

Ammonia volatilization from soils fertilized with urea and varying rates of urease inhibitor NBPT

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Rawluk, C. D. L., Grant, C. A. and Racz, G. J. 2001. **Ammonia volatilization from soils fertilized with urea and varying rates of urease inhibitor NBPT.** *Can. J. Soil Sci.* **81**: 239–246. Loss of N as ammonia (NH₃) from surface-applied urea fertilizer may be high if hydrolysis takes place at the soil surface. The urease inhibitor **N-(n-butyl) thiophosphoric triamide (NBPT)** may reduce NH₃ loss from urea by delaying hydrolysis. Field studies using surface chambers were conducted in 1996 and 1997 to compare the amount of NH₃ volatilized from surface applications of granular urea (100 kg N ha⁻¹) treated with varying concentrations of NBPT (0, 0.05, 0.10 and 0.15% NBPT wt/wt). The studies were conducted on two Orthic Black Chernozemic soils, a Stockton fine sandy loam and a Newdale clay loam, in May and again in July to determine the relative influence of soil texture and temperature on NBPT performance at the varying rates. Ammonia losses were measured at various times to 12 d after fertilization (DAF) in 1996 and to 21 DAF in 1997. Total NH₃ losses decreased in the order of 0% > 0.05% > 0.15% ≥ 0.10% where use of NBPT reduced total NH₃ loss by 28–88% over the entire study duration, and by 82 to 96% during periods of peak loss from unamended urea. Ammonia volatilization losses from NBPT-amended urea treatments were lower in May than in July. The total loss measured at all rates of NBPT was higher for the fine sandy loam soil except in May 1997 where cool conditions resulted in slightly lower loss than for the clay loam soil. Amending urea with NBPT at a rate as low as 0.05% wt/wt can reduce NH₃ loss from surface-placed urea fertilizer, so that a greater proportion of fertilizer N is retained in the soil for plant use. The inhibitor helps reduce the amount of NH₃ derived from urea entering the atmosphere to react or to be deposited elsewhere, and may lessen the need to overfertilize to compensate for potential NH₃ losses.

Key words: N-(n-butyl) thiophosphoric triamide, urease inhibitor, surface applications

Rawluk, C. D. L., Grant, C. A. et Racz, G. J. 2001. **Pertes d'ammoniac des sols amendés avec de l'urée et une quantité variable de NBPT, un inhibiteur de l'uréase.** *Can. J. Soil Sci.* **81**: 236–246. Une quantité importante du N de l'urée épandue en surface peut disparaître sous forme d'ammoniac (NH₃) s'il y a hydrolyse au niveau du sol. Le N-(n-butyl)-triamide de l'acide thiophosphorique (NBPT) est un inhibiteur de l'uréase et pourrait réduire les pertes de NH₃ de l'urée en retardant l'hydrolyse. En 1996 et 1997, les auteurs ont effectué des études sur le terrain au moyen de chambres de surface en vue de comparer la quantité de NH₃ qui s'échappe dans l'air consécutivement à l'application d'urée granulaire (100 kg N ha⁻¹) renfermant une quantité variable de NBPT (0, 0,05, 0,10 et 0,15 % en poids). Les essais se sont effectués sur deux tchernozems orthiques noirs, soit un fin loam sablonneux Stockton et un loam argileux Newdale, en mai puis en juillet, et devaient préciser l'influence relative de la texture et de la température du sol sur l'efficacité du NBPT aux concentrations à l'étude. Les auteurs ont mesuré la perte d'ammoniac à divers moments jusqu'à 12 jours après la fertilisation (JAF) en 1996 et 21 JAF en 1997. La perte totale de NH₃ diminue dans la séquence 0 % > 0,05 % > 0,15 % ≥ 0,10 %, et l'addition de NBPT a réduit la perte totale de NH₃ de 28 à 88 % pendant la durée de l'étude et de 82 à 96 % lors des périodes où les pertes de l'urée non traitées étaient les plus importantes. Les pertes attribuables à la volatilisation de l'ammoniac sont plus faibles en mai qu'en juillet quand l'urée est traitée au NBPT. Quelle que soit la concentration de NBPT, les pertes totales étaient plus élevées pour le loam sablonneux fin, sauf en mai 1997 lorsque le temps frais a donné lieu à des pertes légèrement plus faibles que celles du loam argileux. L'addition de jusqu'à 0,05 % de NBPT en poids à l'urée diminue les pertes de NH₃ après application en surface, si bien qu'une plus grande quantité de N pénètre dans le sol pour la croissance des plantes. L'inhibiteur concourt à réduire la proportion de NH₃ de l'urée qui s'échappe dans l'atmosphère et qui finit par se déposer ailleurs ou se transformer en oxyde nitreux pour accroître l'effet de serre. L'inhibiteur pourrait donc atténuer la nécessité d'une surfertilisation visant à compenser les pertes éventuelles de NH₃.

