

Banding of Urea Increased Ammonia Volatilization in a Dry Acidic Soil

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Volatilization of ammonia following application of urea contributes to smog formation and degradation of natural ecosystems. The objective of this study was to evaluate the impact of (i) incorporation and banding of urea and (ii) surface broadcast of slow-release urea types on NH_3 volatilization in a dry acidic soil. Volatilization was measured using wind tunnels for 25 d after standard urea (140 kg N ha^{-1}) was broadcast, broadcast and incorporated (0–5 cm), or incorporated in shallow bands (3–5 cm) to a conventionally tilled silty loam soil. Urea supplemented with a urease inhibitor or coated with a polymer was also broadcast at the soil surface. Little N diffused out of the polymer-coated granules and ammonia losses were low (4% of applied N). Use of a urease inhibitor also resulted in a low NH_3 loss (5% of applied N) while maintaining soil mineral N at levels similar to plots where untreated urea was broadcast. The rate of hydrolysis of urea broadcast at the soil surface was slowed by the lack of moisture and NH_3 loss (9% applied N) was the lowest of all treatments with standard urea. Incorporation of broadcast urea increased emissions (16% applied N) by increasing urea hydrolysis relative to surface application. Furthermore, incorporation in band also increased emissions (27% applied N) due to a localized increase in soil pH from 6.0 to 8.7. We conclude that incorporating urea in bands in a dry acidic soil can increase NH_3 volatilization compared to broadcast application followed by incorporation.

UREA is by far the most popular synthetic N fertilizer, accounting for 43% of all global sales (Bouwman et al., 2002). When applied at the soil surface, more than 50% of the urea N can be volatilized as NH_3 (Sommer et al., 2004). Such N loss not only decreases the agronomic value of urea but also contributes to smog formation and degradation of natural ecosystems (Galloway et al., 2003).

Treatment of urea with urease inhibitor (Rawluk et al., 2001; Zaman et al., 2008; Sanz-Cobena et al., 2008) or by coating granules (Knight et al., 2007; Vaio et al., 2008) reduces the rate of NH_4^+ release and total NH_3 loss to the atmosphere. Volatilization is also usually reduced when ammonium N fertilizers are incorporated into soils (Fenn and Kissel, 1976; Nye, 1992). Bouwman et al. (2002) summarized NH_3 volatilization data following the application of N sources to agricultural soils and estimated that NH_3 losses from incorporated N were on average 50% lower than those from surface application. However, studies under field conditions typical of dryland agriculture yielded highly variable results with NH_3 volatilization 1.6 to 1.9 (Palma et al., 1998), 1 to 9 (Roelcke et al., 1996), and 7 (Prasertsak et al., 2002) times lower for incorporated than for surface-applied urea.

Incorporating urea in bands (banding) has been shown to reduce NH_3 emissions (Bouwmeester et al., 1985) and this practice is recommended for improving N use efficiency by crops (Fenn and Miyamoto, 1981; Rees et al., 1996; Malhi et al., 2001; Sommer et al., 2004). However, the enzymatic hydrolysis of urea to NH_4^+ consumes H^+ and consequently increases the pH in the vicinity of the applied urea (Overrein and Moe, 1967). Accordingly, Sommer et al. (2004) noted that banding urea at the surface of an acidic soil may result in higher pH in the band and increase NH_3 volatilization. The efficiency of banding to reduce N loss from the soil through volatilization may therefore be dependant on the buffer capacity of the soil (Ferguson et al., 1984; Izaurralde et al., 1987) that influences how much of the hydrolyzed urea is retained in the soil as NH_4^+ or NH_3 . In sandy soils with low buffer capacity, placement of high concentrations of urea under the soil surface may result in NH_3 losses greater than with surface applications (Buresh, 1987).

Reduction in NH_3 volatilization following incorporation of urea is influenced by complex interactions between application methods, soil properties, and urease activity (Sommer et al., 2004). The objective of this study was to evaluate the impact of (i) incorporation

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Published in *J. Environ. Qual.* 38:1383–1390 (2009).
doi:10.2134/jeq2008.0295

Received 27 June 2008.

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and banding of urea and (ii) surface broadcast of slow-release urea types on NH_3 volatilization in a dry acidic soil.

Materials and Methods

Experimental Site and Treatments

The study was conducted at the research farm of the Institut de recherche et de développement en agroenvironnement (IRDA) located near Québec City, Canada (latitude: $46^\circ 05'$, longitude: $71^\circ 02'$, altitude, 110 m). Mean air temperature in Québec City is 4.2°C and annual precipitation is 1213 mm. The soil was a Le Bras silty clay loam ($270 \text{ g clay kg}^{-1}$; $420 \text{ g silt kg}^{-1}$; loamy, mixed, frigid, Typic Humaquept) (Table 1).

