Comissão 3.2 - Corretivos e fertilizantes

AMMONIA VOLATILIZATION FROM NITROGEN FERTILIZERS IN NO-TILL WHEAT AND MAIZE IN SOUTHERN BRAZIL(1)

Fernando Viero(2), Cimélio Bayer(3), Sandra Mara Vieira Fontoura(4) & Renato Paulo de Moraes(5)

SUMMARY

Crop residues on the soil surface of no-till systems can intensify ammonia volatilization from N fertilizers applied to cereal crops. This study assessed the magnitude of N losses through ammonia volatilization from urea applied to no-till winter (wheat) and summer crops (maize) on a Typic Hapludox in the south-central region of Paraná, southern Brazil. In addition, the potential of alternative N sources (urea with urease inhibitor, liquid fertilizer, ammonium nitrate and ammonium sulfate) and different urea managements (fertilizer applied in the morning or afternoon) were evaluated. Two experiments with maize and wheat were carried out for two years, arranged in a randomized block design with four replications. Nitrogen volatilization losses were assessed with a semi-open static collector until 21 days after fertilization. In winter, the losses were low (<5.5 % of applied N) for all N sources, which were not distinguishable, due to the low temperatures. In the summer, volatilization rates from urea were higher than in the winter, but did not exceed 15 % of applied N. The main factor decreasing N losses in the summer was the occurrence of rainfall in the first five days after fertilization. Urea with urease inhibitor, nitrate and ammonium sulfate were efficient to decrease ammonia volatilization in maize, whereas the application time (morning or afternoon) had no influence.

Index terms: nitrogen fertilization, efficiency, yield.

---

(1) Excerpt from the Master's Dissertation of the first author at Universidade Federal do Rio Grande do Sul - UFRGS (Federal University of Rio Grande do Sul). Received for publication on April 11, 2013 and approved on July 2, 2014.

(2) Doctoral student, Graduate Program of Soil Science, UFRGS. Av. Bento Gonçalves, 7712. CEP 91540-000 Porto Alegre (RS), Brazil. E-mail: fernandoviero@gmail.com

(3) Associate Professor, Soil Science Department, UFRGS. E-mail: cimelio.bayer@ufrgs.br

(4) Researcher, Fundação Agrária de Pesquisa Agropecuária - FAPA. Praça Nova Pátria, s/n. CEP 85139-400 Distrito de Entre Rios, Guarapuava (PR), Brazil. E-mail: sandrav@agraria.com.br

(5) Agricultural Technician, FAPA. E-mail: renatop@agraria.com.br

RESUMO: *VOLATILIZAÇÃO DE AMÔNIA DE FERTILIZANTES NITROGENADOS APLICADOS NAS CULTURAS DO TRIGO E DO MILHO EM PLANTIO DIRETO, NO SUL DO BRASIL*

*Os resíduos culturais na superfície de solos em plantio direto (PD) podem intensificar a volatilização de amônia, quando da aplicação dos fertilizantes nitrogenados em sistemas de produção de cereais. Este estudo visou avaliar a magnitude das perdas de N por volatilização, quando da aplicação superficial de ureia nas culturas do trigo e do milho, em Latossolo Bruno em PD, no centro-sul do Paraná. Adicionalmente, avaliou-se o potencial de fontes alternativas de N (ureia com inibidor de urease, fertilizante líquido, nitrato de amônio e sulfato de amônio) e de variantes no manejo da ureia (fertilizante aplicado pela manhã ou à tarde) em reduzir as perdas de amônia por volatilização. Dois experimentos foram conduzidos, por dois anos, com as culturas do trigo (*Triticum aestivum *L.) e milho (*Zea mays *L.), seguindo um delineamento de blocos casualizados, com quatro repetições. As perdas de N por volatilização de amônia foram avaliadas utilizando-se um coletor semiaberto estático, no período de até 21 dias após a aplicação dos fertilizantes. No inverno, as perdas foram baixas para todas as fontes nitrogenadas (<5,5 % N aplicado) em razão das baixas temperaturas e independentes do regime de chuvas. No verão, as taxas de volatilização de amônia, quando da aplicação superficial de ureia, mantiveram-se inferiores a 15 % do N aplicado e foram dependentes da ocorrência de chuvas nos primeiros cinco dias após a aplicação do fertilizante. A utilização de ureia com inibidor de urease, nitrato e sulfato de amônio foi eficiente na redução das perdas de N por volatilização na cultura do milho, enquanto o horário de aplicação (manhã ou tarde) não teve influência.*

Termos de indexação: adubação nitrogenada, eficiência, rendimento.

INTRODUCTION

Maize and wheat are among the major grain crops produced in Brazil, grown on about 13 and 2 million hectares, respectively, mostly in the no-till (NT) system (CONAB, 2012). The yields of both crops increased over the years at the national level, although the mean yield in the field did not reach 50 % of the yield ceiling at the experimental level. Nitrogen fertilization is one the technologies for which optimization is being sought in order to increase crop yields, in view of the estimated efficiency of around 60 % (Fontoura & Bayer, 2009).

One of the important forms of N fertilization is the surface application of urea (Fontoura & Bayer, 2010). This is the most commonly used N source in grain crops, due to its lower cost per nutrient unit, for its availability and accessibility, being more competitive, particularly in situations where lower volatility losses are expected, e.g., in the driest and coldest months (Cantarella et al., 2008). However, recently the suitability of urea has been questioned, due to the possibility of its reduced efficiency by volatilization losses, which is increased under no-tillage management systems (Rojas et al., 2012), with losses ranging from 35 to 78 % of the N applied in warm climate, as in southeastern Brazil (Lara Cabezas et al., 1997b; Costa et al., 2003; Lara Cabezas & Souza, 2008; Pereira et al., 2009).

However, N volatilization losses vary greatly according to the climatic conditions, decreasing significantly with decreasing temperature (Ernst & Massey, 1960; Tasca et al., 2011). Rainfalls close to the time of fertilizer application also influence the magnitude of N volatilization losses. Low rainfall leads to urea solubilization, but the limited diffusion of N in the soil profile causes high volatilization losses (Bouwmeester et al., 1985), which can reach up to 50 % of applied N (Holcomb et al., 2011). However, rainfall after N application contributes to reduce N volatilization losses (Ferguson et al., 1984), for determining fertilizer solubility and diffusion of NH_4^+ in the soil profile, contributing to its adsorption to soil particles (Clay et al., 1990). In this situation, N volatilization losses decrease to less than 5 % of the applied N (Dawar et al., 2011; Holcomb et al., 2011).