Mots clés: N-(n-butyl)-triamide de l'acide thiophosphorique, inhibiteur de l'uréase, applications en surface

Urea is the dominant form of fertilizer N used in Western Canada (Agriculture and Agri-Food Canada 1999) as it is an economical and efficient source of fertilizer N if properly managed (Byrnes and Freney 1995). Once applied to the soil, urea is rapidly hydrolysed by urease enzymes in the soil and organic material to yield 2 NH₄⁺ per CO(NH₂)₂ (Sherlock and Goh 1985). This ammonium is susceptible to

volatile loss to the atmosphere as NH₃ if present in sufficient concentration near the soil surface (Koelliker and Kissel 1988). The potential for NH₃ volatilization is greatest when urea fertilizer is surface-applied where soil conditions promote rapid granular dissolution, but restrict movement of urea into soil (McInnes et al. 1986; Clay et al. 1990). Conditions that affect NH₃ volatilization include soil physi-

cal and chemical properties, and temperature and moisture regime (Hargrove 1988; Kissel and Cabrera 1988).

Substantial NH_3 volatilization reduces the amount of fertilizer N available to the growing crop and may contribute to both localized and long-range pollution. High concentrations of NH_3 in the atmosphere can result in formation of the greenhouse gas N_2O and acidification of soil and surface waters (Janzen 1999). Applying excess urea fertilizer to compensate for possible NH_3 volatilization losses may lead to increased N_2O in the soil and nitrate leaching to groundwater.

Treating urea fertilizer with the urease inhibitor NBPT may reduce NH_3 loss from surface applications (Clay et al. 1990; Bremner et al. 1991). Once applied to the soil, NBPT converts to its oxon analog **N-(n-butyl) phosphoric triamide (NBPTO)**, which is the actual inhibitor of urease activity (McCarty et al. 1989; Creason et al. 1990). The inhibitor occupies the urease active site, inactivating the enzyme (Mobley and Hausinger 1989; Kolodziej 1994) to delay the onset and reduce the rate of NH_3 volatilization (Christianson et al. 1990). The delay in hydrolysis reduces the concentration of NH_3 present near the soil surface, which decreases the potential for volatilization and improves the opportunity for rainfall to move urea deeper into the soil. The inhibitor may serve as an environmentally sound management alternative to increasing urea fertilizer rate, providing its use is economical.

The performance of NBPT at varying concentrations has been studied under controlled laboratory conditions, which showed increased inhibition of urease activity with increasing rate of NBPT applied with urea (Carmona et al. 1990). Christianson et al. (1990) observed 68% inhibition of urea hydrolysis at 0.01% NBPT wt/wt with 1.5 to 3 times lower NH_3 losses when the rate was increased to 0.1%.

Field trials investigating NBPT performance at varying rates are limited (Watson et al. 1994a), and although results tend to agree with laboratory studies, NBPT use at lower than the recommended rate of 0.14% wt/wt has not been evaluated for Chernozemic soil in the Black Soil Zone of the Eastern Canadian Prairies. Microplot field studies were established near Brandon, MB, to measure the pattern and amount of NH_3 volatilization from urea amended with varying rates of the urease inhibitor NBPT, and to evaluate the relative performance of these rates under two different soil

textures and different temperature regimes encountered in the field.