The trial was performed on plots that had a history of annual moldboard plowing and that had been cropped to wheat in 2005 and 2006. The site was moldboard plowed and harrowed in May 2007, tilled using a roto-tiller in early June 2007, and kept free of vegetation during the study by manually removing weeds. Each experimental plot received urea granules (diameter: 2–4 mm) at a rate of 140 kg N ha^{-1} at 0930 h on 11 June 2007. Treatments were surface broadcasting by spreading standard urea granules evenly over the plot surface (Broadcast), broadcasting and incorporation into the top 5 cm using a 3-tooth (5-cm spacing) rake (Broadcast/Incorporated), and banding (Banded/Incorporated). The band was made using a hand hoe and consisted of a narrow V-shape trench 5 cm deep. Urea was placed in the trench, distributed between 3 and 5 cm and covered with soil. Urea supplemented with the urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide (4 mg g^{-1}) (NBPT) and a polymer-coated urea (Polymer-Coated) were also surface broadcast as additional treatments. These two slow-release products were obtained from local commercial distributors.

Volatilization Measurements

Ammonia volatilization was measured from 11 June to 6 July 2007 using wind tunnels (Lockyer, 1984; Rochette et al., 2001) on a series of 15 plots (five treatments, three replicates). Each plot was completely covered by a tunnel consisting of a $0.5 \times 2 \text{ m}$ Plexiglas dome attached to a steel duct housing a fan that drew air through the tunnel at a rate of $15 \text{ m}^3 \text{ min}^{-1}$. Air entering and leaving the dome was sampled at 3 L min^{-1} and passed through a 100-mL $0.005 \text{ mol L}^{-1} \text{ H}_3\text{PO}_4$ trap to capture the emitted NH_3 . Air volumes were measured with a domestic gas meter and NH_4^+ in the traps was analyzed by colorimetry (Model QuickChem 8000 FIA+, Lachat Instruments Ltd, Loveland, CO). Air temperature and velocity under the tunnels were measured using a hot-wire sensor (Model KM 4007, Comark Ltd., Hertfordshire, UK). The NH_3 fluxes (F_{NH_3} , $\text{mg N m}^{-2} \text{ h}^{-1}$) were calculated as:

$$F_{\text{NH}_3} = \frac{f}{A} (e_o - e_i)$$

where f (L h^{-1}) is the air flow rate through the tunnel, A (m^2) is the enclosed surface area, and e_i and e_o ($\text{mg NH}_3\text{-N L}^{-1}$) are the NH_3 concentrations of the air entering and leaving the tunnel. Tunnels were deployed on the experimental plots immediately after urea application (<5 min). Ammonia traps were changed each hour

for the first 2 h, every 2 h for 8 h, then at 8-h intervals until 105 h and thereafter daily for the remainder of the experiment. A meteorological station was installed at the site to record daily rainfall, air temperature, soil temperature (2 cm), relative humidity, wind speed, and wind direction. Soil water content in the top 10 cm was measured using 15-cm TDR probes at experiment initiation and periodically throughout the experiment.

Tunnels were kept in place for the duration of the experiment, and the impact of rainfall on NH_3 volatilization was investigated by adding water at the soil surface during the experiment. All plots received 5 mm of simulated rainfall 7 and 14 d after initiation of treatments, and 20 mm after 21 d.

Soil Sampling and Analyses

Adjacent to the site where the tunnels were installed, 24 additional plots receiving the same treatments as the tunnels (and an unamended control) ($0.75 \times 4 \text{ m}$; six treatments; repeated four times in randomized blocks) were prepared for soil sampling. They were covered with a clear plastic greenhouse ($5.5 \times 10.0 \text{ m}$; Les Serres Harnois, St-Thomas-de-Joliette, QC) fully opened at both ends to simulate conditions under the wind tunnels. Air flow in these greenhouses was estimated to be slightly higher during the day but lower at night than inside the wind tunnels. Soil samples were taken daily during the first 3 d and every 3 to 6 d afterward. The top 10 cm of the soils was collected using a stainless steel (3-cm diam.) core. The top 6 cm of the cores were then divided in half and labeled as upper surface layer and lower surface layer. As the soil had recently been tilled, some compaction occurred in the soil core and actual sampled depths were estimated to be approximately 0 to 4 cm and 4 to 8 cm for the upper and lower soil layers, respectively. On plots where urea was broadcast, a composite soil sample was taken, consisting of eight randomly distributed sample points. Soil samples from Banded/Incorporated plots consisted of nine subsamples taken directly in the band.

Samples were transported immediately to the laboratory and analyzed for pH (2:1 soil/water ratio) and mineral N extractable with $1 \text{ mol L}^{-1} \text{ KCl}$ (10 g of field moist soil in 40 mL KCl). For mineral N, soil slurries were shaken for 1 h on a reciprocal shaker, centrifuged ($3000 \times g$; 10 min), and filtered through Whatman no. 42 filter papers pre-washed with $1 \text{ mol L}^{-1} \text{ KCl}$. The extracts were frozen (-20°C) and stored until being analyzed for NH_4^+ and $\text{NO}_3^- + \text{NO}_2^-$ by colorimetry with the automated analyzer as previously described for NH_3 traps.