The occurrence of drought periods (dry spells) is one of the main factors related to crop failure in Southern Brazil, periods in which the high losses of N by volatilization possibly contribute to the low crop yields. Among the practices that can potentially reduce N volatilization losses include the incorporation of N fertilizer (Silva et al., 1995) and the use of N sources with lower potential volatilization loss than urea (Lara Cabezas et al., 1997a; Vitti et al., 2002). The use of urease inhibitors (Sanz-Cobena et al., 2011; Tasca et al., 2011; Soares et al., 2012) and liquid fertilizers have been suggested as alternatives to N topdressing in several grain crops, both for winter and summer (Cantarella et al., 2008; Fontoura & Bayer, 2010). However, results vary according to the regional climate conditions, so that recommendations for alternative sources or management practices should be tested at regional level (Fontoura & Bayer, 2010).

The objective of this study was to quantify the magnitude of ammonia volatilization losses from urea applied to no-till wheat (winter) and maize (summer growing season) on a Typic Hapludox (Latossolo Bruno) in the south-central region of Paraná, as well as to evaluate the potential of reducing N volatilization losses due to the time of urea fertilization (morning or afternoon) and the use of alternative N sources.

MATERIAL AND METHODS

General description of the experiments

This study was carried out in 2009 and 2010 on an experimental field at Agrarian Foundation of Agricultural Research - FAPA (25° 33' S and 51° 29' W), located in the district of Entre Rios, Guarapuava, State of Paraná, Brazil. The regional climate, according to the Köppen climate classification, is humid subtropical (Cfb). The mean annual temperature is 16.8 °C, with monthly mean temperatures ranging from 20.5 °C (January) to 12.5 °C (July). The mean annual rainfall is 1,955 mm. The soil of the experimental area was classified as a clayey Typic Hapludox (Latossolo Bruno alumínico by the Brazilian Soil Classification System, Embrapa, 2013), containing approximately 60 % clay and under NT cultivation for over 25 years.

The study consisted of two experiments, conducted for two years (2009 and 2010), one with wheat (*Triticum aestivum* L.) in winter, and the other with maize (*Zea mays* L.) in summer. The experiments were arranged in a randomized complete block design with four replications. The experiment with wheat (2009 and 2010) and the experiment with maize (2009/10 and 2010/11) were conducted in succession to soybean (*Glycine max* L.) and white oat (*Avena sativa* L.), respectively, according to the research protocol of FAPA, by which the crop sequence in the experimental areas follows the most commonly used crop rotation (wheat-soybean/barley-soybean/white oat-maize) of the region. The chemical properties of the soil (0-20 cm layer) of the two experiments, conducted in two years in different areas, are presented in table 1.

The following N sources were evaluated in the wheat experiment: urea, urea with urease inhibitor NBPT [N-(n-butyl) thiophosphoric triamide] (only in the 2009 growing season), liquid fertilizer, ammonium nitrate and ammonium sulfate. For all N sources, 50 kg ha^{-1} N was surface-applied in a single side-dressing at the beginning of tillering (growth of the 5th leaf), early in the morning. In the 2009 growing season, the fertilizers were applied on August 14 and in the 2010 growing season on August 18.

In the experiment with maize, the following N sources were tested: urea, urea with urease inhibitor NBPT, ammonium nitrate and ammonium sulfate. Fertilizers were applied to the soil surface early in the morning, except for urea, for which application in the afternoon was tested as well. Nitrogen was applied to maize in a single side-dressing of 150 kg ha^{-1} day^{-1} N, in the V_6 stage, on November 16, 2009 and December 8, 2010.

In both experiments, an additional treatment was conducted with urea application in the afternoon (only in 2010 in wheat) and a control treatment (without N fertilization). The composition of N fertilizers used in terms of N content and form are detailed in table 2.

Ammonia collection and analysis

Ammonia (NH_3-N) volatilization losses were measured on the 1st, 3rd, 5th, 9th and 19th day after N fertilization of wheat, and on the 1st, 3rd, 5th, 10th and 20th (21st in 2009/10) day after N fertilization of maize.

A semi-open static collector was used to quantify the volatilized ammonia (Cantarella et al., 1999; Jantalia et al., 2012). The collection chambers consisted of a transparent acrylic cylinder (diameter 0.15 m, height 0.35 m), on which a protection was fixed to prevent rain from entering the chamber. The collection chambers were installed on polyvinyl chloride (PVC) bases previously inserted 0.025 m deep into the soil. Five bases per plot were installed, which allowed the use of one base per collection. In this way, the collection chambers were transferred to subsequent bases at every collection, so that the environmental conditions (rain, wind, temperature) from the previous

Table 1. Soil chemical properties in the 0-0.2 m layer in the experimental areas of wheat and maize in two study years

Crop	MO	pH($CaCl_2$)(1)	H+Al	Al	Ca	Mg	K	$CEC_{pH\ 7.0}$	P	V
	g dm^{-3}		cmol$_c$ dm^{-3}						mg dm^{-3}	%
					2009					
Wheat	38.2	5.5	5.4	0.0	6.8	3.0	0.73	15.9	17.1	66.4
Maize	30.4	6.0	3.7	0.0	6.7	3.6	1.14	15.1	8.2	75.5
					2010					
Wheat	34.7	5.4	5.4	0.0	6.3	3.0	0.95	15.6	18.1	65.7
Maize	38.2	6.1	3.2	0.0	7.1	3.9	0.41	14.6	16.9	78.2

(1) 0.05 mol L^{-1} $CaCl_2$.

period were reflected in the ammonia losses after fertilization, minimizing interferences caused by the presence of the collection chamber (Cantarella et al., 1999).