MATERIALS AND METHODS

Field experiments were conducted in 1996 and 1997 in May and July on two Orthic Black Chernozemic soils located near Brandon, MB, a Newdale clay loam ($50^\circ 10' \text{N}$) and a Stockton fine sandy loam ($49^\circ 50' \text{N}$). The 1996 trials commenced on 21 May and 16 July on the clay loam and on 28 May and 17 July on the fine sandy loam soil. Trials in 1997 began on 20 May and 24 July on the clay loam soil and on 6 May and 24 July on the fine sandy loam. Selected physical and chemical properties (Carter 1993) were determined from two air-dried samples composited from four holes taken between treatment reps on each soil type to a depth of 15 cm at the beginning of the May studies in 1996 and 1997 (Table 1).

Each experiment was arranged as a randomized complete block design having three replicates with five treatments. The treatments consisted of 100 kg urea N ha^{-1} at rates of 0, 0.05, 0.10 and 0.15% NBPT wt/wt supplied as Agrotain (IMC-Agrico) and a control treatment (no fertilizer or NBPT). Study design and NH_3 capture and analysis procedures followed Grant et al. (1996). White **polyvinyl chloride (PVC)** cylinders, 200 mm in length by 150 mm diameter, were inserted 50 mm into the soil with minimal soil disturbance. Prior to treatment application, surface residue was cleared from the immediate area of fertilizer placement within each cylinder to allow direct contact of fertilizer with soil to eliminate any direct effects of residue on urea hydrolysis and NH_3 volatilization. Filter paper was placed on the soil surface in each cylinder and 150 mL distilled water was added 24 h prior to fertilizer addition to ensure a moist soil surface where granules could dissolve. At each site, the 150 mL H_2O wet the soil to field capacity to a calculated depth of 24 and 22 mm for the clay loam soil in 1996 and 1997, and to 28 and 33 mm for the fine sandy loam soil in 1996 and 1997 using the equation:

$$\text{Depth of water movement} = 100 \div \text{volumetric field capacity (\%)} \times 150 \text{ cm}^3 \div \text{area of cylinder (cm}^2\text{)}$$

Fertilizer treatments were dispensed on the soil surface at the centre of each cylinder within a 20 mm diameter area.

Table 1. Selected chemical and physical characteristics of soils used^{2y}

Soil name	Sand	Silt	Clay	FC	BD	CEC	OC	CaCO ₃	pH	EC
			(%)		(g cm ⁻³)	(cmol kg ⁻¹)	(%)			(μS cm ⁻¹)
Newdale (1996)	32.2	36.3	31.5	30	1.17	49.8	4.28	1.6	8.0	896
Stockton (1996)	76.0	11.8	12.2	23	1.32	23.1	2.68	0.3	7.6	1092
Newdale (1997)	35.8	32.2	32.0	32	1.22	46.7	4.85	3.6	8.2	740
Stockton (1997)	75.5	11.4	13.1	19	1.34	23.2	2.05	1.4	8.2	756

²All determinations made using 0–15 cm depth composite samples.

^yFC, field capacity; BD, bulk density; CEC, cation exchange capacity; OC, organic carbon; pH in water; and EC, electrical conductivity.

Table 2. Average gravimetric soil water content (GWC) of control treatment soil at study end and average soil temperature at 10 mm during study

Depth	Newdale clay loam				Stockton fine sandy loam			
	May		July		May		July	
	Temp. (°C)	GWC (%)	Temp. (°C)	GWC (%)	Temp. (°C)	GWC (%)	Temp. (°C)	GWC (%)
<i>1996</i>								
0–5 cm	12.3 ± 2.3	28.3 ± 1.2	19.1 ± 1.6	30.3 ± 2.0	16.2 ± 3.2	12.9 ± 1.6	20.5 ± 1.7	13.4 ± 0.7
5–10 cm	–	29.0 ± 1.5	–	27.7 ± 1.4	–	14.9 ± 1.4	–	11.7 ± 1.1
<i>1997</i>								
0–5 cm	17.9 ± 2.6	24.4 ± 1.8	21.6 ± 1.2	26.0 ± 1.0	11.2 ± 3.5	14.9 ± 0.6	23.0 ± 3.1	9.6 ± 1.0
5–10 cm	–	25.7 ± 2.0	–	25.5 ± 1.7	–	16.7 ± 0.4	–	10.9 ± 1.4

