southern Brazil is significantly lower than those observed in regions with a warmer climate.

**Table 2. Cumulative ammonia loss (N-NH<sub>3</sub>), average corn yield, relative grain yield, and average temperature and volume of precipitation in November and in the first five days prior to and after fertilization**

N source	2004/05	2005/06	2006/07	2007/08	Average	Average yield	
						t ha <sup>-1</sup>	% <sup>(1)</sup>
	----- % of applied nitrogen -----						
Control (no N)	-	-	-	-	-	11.7 b	100
Superficial urea	1.3 b	25.4 a	20.1 ab	3.0 bc	12.5	14.0 a	120
Incorporated urea	0.1 c	2.7 d	1.6 d	0.0 d	1.1	14.2 a	122
Ammonium sulfate	1.0 bc	1.6 d	2.4 d	2.5 bcd	1.9	14.3 a	123
Ammonium nitrate	0.7 bc	1.0 d	1.4 d	0.7 bcd	1.0	14.1 a	121
Urea with urease inhibitor	1.4 b	10.7 b	11.7 c	2.5 cd	6.6	14.5 a	124
Controlled - release source	11.3 a	7.3 c	27.3 a	9.3 a	13.8	14.4 a	123
Liquid source of N	-	-	12.9 bc	4.2 b	8.6	15.0 a	129
Average	2.6	8.1	11.1	3.2	6.3	13.9	
Coefficient of variation (%)	22.1	28.9	43.1	46.5		4.4	
Average temperature (°C)	18.3	18.7	18.9	18.1			
Rain (mm)	185.0	58.6	104.8	22.4			
Prior rain (mm)	45.0	19.2	50.4	13.2			
After rain (mm)	38.0	0.0	0.0	5.2			

<sup>(1)</sup> In comparison to the control treatment. Averages followed by the same letter in a column do not differ according to the Tukey test at 5 % level.

Among the evaluated years, the volume of rain that occurred within five days after N application affected N volatilization (Table 2 and Figure 3). Cumulative N losses due to the application of urea (% of applied N) decreased exponentially as the volume of rain that fell after fertilization increased (Figure 3). However, a relationship between volatilization and the total monthly volume of precipitation or the volume of rain that fell five days prior to N application was not observed. These results were similar to those obtained by Lara Cabezas et al. (1997a), who demonstrated that NH<sub>3</sub> emissions can be reduced by irrigating the crop after nitrogen application. Moreover, irrigation prior to fertilization did not have an effect on N losses. Precipitation after urea application was highly effective at distributing NH<sub>4</sub><sup>+</sup> to soil microsites with a lower pH, which contributed to the adsorption of ions to soil colloids. Rainfall also transported fertilizer on the straw to the surface of the soil (Lara Cabezas et al., 1997a).

When precipitation occurred after fertilizer application (2004/05 and 2007/08), the daily N volatilization rate and the cumulative losses of NH<sub>3</sub> throughout the 20 days evaluation period was significantly different from the results obtained when rainfall did not occur after application (2005/06 and 2006/07) (Figure 2). The lack of rain after N application affected the N volatilization process throughout the entire 20 day evaluation period; however, the rate of volatilization decreased over time. Alternatively, when rainfall followed N application, NH<sub>3</sub> volatilization was restricted for the period of three days after fertilization. Therefore, in years when rainfall did not occur after urea application, the greatest losses of N through NH<sub>3</sub> volatilization were due to high volatilization rates immediately after application as well as the prolongation of the volatilization period (Figure 2).

### Effects of urea incorporation and other N sources on N-NH<sub>3</sub> volatilization

The efficiency of urea incorporation and the effect of N sources decreasing N losses can be better evaluated if the data from dry and warm years is mainly considered (second and third years), which showed the highest values of NH<sub>3</sub> volatilization. On average, in the second and third years, cumulative N-NH<sub>3</sub> losses of incorporated urea, ammonium sulfate and ammonium nitrate decreased from 22.8 % of applied N to 2.2, 2.0 and 1.2 %, respectively (Figure 2, Table 2).

The reduction of NH<sub>3</sub> volatilization by urea incorporation is due to buffering effects of the soil pH, which results from increased fertilizer-soil contact (Rodrigues & Kiehl, 1986; Silva et al., 1995; Lara Cabezas et al., 1997b; Lara Cabezas et al., 2000; Sangoi et al., 2003). In contrast to the effects of urea hydrolysis, ammonium sulfate and ammonium nitrate reduce NH<sub>3</sub> volatilization because they do not increase the pH of the soil surrounding the granule when they dissolve (Ferguson et al., 1984; Cantarella, 2007). Another factor that contributes to reduced ammonia losses from ammonium sulfate and ammonium nitrate is the presence of SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> anions, which favor the migration of NH<sub>4</sub><sup>+</sup> to regions with a lower pH and the retention of ammonia in soil colloids (Fenn & Hossner, 1985).