The bases were installed prior to fertilization and covered with plastic wrap to avoid fertilizer addition in the base area when applying fertilizer to the plot. Immediately after N fertilization in the plot, the plastic film covering the base was removed and the fertilizer applied in the area of the bases. Within the collection chambers, shortly after fertilization, two absorber disks of polypropylene (sponge) thickness 2.0 cm and density 28, soaked in sulfuric acid solution (0.5 mol L^{-1}) and glycerin (2 %) were installed. The first foam fixed at a height of 15 cm above the soil is supposed to capture NH_3 volatilized from soil in the chamber. The second sponge, fixed at 30 cm from the ground, has the function of capturing external NH_3 in the chamber, preventing contamination of the bottom sponge (Da Ros et al., 2005). During data collection, the foam disks were exchanged, and the lower disk was stored in a plastic bag and refrigerated (5 °C) for later extraction of ammonia retained in the acid solution as NH_4^+ (Lara Cabezas et al., 1997a).

The NH_4^+ retained in the absorber disk was extracted by successive washings (about five) with 1.0 mol L^{-1} KCl solution, the rinsing water collected in a volumetric flask, and the volume completed to 500 mL. To a 20 mL aliquot of this solution, 0.2 g of MgO was added and subjected to distillation in a semi-micro Kjeldhal distiller (Tedesco et al., 1995). The amount of NH_3-N volatilized was calculated based on the total volume of the solution used for washing the sponges (500 mL), and the results expressed as daily NH_3 volatilization rates (kg ha^{-1} day^{-1}). Cumulative NH_3-N losses (kg ha^{-1}) in each treatment were calculated by adding up daily losses throughout the evaluation period followed by subtraction of the losses from the control treatment without N fertilization. The losses were expressed on an area basis (kg ha^{-1} N) and percentage of applied N (Rojas et al., 2012).

Rainfall and temperature

The maximum, minimum and mean air temperature and rainfall data (Figure 1) were measured by an automatic weather station of FAPA, installed at a distance of 500 to 1,000 m from the experiments.

Statistical analysis

The results were subjected to analysis of variance and treatment means compared by the Tukey test at 5 %. The influence of daily mean temperature and rainfall of the first five days after fertilization on cumulative NH_3-N volatilization was evaluated by multiple linear regression coefficients.

RESULTS AND DISCUSSION

Rainfall and air temperature

To support the interpretation of the NH_3 volatilization data, the pattern of rain and air temperature in the experimental periods will be briefly presented (Figure 1).

The winter periods in which the experiment was conducted with wheat differed in terms of the mean temperature and amount of rainfall. The second winter (2010) was 2.1 °C warmer and drier than the winter of 2009 (mean temperature 13.8 °C), and no rain was recorded in the 19 days after fertilization. Nevertheless, the rain amount in 2009 was 83 mm in the evaluation period, 90 % of which fell between the 3rd and 6th day after fertilization (Figure 1a,b).

In the summer experiment with maize, daily temperatures ranged between 12 and 30 °C in 2009/10 and between 0 and 28.6 °C in 2010/11, corresponding to daily mean temperatures of 19.8 and 18.3 °C, respectively (Figure 1c,d). With regard to rainfall, the first growing season was characterized by a rainfall of 117 mm in the sampling period and a period of three days without rain after N fertilization. After this period, rainfall was regular throughout almost the entire sampling period. In the second growing season, the total rainfall volume in the sampling period was 138 mm, and 65 % (86.8 mm) of the total volume fell between the 2nd and 5th day after fertilization.

Daily volatilization rate

The daily volatilization rates of NH_3-N in the wheat experiment in both winter growing seasons were highest until the 5th day after fertilization in all treatments (Figure 2a,b). According to Lara Cabezas et al. (1997b), the initial loss is higher because urea hydrolysis begins immediately after fertilizer

Table 2. Content and forms of N in the fertilizers used in the experiments

Fertilizer	NH_2-N	NH_4^+-N	NO_3^--N	Total
	%			
Urea/Urea with urease inhibitor	45	-	-	45
Liquid fertilizer	14	9	9	32
Ammonium nitrate	-	17	17	34
Ammonium sulfate	-	21	-	21

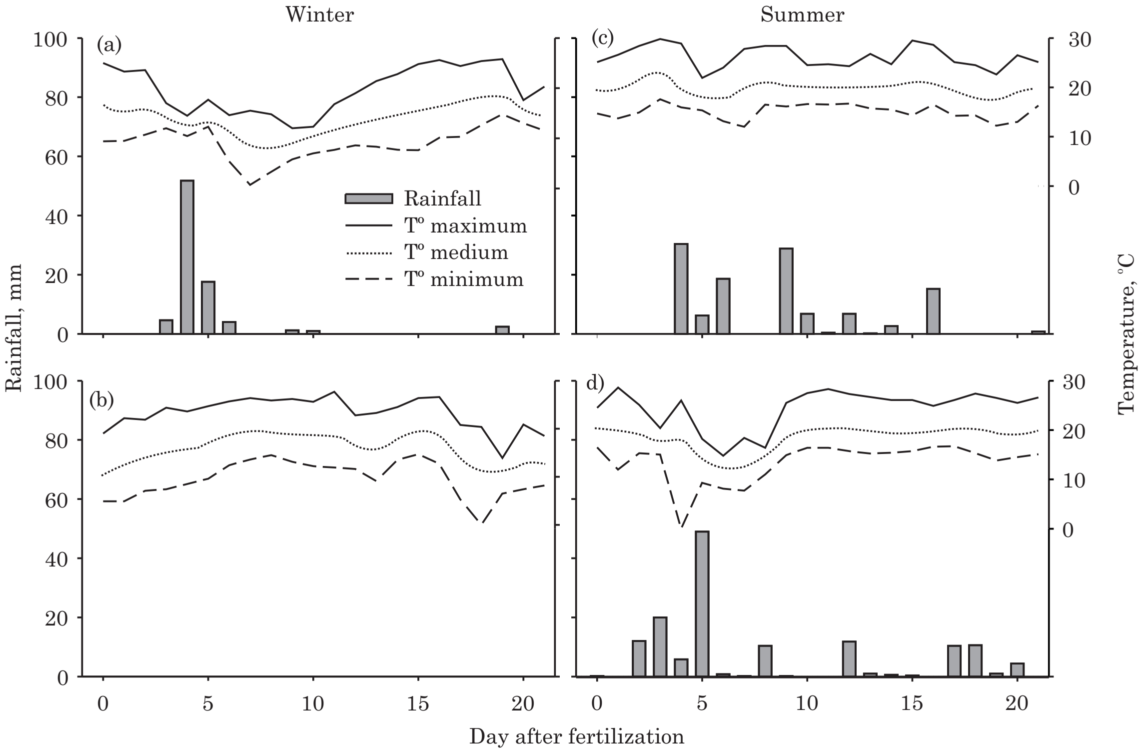

Figure 1. Rainfall, air temperature (maximum, medium and minimum) in the experiment with wheat (a, b) and maize (c, d), in two growing seasons (2009 and 2010) in the south-central region of Paraná.