Soil urease activity was determined at the onset of the experiment by determining the amount of NH_4^+ produced during a 30-min incubation of 1 g of soil at 37°C in the presence of 1 mL of a urea solution ($3 \text{ g } 100 \text{ mL}^{-1}$) (Nannipieri et al., 1978).

Statistical Analyses

The PROC MIXED procedure with restricted maximum likelihood (REML) in SAS/STAT software, Version 8 of the SAS/STAT System for Unix was used to compare average emissions for replicate measurements throughout the monitoring period (SAS Institute, 1989). The average emissions for different treatments were compared for the day of application,

Day 2, Day 3 to 5, Day 5 to 10, and Day 10 to the end of the monitoring period with replicate measurements in time treated as repeated measures. Covariance structures were selected based on information criteria calculated by SAS (SAS Institute, 1989; Wang and Goonewardene, 2004). Differences in cumulative $\text{NH}_3\text{-N}$ loss among treatments were tested using an ANOVA with the PROC GLM procedure in SAS/STAT at the end of each of the sub-periods and at the end of the monitoring period to evaluate if and at what point total cumulative N loss differed among treatments. For each day and at each sampling depth, differences in soil characteristics among treatments were tested by ANOVA also using the PROC GLM procedure in SAS/STAT.

Results and Discussion

Air temperature during the experiment was typical of mean early summer climatic conditions in Québec City with variations from 12 to 24°C (Fig. 1a). The temporal pattern of soil temperature at 2 cm was similar to that of air temperature but of smaller amplitude. Soil water content in the 0 to 10 cm soil surface layer averaged $0.12 \text{ m}^3 \text{ m}^{-3}$ and varied little during the experiment (Fig. 1b). Atmospheric water vapor pressure deficit remained relatively high throughout the experiment (Fig. 1b), indicating that conditions favored rapid evaporation and soil drying.

Ammonia Emissions

Ammonia emissions were low during the first 2 d after application for all treatments except for a short flush in the first hour from the Broadcast treatment (Fig. 2a, Table 2), likely due to NH_4^+ present on the urea granules. For the first 2 d, average emissions from Broadcast plots were 0.7 times those from

Table 1. Selected properties of the silty clay loam soil at the experimental site.

Properties	Soil layer	
	0–4 cm	4–8 cm
pH	5.4 (0.2)†	5.6 (0.1)
CEC (meq 100 g ⁻¹)	17.3 (1.4)	17.9 (1.8)
Ca (meq 100 g ⁻¹)	3.3 (0.3)	3.1 (0.6)
Base saturation (%)	22.8 (3.7)	20.1 (4.5)
Clay (g kg ⁻¹)	175.0 (0.5)	177.0 (0.7)
Total C (g C kg ⁻¹)	22.0 (0.13)	22.0 (0.12)
Total N (g N kg ⁻¹)	1.9 (0.2)	1.8 (0.1)
Urease activity ($\mu\text{g NH}_3\text{-N g}^{-1} \text{ h}^{-1}$)	55 (18)	45 (25)

† Numbers in parentheses represent standard deviations ($n = 3$).

Broadcast/Incorporated plots and 1.8 times higher than those from Banded/Incorporated plots. From Day 3 through 5, emissions remained low in the plots where urea was broadcast while they increased sharply in the Banded/Incorporated treatment. Emissions of NH_3 from the Banded/Incorporated treatment lagged slightly behind urea hydrolysis with concentrations of NH_4^+ in the soil increasing by one order of magnitude after 2 d (Fig. 3a and 3b), compared with NH_3 emissions which began to increase on Day 3 and 4 (Fig. 2a). This delay likely corresponds to the time required for the increased NH_3 source strength to modify the vertical NH_3 gradient from placement depth up to the soil surface.

Applying urea in incorporated bands is recommended to reduce NH_3 volatilization (Sommer et al., 2004) and emission peaks up to 10 times greater in the Banded/Incorporated than in the Broadcast/Incorporated plots were not expected. Emissions of NH_3 are proportional to the NH_3 source strength and inversely proportional to the resistance against transfer to the atmosphere. Assuming that the resistance to NH_3 transfer was similar for both