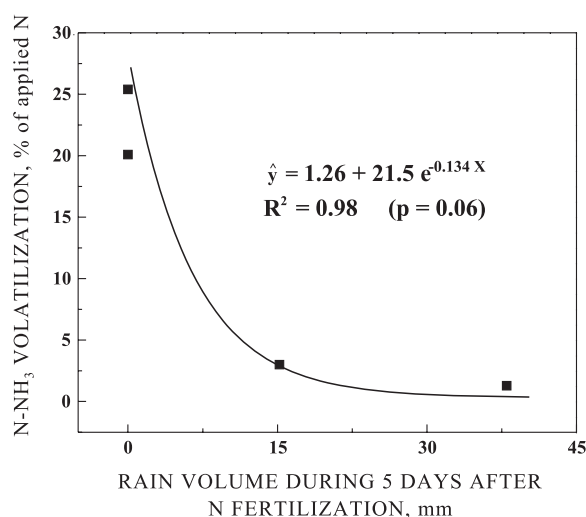
In general, controlled-release, liquid and urea with urease inhibitor N sources provided NH<sub>3</sub> losses that were less than those of surface-applied urea and greater than those of ammonium sulfate and ammonium nitrate (Figure 2, Table 2). In drier years (second and third years), average N losses of urea with urease inhibitor, controlled-release and liquid sources were 11.2, 17.3 and 12.9 % (only third year) of the total

applied N, respectively. Compared to superficial urea treatment, these products reduced N volatilization from 51, 24 and 43 % (Table 2). However, in years with greater volumes of precipitation, controlled-release N sources presented cumulative losses that were higher than those of surface applied urea (Figure 2, Table 2). Across the four years, N losses of 13.8 % of the total applied N were observed with controlled-release N source, which was higher than that of surface-applied urea (12.5 % of applied N).

### Corn grain yields

Surface N fertilization increased corn yield in all four years, but significant differences among N sources were not observed (Table 2). On average, N fertilization increased corn yield by 23 %, compared to the yield obtained from the control treatment (11.7 t ha<sup>-1</sup>).

The results obtained from all four years were analyzed, and a relationship between relative corn yield and cumulative N losses (% of applied N) was not observed, which probably was due to the high capacity of soil to N supply that is supported by high levels of soil organic matter (Table 1) and high corn yield of the control treatment without N fertilization (11.7 t ha<sup>-1</sup>). Thus, an application of 150 kg ha<sup>-1</sup> of N was greater than the amount of N demanded by the crop. Furthermore, the use of wild radish as the preceding crop played a significant role in supplying N to corn. Specifically, the recycling of biomass and the release of N via the decomposition of vegetal residues with low C:N ratio increased the N supply (Fontoura & Bayer, 2009).



**Figure 3.** The relationship between the volume of rainfall in the five day period after superficial urea application and the cumulative ammonia volatilization in the 20 day period after N application (150 kg ha<sup>-1</sup>) in a no-till corn. Each data point refers to a harvest year.

### Economic aspects

Except for controlled-release N, alternative N sources reduced NH<sub>3</sub> volatilization by 3.9 % (liquid N source) to 11.5 % (ammonium nitrate) in comparison to surface-applied urea. Based on the market values of these products over the past ten years, the cost of ammonium sulfate and ammonium nitrate per unit of N is 20 % greater than that of urea (USDA/ESR, 2008). Moreover, the cost of urea with urease inhibitor, controlled-release N and liquid N is 15 and 150 % higher than that of urea. Therefore, the additional cost of alternative N fertilizers is greater than the corresponding reduction in N volatilization. Thus, substitution of urea in the South-Central region of the State of Paraná is not economical.

Alternatively, urea incorporation, which costs R\$ 18.80 per ha, is cheaper than the cost of the N lost by volatilization due to superficial application of urea (R\$ 45.00 per ha, considering the loss of 12.5 % of 150 kg ha<sup>-1</sup> N at a cost of R\$ 2.4 kg<sup>-1</sup> of N). However, factors other than the costs of urea incorporation should be considered before this method is adopted. For instance, the operational efficiency of N incorporation is lower (~3 ha h<sup>-1</sup>) than that of surface applications (~12 ha h<sup>-1</sup>). Due to the low operational efficiency of urea incorporation, this method is not indicated for the cultivation of large fields.

### CONCLUSIONS

1. On average of the four harvesting seasons, the surface application of urea to no-till corn in the South-Central region of the State of Paraná resulted in N losses of 12.5 % of the total applied N. Moreover, greater losses were observed when lower volumes of rain fell after fertilization.

2. Urea incorporation and the use of ammonium sulfate, ammonium nitrate, liquid N source, and a urea with urease inhibitor reduced ammonia volatilization. However, reduction of NH<sub>3</sub> volatilization was not observed with a controlled-release N source that showed an average volatilization higher than that observed to surface-applied urea.

3. The loss of N through volatilization of surface-applied urea was low; thus, fertilizer replacement is not necessary in the South-Central region of the State of Paraná. The incorporation of urea is economically advantageous; however, other aspects of this practice, such as low operational efficiency, should be considered.

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