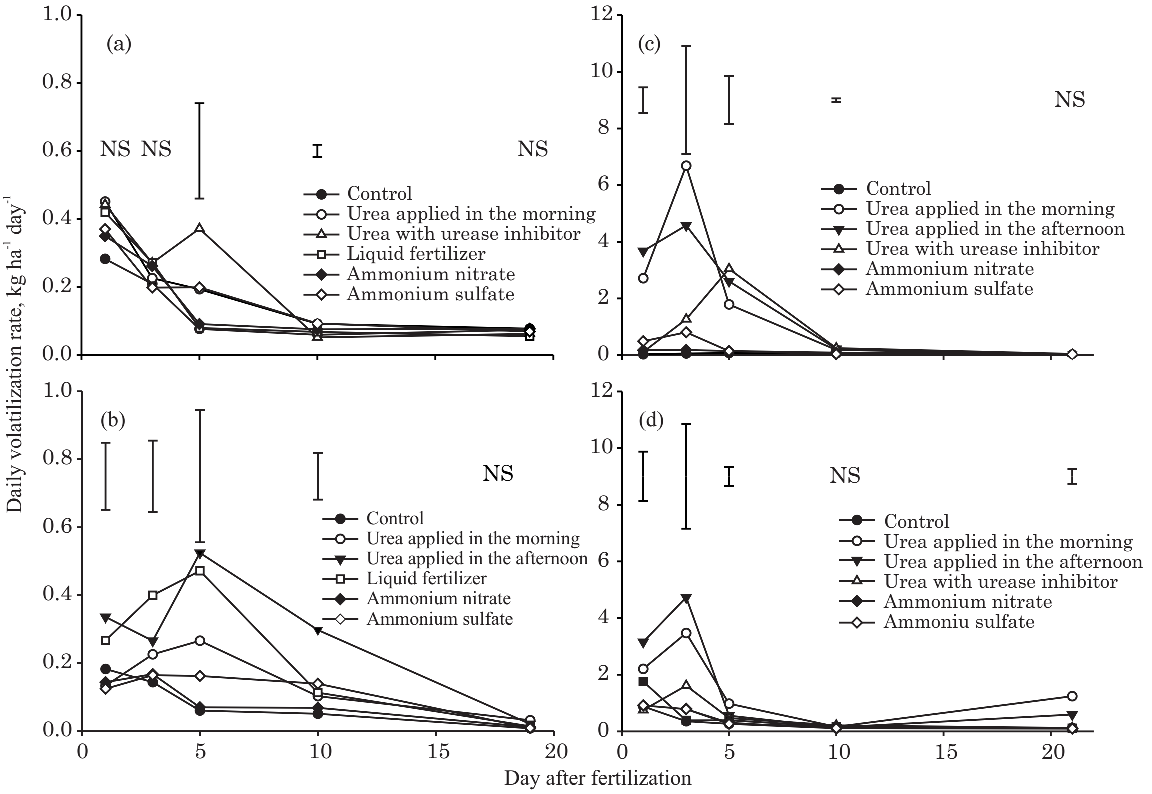

Figure 2. Daily volatilization rates recorded in the experiments with wheat [winters 2009 (a) and 2010 (b)] and maize [summers of 2009/10 (c) and 2010/11 (d)] in the south-central region of Paraná. Vertical bars indicate the least significant difference by Tukey's test at 5 %. NS: not significant. The scale of the y-axis of figures representing winter (a, b) and summer (c, d) are different.

application to the soil, however, it is related to soil moisture at the time of application (Da Ros et al., 2005). After this period, volatilization losses were generally low for all tested N sources.

In the 2009 growing season, similar NH_3 volatilization peaks were observed in all treatments on the 1st day after fertilization, with mean losses of about 0.40 kg ha^{-1} day^{-1} N. A second peak of similar magnitude was observed on the 5th day after fertilization from urea with urease inhibitor. In turn, in the second wheat growing season (2010), NH_3 volatilization was highest on the 5th day after N fertilization. The highest loss rate was 0.53 kg ha^{-1} day^{-1} N, when urea was applied in the afternoon. While the loss rates from liquid fertilizer and urea applied in the morning were statistically similar to those from urea applied in the afternoon, losses were lower from ammonium sulfate and ammonium nitrate (Figure 2b).

This difference in the volatilization peaks between the two wheat growing seasons was apparently not related to rainfall, since in the first season rains occurred only after the 3rd day after application, while in the second season there were no rains in the 19 days after fertilizer application. Neither can the delay in the volatilization peak in the second year be explained by air temperature, since the air temperature was 2.1 °C higher in the sampling period of the second than the first year. Possibly, this difference between the occurrence of volatilization peaks in the two winter growing seasons was related to the soil moisture level at fertilizer application (Da Ros et al., 2005). In the first year, a higher moisture content of the soil may have caused fertilizer solubilization immediately after application, while in the second year, solubilization may have been lower due to the drier soil. Considering the absence of rain in the sampling period of the second year, fertilizer solubilization may have been influenced by the occurrence of night dew. However, this hypothesis would have to be confirmed in future studies, since no data are available on soil moisture at fertilizer application in this study.

The daily volatilization rates in the two summer growing seasons also varied between the two study years (Figure 2c,d), with higher rates in the first. In the growing season 2009/10, the daily volatilization loss was highest in treatments with urea applied in the morning and evening, in which volatilization peaks of 6.6 and 4.6 kg ha^{-1} day^{-1} N were recorded, respectively, on the 3rd day after application. Urea with urease inhibitor lost a daily maximum of 3.0 kg ha^{-1} N on the 5th day after application, which was approximately 50 % less than in the treatment with common urea applied in the morning (corresponding treatment without urease inhibitor).