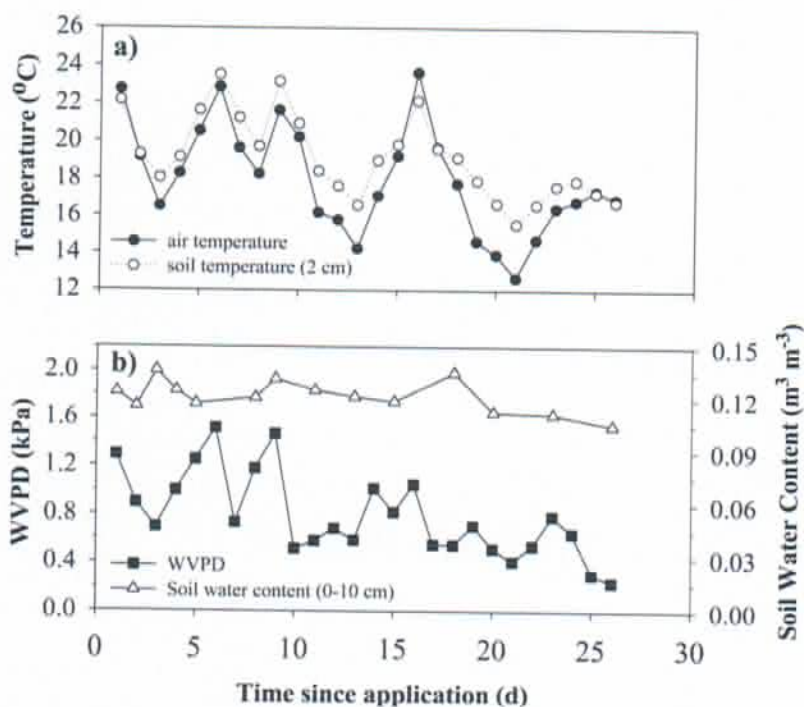


Fig. 1. Air temperature and soil temperature at 2 cm (a), and air water vapor pressure deficit (WVPD) and soil water content (b) during the experiment.

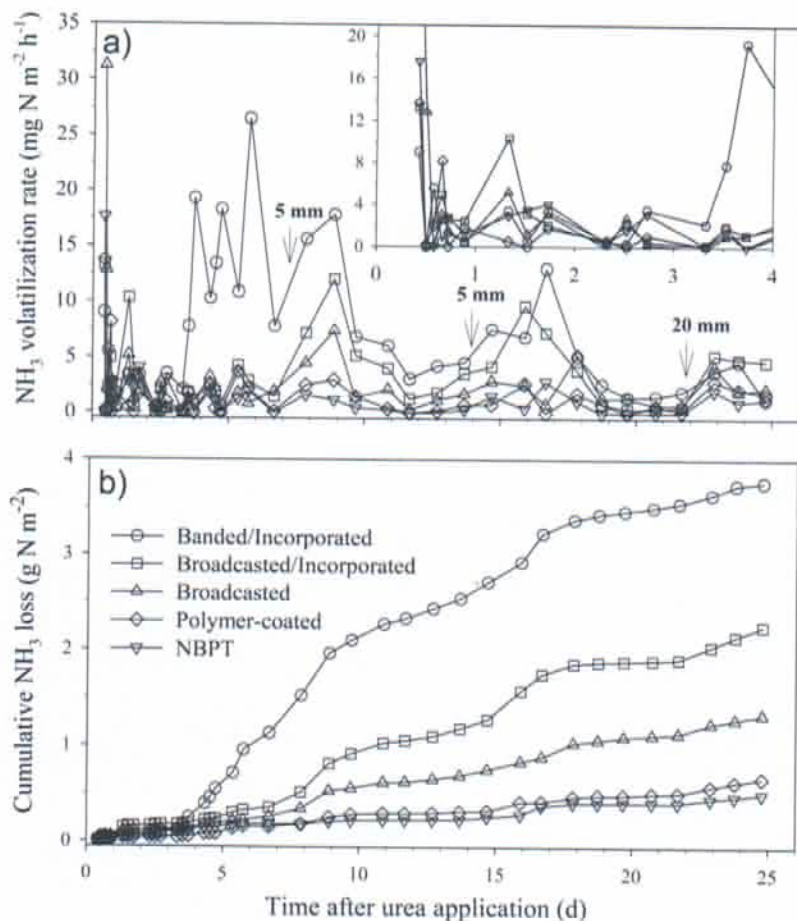


Fig. 2. Ammonia emissions (a) and cumulative losses (b) from different application methods and urea types. Treatments were initiated at 0930 h on Day 1. NBPT = urea treated with urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide.

Table 2. Average fluxes of $\text{NH}_3\text{-N}$ following land application of urea during different sub-periods throughout the experiment.

Urea application method or type	mg $\text{NH}_3\text{-N m}^{-2} \text{h}^{-1}$				
	Day 1	Day 2	Days 3–5	Days 5–10	Days 10–25
Broadcast	8.1	2.5	1.2	2.9c†	2.0b
Broadcast/Incorporated	4.2	4.7	1.3	5.2b	3.6ab
Banded/Incorporated	2.7	1.7	8.4	14.0a	4.7a
NBPT†	4.2	1.0	0.8	1.9c	1.0b
Polymer-Coated	3.9	2.8	1.1	0.9c	0.9b
Treatment <i>P</i> value	NS	NS	NS	> 0.001	> 0.001
Treatment x time <i>P</i> value	NS	NS	> 0.05	> 0.001	> 0.001

† Urea treated with urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide.