Immediately following fertilization, each cylinder was fitted with two polyfoam discs, 25 mm thick and 160 mm in diameter, previously double washed with distilled water, 0.001 M H₂SO₄ and a glycerol-phosphoric acid solution (100 mL 14.7 M H₃PO₄, 125 mL glycerol and 2275 mL deionized water), with excess liquid removed after each washing by wringing. The lower disc was inserted within the cylinder at 50 mm above the soil surface to trap volatilized NH₃ and the second disc placed 50 mm below the top of the cylinder to prevent drying and atmospheric NH₃ contamination of the lower disc. Each disc was designed to fit tightly within the cylinder to minimize escape of gaseous NH₃. Plexiglass sheets were positioned approximately 300 mm above the cylinders to provide protection from rainfall.

On specified DAF during each trial (at 1, 2, 5, 8, 12 DAF in 1996 and extended to 15, 19 and 21 DAF in 1997) the upper disc was lifted, the lower disc removed, a fresh disc inserted to 50 mm above the soil surface, and the upper disc replaced. The lower disc was immediately transferred to a re-sealable, airtight plastic bag containing 250 mL 2 M KCl. The disc was then thoroughly rinsed in the KCl solution to extract the trapped NH₃, and the solution extract decanted into vials which were sealed and stored frozen until analysis. The KCl extract was analyzed at room temperature for ammonium-N content using a Technicon Autoanalyzer (Technicon Industrial Systems 1977).

At the end of each trial, soil gravimetric water content was measured in the control treatment cylinder of each block (Table 2) (Carter 1993). Soil temperature within the cylinders at 10 mm below the soil surface was measured throughout each trial period on each soil in both study years using thermister type soil temperature sensors connected to a LICOR datalogger. The sampling interval was every 60 s and the data reported as daily means, highs and lows. Data recording in May 1997 was delayed until 7 DAF for the clay loam site and until 3 DAF for the fine sandy loam site, and in July 1997 for the clay loam soil, data recording ended at 9 DAF. Daily mean temperature data is presented with cumulative NH₃-N Loss data in Fig. 1.

Statistical analyses were conducted on log-transformed data (log + 1) (Steel et al. 1997) using the MIXED models procedure of the SAS Institute, Inc. (Littell et al. 1998) and contrast analysis. Analyses were performed on cumulative gaseous NH₃ loss to 5 DAF, from 5 DAF to 12 DAF from

15 to 21 DAF (1997 only) and on total NH₃ loss. Data were analyzed separately by trial and year as significant interactions occurred between year, soil, study period and treatment.

RESULTS

Soil temperatures during the May trials were cooler than during the July trials for both years and both soils (Table 2 and Fig. 1). In May, soils gradually warmed as air temperature increased, so there was a larger range in temperature than during the July studies. Temperature of the fine sandy loam was more susceptible to fluctuations in air temperature than the clay loam soil and, therefore, temperature differences between sites were most evident in the spring when air temperature was more variable. Soil temperatures during the July studies in 1996 and 1997 tended to be more similar for both soil types, but were highest during the 1997 July trial on the Stockton soil, reaching 27°C by 14 DAF before dropping to about 18.5°C for the remainder of the study (Fig. 1.).

Gravimetric soil water content within the cylinders at the end of each trial was similar for the May and July trials conducted on the same soil type in 1996 and for the clay loam soil in 1997 (Table 2). On the fine sandy loam soil in 1997, water content in May was 79% of field capacity, but only 51% in July. In May 1997, soil temperatures of the fine sandy loam were low so the soil did not dry as rapidly as in May 1996, while in July, the comparatively high soil temperatures at the beginning of the study may have increased water loss from the soil relative to other trials. Final water content was consistently higher and closer to field capacity for the clay loam than the fine sandy loam soil.