In the 2010/11 growing season, the highest daily volatilization rates were also recorded in treatments with urea applied in the morning and afternoon. However, these losses were lower than in the first growing season, with maximum volatilization rates of 3.5 and 4.7 kg ha^{-1} day^{-1} of applied N for urea applied in the morning and afternoon, respectively. The lower daily volatilization rates in the second growing season were most likely related to rainfall from the 2nd day after N fertilization, while in the first growing season rains occurred only after the 4th day after fertilization. The decrease of approximately 50 % in N volatilization losses of urea from the first to the second growing season was due to the incorporation of N in the soil by rainwater (Sanz-Cobena et al., 2011), limiting the rise in pH around the urea granules and consequently, ammonia formation. In addition, the transport of urea hydrolysis products in deeper layers can promote ammonium adsorption to negative charges in the soil (Rojas et al., 2012).

In the summer growing seasons, the daily volatilization rates (Figure 2c,d) were clearly higher than those in winter crops (Figure 2a,b) in the treatments with surface application of urea. In general, ammonia volatilization losses were higher in the 1st day after application, both in winter and in summer, although it was noteworthy that the losses of N applied as urea were approximately 10 times lower in winter. One factor that partially explains this behavior was the N rate applied, which was three times lower in winter (50 kg ha^{-1}) than in summer (150 kg ha^{-1}). Another factor that possibly influenced the differentiated loss was the temperature since the higher temperatures in summer accelerate microbial activity and hydrolysis of N fertilizers (Bouwmeester et al., 1985).

Cumulative NH_3-N losses

The cumulative N losses by volatilization in the first winter growing season (2009) were less than 2 % of applied N in all N fertilizers (Figure 3a). Losses from urea with urease inhibitor and common urea were approximately 2.0 and 1.4 % of applied N, respectively. Other fertilizers losses were less than 1.0 % of the applied N.

In the winter in the South-Central region of Paraná, with low mean temperatures (13.8 °C), N volatilization losses are naturally low, mainly from N-NH_2-containing sources that depend on microbial activity for ammonification ($NH_2 \rightarrow NH_4^+$). Similarly, fertilizers such as nitrate and ammonium sulfate with acidic reaction in the soil, lost less than 1.0 % of the applied N, as observed in other studies that also reported low volatilization losses from these two N sources (Lara Cabezas & Souza, 2008; Fontoura & Bayer, 2010).

This growing season, the cumulative losses of N by ammonia volatilization from common urea and urea with urease inhibitor were concentrated in a period of the first five days after application, in which about 50 % of N was volatilized. However, with regard to the application of nitrate and ammonium sulfate, losses occurred at lower and more constant rates with occurrence of approximately 70 % of the total losses within 10 days after application.

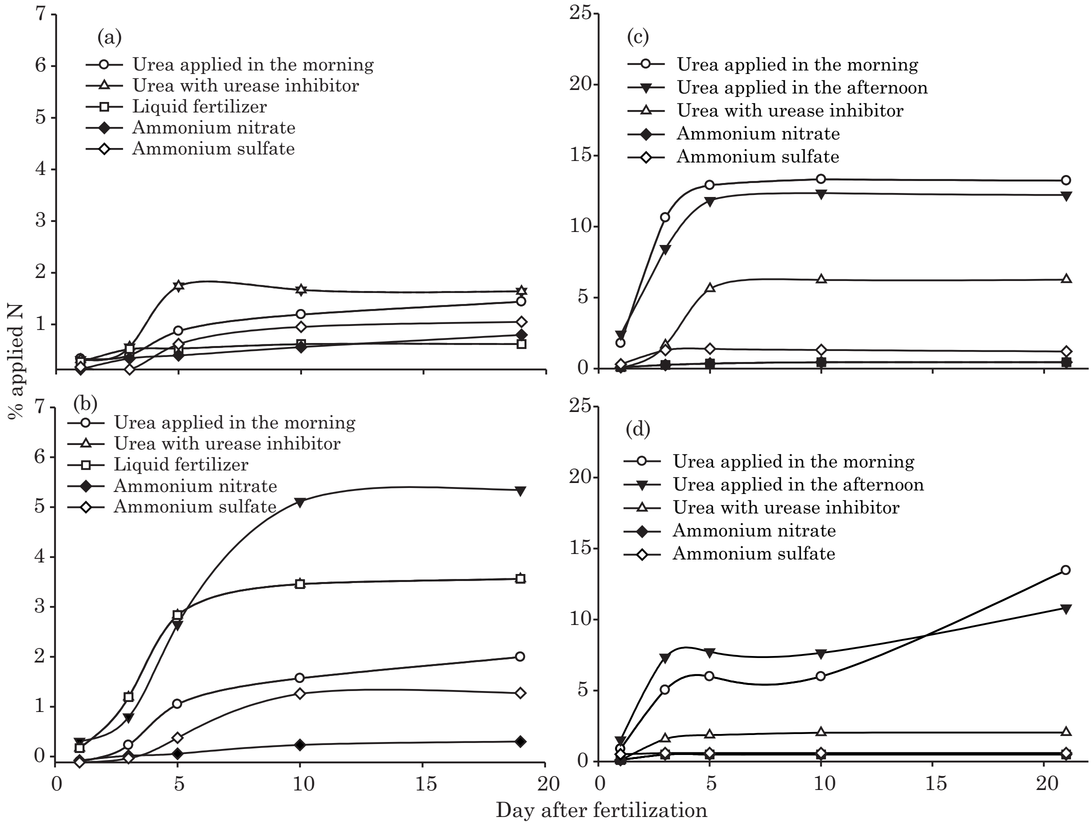

Figure 3. Percentage of applied N lost through ammonia volatilization from different N sources applied in winter [wheat; growing seasons 2009 (a) and 2010 (b)] and summer [maize; growing seasons 2009/10 (c) and 2010/11 (d)], in the south-central region of Paraná. Note: the scale of the y-axis of figures representing winter (a, b) and summer (c, d) are different.

In the 2010 growing season, the volatilization loss was highest from urea applied in the afternoon, with approximately 5.4 % of applied N. When applied in the morning, similarly to the previous year, losses from urea were also low (<2 % of applied N), and slightly lower than losses from liquid fertilizer (3.6 % of applied N). In an experiment with wheat in the winter in São Paulo State, Boaretto et al. (2004) found N volatilization losses ranging from 5 to 12 % of N applied as urea, higher than those recorded in the winter in the South-Central region of Paraná. Possibly, the lower volatilization losses recorded in south-central of Paraná were related to lower daily temperatures (~14 °C), than in the Southeast region (~21 °C).