‡ Values in the same column with same letter are not significantly different ($P < 0.05$).

urea incorporation methods (banded and broadcast), differences in volatilization are therefore likely related to differences in NH_3 availability. When soil samples were taken directly in the band, the concentrations of $\text{NH}_4\text{-N}$ were 10 to 15 times those observed in the soils of the Broadcast and Broadcast/Incorporated plots (Fig. 3a and 3b). The concentrations in the Banded/Incorporated treatment reached their maximum on Day 8 at about $1000 \text{ mg N kg}^{-1}$ compared to the surface broadcast application that attained a maximum of 150 mg N kg^{-1} at the end of the monitoring period. This result suggests that there was little substrate inhibition of hy-

drolysis of the urea in the band (Nye, 1992) and that most of the urea was hydrolyzed in the first week after application. With such a rapid hydrolysis, the pH of the soil in the immediate vicinity of the band rose from 6.0 to 8.7 in the upper surface layer and to 7.2 in the lower surface layer (Fig. 3e and 3f). According to the thermodynamic equilibrium of NH_4^+ ions in solution based on a pK_a of 9.2 (NIST 46.7; Cox et al., 1989), an increase in pH from 6.0 to 8.5 represents an increase of two orders of magnitude in the concentration of aqueous NH_3 in solution. The NH_3 source strength was therefore much greater in the incorporated bands than in the soil where broadcast urea was incorporated. Diffusion as well as convective transport of dissolved NH_4^+ with the water flow driven by surface evaporation were likely involved in the upward movement of ammoniacal N. We therefore conclude that the high rate of volatilization from the Banded/Incorporated treatment was associated with the high concentration of NH_3 caused by the hydrolysis of urea concentrated in a small volume of soil and the consequent increase in soil pH. Rochette et al. (2008b) observed similar $\text{NH}_3\text{-N}$ losses when urea was incorporated in bands (31% of applied N) and though soil conditions were not measured in the band, high emissions were likely due to the same mechanisms.

Hydrolysis of broadcast (incorporated or not) untreated urea also began shortly after urea application, as indicated by changes in soil NH_4^+ content and pH (Fig. 3 a, b, e, f). However,