Total NH₃ volatilization loss, expressed as a percent of applied N from untreated urea (0% NBPT), was similar for each trial, in the range of 20 to 26% of the applied N, with the exception of the July 1997 trial on the fine sandy loam soil where NH₃ loss was 50% of applied urea-N (Fig. 1). Treatment of urea with NBPT at rates of 0.05, 0.10 and 0.15% moderated the rate and reduced the total amount of NH₃ volatilization (Tables 3 and 4, Fig. 1). Use of NBPT reduced total NH₃ loss by up to 85% in the May trials and up to 75% in the July trials on the clay loam soil, and by up to 81% in the May trials, but up to only 37% for the July trials on the fine sandy loam soil. During the first 5 to 8 DAF the amount of NH₃ volatilized was markedly higher for un-

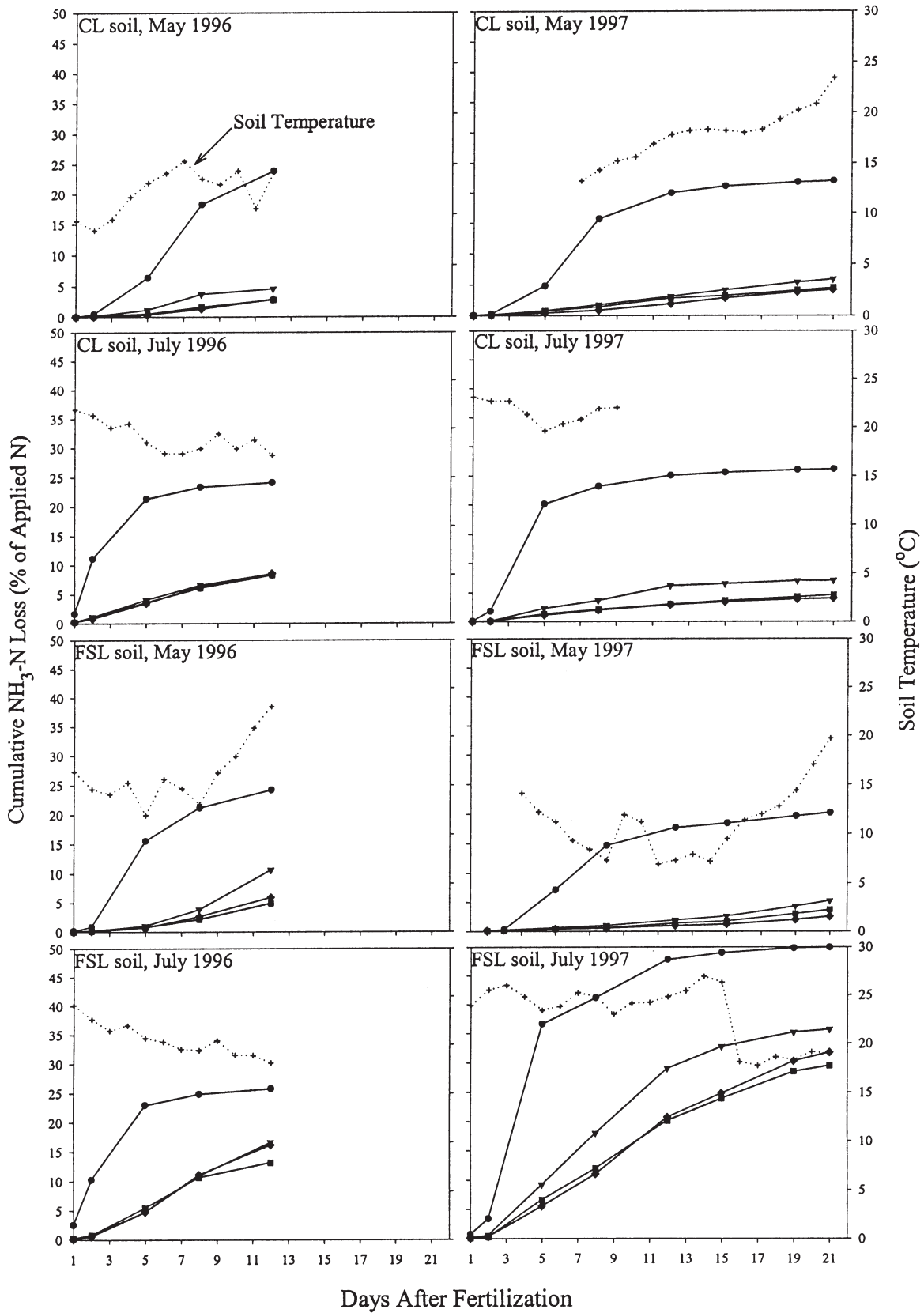


Fig. 1. Cumulative ammonia loss from urea fertilizer amended with NBPT (0.0 ●, 0.05 ▼, 0.10 ■, and 0.15 ◆ wt/wt), minus control for 1996 and 1997 studies on Newdale clay loam (CL) and Stockton fine sandy loam (FSL) soils.