These mean air temperatures observed in winter in SP (Boaretto et al., 2004) were close to the mean temperatures recorded in the summer experiment with maize. In the first maize crop (2009/10), volatilization losses were highest in treatments with urea application in the morning and the afternoon with 13.2 and 12.2 % of applied N, respectively. In the same season, fertilization of urea with urease inhibitor resulted in intermediate losses (~6.0 % of applied N), while losses were lowest, with approximately 0.4 and 1.2 % of applied N, respectively, after the application of nitrate and ammonium sulfate.

Similarly to 2009/10, volatilization losses in the 2010/11 growing season were highest in treatments with common urea, with 13.5 and 10.8 % of applied N, respectively, for urea application in the morning and afternoon (Figure 3d). When urea was applied with urease inhibitor, losses did not exceed 2.0 % of the applied N, while nitrate and ammonium sulfate resulted in volatilization losses of less than 0.6 % of the applied N.

Comparing the cumulative losses of NH$_3$-N in the experiments in the different seasons it was noticed that the cumulative losses with surface application of urea to maize (<13.5 % of applied N) were much higher than the losses recorded in the winter. However, these losses observed in summer in the South-Central region of Paraná were very low compared to losses exceeding 50 % of the applied N, registered in southeastern Brazil (Lara Cabezas et al., 1997a; Costa et al., 2003; Pereira et al., 2009), but closer to the losses recorded by Da Ros et al. (2005) and Rojas et al. (2012) in southern Brazil. Moreover, the results obtained in the experiment with maize, in both years, corroborate the results reported by Fontoura & Bayer (2010), who analyzed NH$_3$-N losses in four consecutive years in the same region and found a mean annual NH$_3$ volatilization loss of 12.5 % of N applied as urea, while in the wettest and driest years, respectively, the losses ranged from 1.3 to 25.4 % of applied N.

In an attempt to mitigate these urea losses, a treatment with fertilization in the late afternoon was evaluated; in this case, night dew could contribute to urea solubilization and reduce losses, aside from the cooler temperatures at night. However, since the losses after fertilization in the late afternoon were statistically equal to the treatment with urea application in the morning, this management is not a viable strategy for reducing N losses by NH_3 volatilization (Table 3). Similarly, Basso et al. (2004) applied pig manure at different times of the day to identify possible changes in the pattern of N volatilization loss, but also found that the time of application did not consistently affect N volatilization losses.

Among the management possibilities of N side-dresssing, the addition of urease inhibitor to urea has been investigated in view of its efficiency in reducing NH_3-N losses (Cantarella et al., 2008; San Francisco et al., 2011; Sanz-Cobena et al., 2011; Tasca et al., 2011; Soares et al., 2012). In the summer experiments, volatilization losses were reduced by approximately 50 %, compared to the common urea treatments, thus demonstrating the efficiency of the urease inhibitor in reducing volatilization. However, at the cooler winter temperatures, no effect of urease inhibitor in reducing volatilization losses was detected. This was evident in the winter of 2009, in which N loss from urea with urease inhibitor was similar to common urea. This may be due to the low temperatures in the evaluation period. According to Cantarella et al. (2008), the use of urease inhibitor with urea can reduce volatilization losses between 15 to 78 %. The magnitude of the inhibitor effect is influenced by the weather conditions, mainly by the occurrence or absence of rain, in the days after fertilizer application.

From the fertilizers alternative to urea applied in winter 2009, at cool temperatures, the N losses from liquid fertilizer, nitrate and ammonium sulfate were similar (Figure 3, Table 3). In turn, in the second winter growing season, most N was lost from liquid fertilizer, although still a low loss. The low NH_3-N losses from nitrate and ammonium sulfate indicate these fertilizers as a good alternative to urea, especially when environmental conditions favor NH_3 loss, as observed in the summer. However, these fertilizers may be more susceptible to leaching losses due to their solubility and mobility in soil (Lara Cabezas et al., 1997a). In addition, the feasibility of substituting urea by these sources depends on an economic analysis in view of the higher cost per unit of N (Fontoura & Bayer, 2010). In the summer growing season of 2009/10, in which the mean temperature of five days after fertilization was higher and rainfall lower, cumulative N volatilization losses were highest from common urea applied in the morning (Table 4). In the following growing season, when the mean temperature for the same period was lower and rainfall higher than in the previous, the cumulative NH_3 losses from common urea applied in the morning were lower. However, in this period it was not possible to discriminate which factor, temperature or rainfall, was the most determinant in reducing N volatilization losses. Unlike in the summer growing seasons, urea NH_3 losses were low in both winter crops, independent of the rainfall volume in the five days after application, but controlled by the low temperatures in this period.

The amount of N lost by volatilization when common urea was applied to the soil surface in the morning was strongly influenced by the weather, as seen when both growing seasons of wheat and maize were evaluated together (Table 4). The interaction between the daily mean temperature and rainfall in the first five days after urea application were determinant for the amount of volatilized N ($\hat{y} = -26.475 + 1.930\,T + 0.0026\,PP$, $r^2 = 0.70^{**}$) (Table 4). According to the standardized coefficients of multiple regression (Table 4), the mean daily temperature ($\beta = 0.987$) had a greater influence on volatilization losses than rainfall ($\beta = 0.050$) in the period.

Table 3. Cumulative ammonia volatilization losses from different nitrogen top-dressing fertilizers applied to wheat and maize under no-tillage in two study years

Treatment	Winter		Summer	
	2009	2010	2009/10	2010/11
	kg ha^{-1} NH_3-N			
Urea applied in the morning	0.7^{ns}	1.0 bc	19.9 a	20.2 a
Urea applied in the afternoon	-	2.7 a	18.3 ab	16.2 a
Urea with urease inhibitor	0.8	-	9.4 c	3.1 b
Liquid fertilizer	0.3	1.8 ab	-	-
Ammonium nitrate	0.4	0.1 c	0.7 c	0.5 b
Ammonium sulfate	0.5	0.6 bc	1.8 bc	0.9 b
CV(1) (%)	75.5	42.3	35.1	43.1

(1) Coefficient of variation. Means followed by different letters in the column differ by the Tukey test at 5 %. ns not significant.