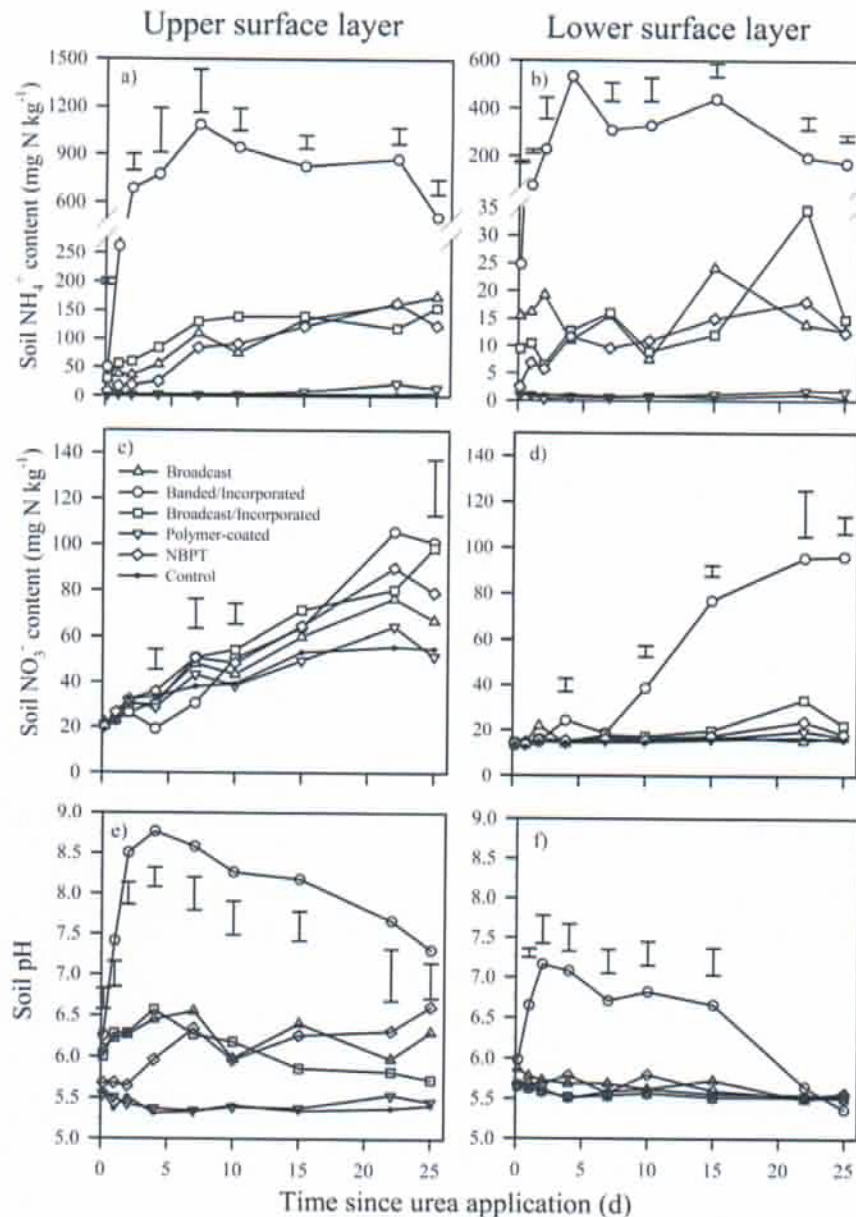


Fig. 3. Soil mineral N and pH after urea application. Upper and lower soil surface layers corresponded approximately to the 0–4 cm and 4–8 cm soil layers, respectively. Plots were randomly sampled except for the Banded/Incorporated plots which were sampled on the band. NBPT = urea treated with urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide. Vertical bars represent LSD_{0.05} for treatment comparison at each sampling date.

the magnitude of these changes was much smaller than in the Banded/Incorporated plots because of the mixing of urea with a greater volume of soil. During the first 5 d, lower rates of hydrolysis of the slow-release urea (Polymer-Coated and NBPT) resulted in low soil NH_4^+ content and pH and, consequently, in the low NH_3 volatilization losses (Fig. 2 and 3; Table 3).

From Day 5 to 10, emissions from the Banded/Incorporated plots remained high (mean = 14 mg NH_3 m⁻² h⁻¹) and peaked at approximately 25 mg NH_3 m⁻² h⁻¹. Emissions from the Broadcast/Incorporated treatment increased (mean = 5 mg NH_3 m⁻² h⁻¹) and peaked on Day 8 (12 mg NH_3 m⁻² h⁻¹) after application of 5 mm of water at Day 7 (Fig. 2a, Table 2). The increase in emission following water application was greater in the plots where untreated urea was incorporated than on the Broadcast plots. Water allows

the dissolution of soil NH_4^+ required for the formation of volatile NH_3 . However, such a small amount of water only wetted the top (approximately 8 mm) of this dry soil and should therefore have had a greater impact in the plots where urea was applied at the surface. This indicates that factors other than soil water content, such as a slow rate of urea hydrolysis, resulted in low concentrations of soil NH_4^+ and NH_3 source strength in the Broadcast plots. During this period, emissions remained lowest in the slow-release urea treatments. However, it is noteworthy that similar low emissions were observed with greater soil NH_4^+ concentrations in the NBPT than in the Polymer-Coated treatment.

Emissions from the Banded/Incorporated plots remained higher than in the other treatments during most of the final 15 d of the monitoring period. This is in agreement with a higher

Table 3. Cumulative losses of NH₃-N following land application of urea at different moments during the experiment.

Urea application method or type	Cumulative NH ₃ losses				
	Day 1	Day 2	Day 5	Day 10	Day 25
	mg NH ₃ -N m ⁻²				
Broadcast	54	120	194	563b [‡]	1331b
Broadcast/Incorporated	40	165	245	921b	2250b
Banded/Incorporated	23	68	553	2102a	3768a
NBPT†	40	45	88	290c	669c
Polymer-Coated	31	88	159	225c	508c
Treatment P value	NS	NS	NS	> 0.001	> 0.001

† Urea treated with urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide.

‡ Values in the same column with same letter are not significantly different ($P < 0.05$).

NH₃ source strength resulting from higher soil NH₄⁺ and pH. Interestingly, nitrification in the upper soil layer of Banded/Incorporated plots was similar to the other plots (except Polymer-Coated and Control plots) (Fig. 3b) despite much greater concentrations in soil NH₄⁺ (Fig. 3a). We hypothesize that nitrification was inhibited in these plots by the high soil pH (Yadvinder et al., 1994). Consequently, NH₃ volatilization was the main fate for soil NH₄⁺ and soil pH remained high until the end of the measurement period. From Day 10 to 25, emissions from the Broadcast/Incorporated plots were generally greater than from the Broadcast treatment and again tended to increase more following water addition. Finally, the temporal pattern of emissions from the NBPT and Polymer-Coated treatments was similar to the Broadcast treatment, but emissions were 50% lower during this final period, averaging approximately 1 mg NH₃ m⁻² h⁻¹.

Cumulative Nitrogen Loss

Surface Applications

Cumulative NH₃-N volatilization from the Broadcast treatment represented 9% of applied N (Fig. 2b, Table 3). This N loss is lower than the 18 to 26% range used for global emission estimates from urea applications (Bouwman et al., 2002) and lower than values typically observed in the literature (Sommer et al., 2004). It is also in contrast to a study performed in 2006 at an adjacent site in which cumulative emissions accounted for 65% of applied N (Rochette et al., 2008b). Both studies were conducted on the same soil series under similar meteorological conditions but the 2006 site was under no-till. Tillage can influence NH₃ volatilization following broadcasting of urea in several ways (Rochette et al., 2008a). Incorporation of crop residues typically decreases urease activity near the surface of tilled soil (Bergstrom et al., 1998; Palma et al., 1998). Accordingly, urease activity was 255 μg NH₄-N g⁻¹ h⁻¹ in the no-till site in 2006 (Rochette et al., 2008b) compared to 55 μg NH₄-N g⁻¹ h⁻¹ in this study. The low bulk density of the tilled soil also resulted in a much lower mean volumetric water content in the present study (0.12 m³ m⁻³; s.d. = 0.01 m³ m⁻³) than in Rochette et al. (2008b) (0.26 m³ m⁻³; s.d. = 0.04 m³ m⁻³). Therefore, urea dissolution and hydrolysis on the tilled soil surface was possibly impeded by the lack of moisture at the soil surface. As a result, urea granules could be seen on the "fluffy" tilled soil surface more than 48 h

after application while they had disappeared in less than 18 h in the study of Rochette et al. (2008b). We conclude that the release of urea to the soil environment occurred at a slower rate in this study than in Rochette et al. (2008b), resulting in a lower availability of NH₄-N for volatilization.

Surface applications of slow-release urea resulted in even lower NH₃-N losses, representing 5 and 4% of total applied N for the NBPT and Polymer-Coated treatments, respectively. Such reductions of 60% in volatilization losses from NBPT-treated compared to regular urea are in agreement with previously reported reductions of 28 to 88% (Rawluk et al., 2001; Singh et al., 2004). In the case of the polymer-coated urea, the decrease can be explained by the very slow apparent release of N as indicated by the lack of an increase in soil N (Fig. 3a, b, c, d). However, in the case of the granules supplemented with NBPT, the soil N concentration was 50% lower than those from uncoated urea granules for the first 5 d ($P > 0.05$, two sampling days out of three), but gradually increased and was similar to the concentration in the Broadcast treatment after 10 d. The urease inhibitor reduced the rate of urea hydrolysis relative to the untreated urea granules. This likely allowed soils to more effectively buffer pH change (Fig. 3e) and adsorb NH₄⁺ ions on the soil particles, consequently reducing accumulation of NH₄⁺ in the soil solution and limiting the chemical dissociation to NH₃.

Broadcast Incorporated

Total cumulative NH₃ emissions from the Broadcast/Incorporated plots during the experiment were 2.3 g N m⁻² or 16% of applied urea N (Fig. 2b; Table 3). This value is high relative to a mean loss of 5 to 15% obtained from a global dataset (Bouwman et al., 2002). The greater losses in the present study can be explained by conditions favoring NH₃ volatilization including a warm soil as well as the absence of a growing crop and high rainfall. The emissions in the Broadcast/Incorporated treatment resulted in a cumulative N loss 1.7 times greater than from the Broadcast treatment. Incorporation of NH₄-N sources usually reduces NH₃ volatilization by decreasing NH₄⁺ availability through increased adsorption on soil particles and increasing resistance to NH₃ diffusion to the atmosphere (Sommer et al., 2004). Accordingly, reductions in NH₃-N loss of 8 to 20% were observed when urea was mixed in a variety of soils (du Preez and Burger, 1987; Padilla et al., 1990; Blaise et al., 1996). Broadcast urea hydrolysis occurred more rapidly after application when granules were incorporated due to higher soil water content at depth compared to the soil surface. As a result soil NH₄⁺ concentrations increased more rapidly (Fig. 3a and 3b) in the Broadcast/Incorporated treatment, thereby enhancing NH₃-N loss relative to the Broadcast application. We conclude that the lower N loss when urea was broadcast at the surface was the result of the very low rate of hydrolysis at the soil surface because of dry conditions. As a result, the slow urea hydrolysis not only reduced the NH₄⁺-N available for volatilization but it also likely allowed the soil to buffer soil pH change which minimized the formation of NH₃ hotspots around the granules (Le Cadre et al., 2004).

Incorporation in Bands

The NH_3 cumulative loss from the incorporated bands was 3.8 g N m^{-2} or 27% of the applied urea N (Table 3). There are few reports of NH_3 volatilization following incorporation of urea in bands. Cumulative NH_3 emissions observed by Rochette et al. (2008b) in 2006 at a no-till site adjacent to the present experiment were nearly identical to those in this study (31% of applied N). Emissions reported with banded urea under controlled conditions were lower with 13 (du Preez and Burger, 1987) and 3% (Bouwmeester et al., 1985) of applied N.