This analysis particularly explains the different volatilization losses between seasons, but not the differences between losses in the same season (winter or summer) in different years. In this sense, the volume and distribution of rainfall in the period after N fertilization must be the determinant factor, especially in summer, since in winter low temperatures have a predominant effect (Table 4). In the summer, aside from the mean daily temperature, the occurrence of rain in the first days after fertilization also influenced N volatilization losses (Fontoura & Bayer, 2009).

Grain yield

The grain yield response of wheat and maize to N application was low and unaffected by the different N sources (Table 5). Averaged across both growing seasons and N sources, wheat and maize grain yield increased 8 and 6 % with N application, respectively. Between the growing seasons, the response was greatest in the first growing season of both crops (14 and 13 % for wheat and maize, respectively), while in the second there was virtually no yield increase

Table 4. Mean air temperature and cumulative rainfall in the five days after fertilization (independent variables) and cumulative volatilization losses of ammonia from urea (dependent variable) in the winter (wheat) and in the summer (maize) in two growing seasons (2009 and 2010), and the respective coefficients of the linear multiple regression

		Independent variable		Dependent variable
	Year	Temperature	Rainfall	Cumulative loss
		°C	mm	%
Winter	2009	14.8	74.0	0.9
	2010	14.1	0.0	1.1
Summer	2009	20.5	56.0	12.9
	2010	16.8	87.6	6.0
	Non-standardized coefficient		Standardized coefficient	Significance
	B	Standard error	β	
Constant	-26.475	5.955		0.000
Temperature (°C)	1.930	0.382	0.987	0.000
Rainfall (mm)	0.00259	0.0257	0.050	0.922

Table 5. Grain yield of wheat and maize in two growing seasons (2009 and 2010) as affected by different N fertilizers

Treatment	2009	2010	Mean	2009	2010	Mean
	kg ha^{-1}			%$^{(2)}$		
			Wheat			
Control	4.110 b	4.541^{ns}	4.326^{ns}	100	100	100
Urea applied in the morning	4.669 a	4.593	4.631	114	101	107
Urea applied in the afternoon	-	4.792	4.792	-	106	111
Urea with urease inhibitor	4.763 a	-	4.763	116	-	110
Liquid fertilizer	4.671 a	4.618	4.645	114	102	107
Ammonium nitrate	4.911 a	4.572	4.741	119	101	110
Ammonium sulfate	4.872 a	4.650	4.761	119	102	110
Mean	4.666	4.628	4.678	114	102	108
CV$^{(1)}$ (%)	3.82	7.76				
			Maize			
Control	12.857 b	14.531^{ns}	13.694^{ns}	100	100	100
Urea applied in the morning	14.343 ab	14.738	14.541	112	101	106
Urea applied in the afternoon	14.598 ab	14.724	14.661	114	101	107
Urea with urease inhibitor	15.438 a	13.870	14.654	120	95	107
Ammonium nitrate	14.724 ab	13.732	14.228	115	95	104
Ammonium sulfate	14.936 ab	14.363	14.650	116	99	107
Mean	14.513	14.366	14.523	113	99	106
CV (%)	6.7	4.60				

(1) Coefficient of variation. (2) Calculated in comparison to the control treatment, without N application. Means followed by the same letters, in the columns and for each crop (wheat or maize), did not differ statistically by the Tukey test at 5 %; ^{ns} not significant.

in either crop. The rather inexpressive effect of N fertilization on yield of both crops may be related to high soil N availability, due to the high soil organic matter content (30.4-38.2 g dm^{-3}, Table 1). This high N availability resulted in a low yield increase with N fertilization. Possibly, the fertilization at rates of 50 kg ha^{-1} N for wheat and 150 kg ha^{-1} N for maize led to a surplus of N over the crop demand, resulting in no yield difference between the N sources. For maize, Fontoura & Bayer (2009) found a low response to N fertilization in the same soil, which was attributed to the ability of the soils to supply the crop demand due to the high content of organic matter.

CONCLUSIONS

1. The low winter temperatures (usually below 15 °C) in the south-central region of Paraná lead to low N losses by ammonia volatilization from urea (<5.5 % of applied N) as well as from other N fertilizers applied in no-till systems, with little influence of the rainfall regime.

2. Ammonia volatilization rates from urea are higher during the summer than during the winter in the south-central region of Paraná, although summer losses did not exceed 15 % of applied N. During this warm season, ammonia losses from urea are inversely related to the rainfall volume in the five days following fertilizer application.

3. At high summer temperatures, urease inhibitor, as well as urea substitution with ammonium sulfate and ammonium nitrate can reduce the ammonia volatilization losses from urea, which are however not influenced by the time (morning or afternoon) of urea application.

ACKNOWLEDGEMENTS

This research was supported by the Agrarian Foundation of Agricultural Research (FAPA) and Brazilian National Council of Scientific and Technological Development (CNPq).

LITERATURE CITED

BASSO, C.J.; CERETTA, C.A.; PAVINATO, P.S. & SILVEIRA, M.J. Perdas de nitrogênio de dejeto líquido de suínos por volatilização de amônia. Ci. Rural, 34:1773-1778, 2004.

BOARETTO, A.E.; SPOLIDORIO, E.S.; FREITAS, J.G.; TRIVELIN, P.C.O.; MURAOKA, T. & CANTARELLA, H. Fate of 15N-urea applied to wheat-soybean succession crop. Bragantia, 63:265-274, 2004.

BOUWMEESTER, R.J.B.; VLEK, P.L.G. & STUMPE, J.M. Effect of environmental factors on ammonia volatilization from a urea-fertilized soil. Soil Sci. Soc. Am. J., 49:376-381, 1985.

CANTARELLA, H.; ROSSETO, R.; BARBOSA, W.; PENNA, M.J. & RESENDE, L.C.L. Perdas de N por volatilização da amônia e resposta da cana-de-açúcar à adubação nitrogenada em sistema de colheita de cana sem queima prévia. In: CONGRESSO NACIONAL DA STAB, 1999, Londrina. Anais... Londrina, STAB, 1999. p.1-5.

CANTARELLA, H.; TRIVELIN, P.C.O.; CONTIN, T.L.M.; DIAS, F.L.F.; ROSSETTO, R.; MARCELINO, R.; COIMBRA, R.B. & QUAGGIO, J.A. Ammonia volatilization from urease inhibitor-treated urea applied to sugarcane trash blankets. Sci. Agric., 65:397-401, 2008.

CLAY, D.E.; MALZER, G.L. & ANDERSON, J.L. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. Soil Sci. Soc. Am. J., 54:263-266, 1990.

COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB. Acompanhamento de safra brasileira: Grãos. Safra 2011/12. Oitavo levantamento. Maio 2012. Available at: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/12_05_10_08_49_52_boletim_maio_2012.pdf>. Accessed: May 21, 2012.

COSTA, M.C.G.; VITTI, G.C. & CANTARELLA, H. Volatilização de N-NH_3 de fontes nitrogenadas em cana-de-açúcar colhida sem despalha a fogo. R. Bras. Ci. Solo, 27:631-637, 2003.

DA ROS, C.O.; AITA, C. & GIACOMINI, S.J. Volatilização de amônia com aplicação de ureia na superfície do solo, no sistema plantio direto. Ci. Rural, 35:799-805, 2005.

DAWAR, K.; ZAMAN, M.; ROWARTH, J.; BLENNERHASSETT, J. & TURNBULL, M. Urea hydrolysis and lateral and vertical movement in the soil: Effects of urease inhibitor and irrigation. Biol. Fert. Soils, 47:139-146, 2011.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Sistema brasileiro de classificação de solos. 3.ed. Brasília, Embrapa-CNPS, 2013. 353p.

ERNST, J. W. & MASSEY, H. F. The effects of several factors on volatilization of ammonia formed from urea in the soil. Soil Sci. Soc. Am. J., 24:87-90, 1960.

FERGUSON, R.B.; KISSEL, D.E.; KOELLIKER, J.K. & BASEL, W. Ammonia volatilization from surface-applied urea: Effect of hydrogen ion buffering capacity. Soil Sci. Soc. Am. J., 48:578-582, 1984.

FONTOURA, S.M.V. & BAYER, C. Ammonia volatilization in no-till system in the south-central region of the State of Paraná, Brazil. R. Bras. Ci. Solo, 34:1677-1684, 2010.

HOLCOMB, J.C.; SULLIVAN, D.M.; HORNECK, D.A. & CLOUGH, G.H. Effect of irrigation rate on ammonia volatilization. Soil Sci. Soc. Am. J., 75:2341-2347, 2011.

JANTALIA, C.P.; HALVORSON, A.D.; FOLLETT, R.F.; RODRIGUES ALVES, B.J.; POLIDORO, J.C. & URQUIAGA, S. Nitrogen source effects on ammonia volatilization as measured with semi-static chambers. Agron. J., 104:1595-1603, 2012.

LARA CABEZAS, W.A.R.; KORNDÖRFER, G.H. & MOTTA, S.A. Volatilização de N-NH_3 na cultura de milho: I. Efeito da irrigação e substituição parcial da uréia por sulfato de amônio. R. Bras. Ci. Solo, 21:481-487, 1997a.

LARA CABEZAS, W.A.R.; KORNDÖRFER, G.H. & MOTTA, S.A. Volatilização de N-NH_3 na cultura de milho: II. Avaliação de fontes sólidas e fluídas em sistema de plantio direto e convencional. R. Bras. Ci. Solo, 21:489-496, 1997b.

LARA CABEZAS, W.A.R. & SOUZA, M.A. Volatilização de amônia, lixiviação de nitrogênio e produtividade de milho em resposta à aplicação de misturas de uréia com sulfato de amônio ou com gesso agrícola. R. Bras. Ci. Solo, 32:2331-2342, 2008.

PEREIRA, H.S.; LEÃO, A.F.; VERGINASSI, A. & CARNEIRO, M.A.C. Ammonia volatilization of urea in the out-of-season corn. R. Bras. Ci. Solo, 33:1685-1694, 2009.

ROJAS, C.A.L.; BAYER, C.; FONTOURA, S.M.V.; WEBER, M.A. & VIERO, F. Volatilização de amônia da ureia alterada por sistemas de preparo de solo e plantas de cobertura invernais no Centro-Sul do Paraná. R. Bras. Ci. Solo, 36:261-270, 2012.

SAN FRANCISCO, S.; URRUTIA, O.; MARTIN, V.; PERISTEROPOULOS, A. & GARCIA-MINA, J.M. Efficiency of urease and nitrification inhibitors in reducing ammonia volatilization from diverse nitrogen fertilizers applied to different soil types and wheat straw mulching. J. Sci. Food Agric., 91:1569-1575, 2011.

SANZ-COBENA, A.; MISSELBROOK, T.; CAMP, V. & VALLEJO, A. Effect of water addition and the urease inhibitor NBPT on the abatement of ammonia emission from surface applied urea. Atmos. Environ., 45:1517-1524, 2011.

SILVA, A.J.; LIMA JÚNIOR, M.A.; FERREIRA, N.C.M. & FRAGA, V.S. Perdas de amônia por volatilização proveniente da ureia aplicada a solos dos trópicos úmidos. R. Bras. Ci. Solo, 19:141-144, 1995.

SOARES, J.R.; CANTARELLA, H. & MENEGALE, M.L.D.C. Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. Soil Biol. Biochem., 52:82-89, 2012.

TASCA, F.A.; ERNANI, P.R.; ROGERI, D.A.; GATIBONI, L.C. & CASSOL, P.C. Volatilização de amônia do solo após a aplicação de ureia convencional ou com inibidor de urease. R. Bras. Ci. Solo, 35:493-502, 2011.

TEDESCO, M.J.; GIANELLO, C.; BISSANI, C.A.; BOHNEN, H. & VOLKWEISS, S.J. Análise de solo, plantas e outros materiais. Porto Alegre, Universidade Federal do Rio Grande do Sul, 1995. 174p.

VITTI, G.C.; TAVARES, J.E.; LUZ, P.H.C.; FAVARIN, J.L. & COSTA, M.C.G. Influência da mistura de sulfato de amônio com uréia sobre a volatilização de nitrogênio amoniacal. R. Bras. Ci. Solo, 26:663-671, 2002.