Incorporating urea in bands has been observed to decrease NH_3 -N loss by 35 to 65% (du Preez and Burger, 1987), 84% (Bouwmeester et al., 1985), and 50% (Rochette et al., 2008b) compared to broadcast urea. Accordingly, incorporation of broadcast or banded urea is recommended to mitigate NH_3 volatilization (Bouwman et al., 2002; Sommer et al., 2004). In this study, cumulative NH_3 -N volatilization from the Banded/Incorporated treatment was 2.6 and 1.7 times greater than from the Broadcast and Broadcast/Incorporated treatments, respectively. This was explained by maintained high localized soil pH and NH_4^+ concentrations during most of the experiment in the Banded/Incorporated plots. The low cumulative NH_3 -N loss from the Broadcast plots can be explained, for the most part, by the low rate of urea hydrolysis under the dry conditions at the soil surface.

While not previously reported, high NH_3 loss when urea is incorporated in bands is in agreement with the impact of urea application on the soil environment. Overrein and Moe (1967) observed an increase in soil pH to values between 8.5 and 9 at very high urea application rates (250 to 800 kg ha^{-1}). Toxicity due to high NH_3 concentrations is recognized as a problem that reduces seed germination (Yadvinder et al., 1994; Malhi, 1995). Volatilization losses increased with increasing application rates on acidic soils following surface broadcasting of urea (Black et al., 1987; Watson and Kilpatrick, 1991) but to our knowledge, only one study by Buresh (1987) observed increases in N loss (50% higher) with point placed (incorporated) urea compared to surface application. The soils studied by Buresh (1987) were poor and sandy, suggesting that they would have a low CEC and pH buffer capacity, and that high permeability would have allowed NH_3 to diffuse relatively easily to the surface. The soil in this current study was not as light or poor as that in Buresh (1987) but its low base saturation (Table 1) and water content may have made it more susceptible to volatilization. The precipitation of CaCO_3 acts as a pH buffer during the hydrolysis of urea and furthermore liberates sites on the soil exchange complex for NH_4^+ to adsorb (Fenn et al., 1982); because the Le Bras soil has low Ca and Mg concentrations on the exchange complex (Table 1) this soil and others with similar properties may be prone to large increases in pH during urea hydrolysis.

Many studies that have looked at the effectiveness of the incorporation of urea on reducing N loss, from which recommendations to band urea have been derived, have been performed in the laboratory (Fenn and Miyamoto, 1981; Bouwmeester et al., 1985; du Preez and Burger, 1987; Roelcke et al., 1996; Blaise et

al., 1996). Therefore it is difficult to evaluate if these experiments properly simulated the soil conditions around banded urea in the field. Furthermore, field studies looking at volatilization and plant N uptake using different application methods were performed in cropping systems such as rice or cereals that use narrow row spacing (Sen and Bandyopadhyay, 1986; Padilla et al., 1990; Malhi et al., 1996). In crops such as maize, rows are farther apart and urea is concentrated in fewer bands; thereby increasing urea concentration and the potential for large NH_3 -N loss to the atmosphere.

Crop N uptake and yield have often been observed to be greater when urea is banded and incorporated than when broadcast at the soil surface (Yadvinder et al., 1994; Malhi et al., 1996; Rees et al., 1996; Grant et al., 2001). It is often assumed that the reason for reduced yields when the urea is surface broadcast is a combination of decreased accessibility of N and greater N loss through volatilization. Our results suggest that the influence of N accessibility on the reduced crop N uptake is important as volatilization is still likely to be substantial when urea is incorporated in bands in certain soils.

Conclusions

The application method and type of urea had a large impact on NH_3 volatilization. Little N diffused out of the polymer-coated granules during the experiment and ammonia cumulative emissions were low (4% loss of applied N). Broadcasting urea supplemented with a urease inhibitor delayed the accumulation of soil mineral N compared to plots with untreated urea and also resulted in low NH_3 loss (5% loss of applied N). The rate of hydrolysis of urea broadcast at the soil surface was slowed by the lack of moisture, and N loss (9% of applied N) was the lowest of all treatments that used standard urea. Shallow incorporation (5 cm) of broadcast urea increased cumulative emissions (16% of applied N) because higher soil moisture stimulated urea hydrolysis relative to surface application. Incorporation (3–5 cm) in bands further increased losses (27% of applied N) due to a localized increase in soil pH from 6.0 to 8.7. We conclude that (i) using polymer-coated or NBPT-treated urea reduces total NH_3 losses compared to broadcast application of untreated urea granules, but (ii) that incorporating urea in bands in dry acidic soils can increase NH_3 volatilization, compared to broadcast application followed by incorporation. Consequently, modifications to the recommendations for urea application in incorporated bands may be required under certain conditions. Further research is needed to better understand the interaction between soil properties, such as initial pH, buffer capacity, base saturation or water content, and urea application rate on NH_3 volatilization following incorporation of urea in bands.

Acknowledgments

This study was funded by the GAPS Initiative of Agriculture and Agri-Food Canada. We thank Johanne Tremblay, Nicole Bissonnette, Jean-Marie Noël, Michel Noël, Alain Gonthier, Kenneth Dumont, and Gabriel Lévesque for their assistance in field and laboratory work.

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