Table 3. Contrast analysis probability values of the effect on NBPT rate on ammonia volatilization from urea during the 1996 12-d study on a clay loam and a fine sandy loam soil^z

Source of variation	Sum to 5 DAF ^y		Sum 5 to 12 DAF		Sum to 12 DAF	
	May	July	May	July	May	July
<i>Clay loam</i>						
Untreated vs. NBPT-treated	***	***	NS	NS	***	**
0.05% NBPT vs. 0.15% NBPT	*	NS	NS	NS	NS	NS
0.10% NBPT vs. 0.15% NBPT	NS	NS	NS	NS	NS	NS
NBPT-quadratic	***	***	***	*	***	***
SEM	0.18***	0.36***	0.39***	0.78**	0.43***	0.82***
<i>Fine sandy loam</i>						
Untreated vs. NBPT-treated	***	***	***	NS	***	*
0.05% NBPT vs. 0.15% NBPT	NS	NS	NS	NS	NS	NS
0.10% NBPT vs. 0.15% NBPT	NS	NS	NS	NS	NS	NS
NBPT-quadratic	***	**	***	**	***	***
SEM	0.16***	0.59**	0.44***	0.57**	0.60***	1.02***

^zDetermined using log-transformed data.

^yDAF, days after fertilization; SEM, standard error of log-transformed LS means.

*, **, *** Significant at $P < 0.05$, $P < 0.001$ and $P < 0.0001$, respectively.

Table 4. Contrast analysis probability values of the effect on NBPT rate on ammonia volatilization from urea during the 1997 21-d study on a clay loam and a fine sandy loam soil^z

Source of variation	Sum to 5 DAF ^y		Sum 5 to 12 DAF		Sum 15 to 21 DAF		Sum to 21 DAF	
	May	July	May	July	May	July	May	July
<i>Clay loam</i>								
Untreated vs. NBPT-treated	***	***	***	***	NS	NS	***	***
0.05% NBPT vs. 0.15% NBPT	**	NS	*	*	NS	NS	*	NS
0.10% NBPT vs. 0.15% NBPT	*	NS	NS	NS	NS	NS	NS	NS
NBPT-quadratic	***	***	***	***	***	NS	***	***
SEM	0.07***	0.25***	0.25***	0.37***	0.24**	0.44	0.37***	0.61***
<i>Fine sandy loam</i>								
Untreated vs. NBPT-treated	***	***	***	NS	NS	*	***	NS
0.05% NBPT vs. 0.15% NBPT	NS	NS	*	NS	**	NS	**	NS
0.10% NBPT vs. 0.15% NBPT	NS	NS	NS	NS	*	NS	NS	NS
NBPT-quadratic	***	***	***	***	***	NS	***	***
SEM	0.12***	0.31***	0.23***	0.59***	0.23***	0.69**	0.44***	0.97***

^zDetermined using log-transformed data.

^yDAF, days after fertilization; SEM, standard error of log-transformed LS means.

*, **, *** Significant at $P < 0.05$, $P < 0.001$ and $P < 0.0001$, respectively.

mended urea than for NBPT-amended urea, where NBPT reduced NH₃ losses by 82 to 96%. Throughout the last 7 d of the studies, the amount of NH₃ captured was more similar for all treatments (Tables 3 and 4), indicating the inhibitory effect of NBPT was beginning to diminish and also that the rate of NH₃ loss from untreated urea was decreasing. Extending the study period by 9 d in 1997 showed continued gradual NH₃ loss from NBPT-treated urea, and for the May trials showed greater loss at 0.05% NBPT rate than at 0.10 and 0.15% rates (Table 4).

The inhibitory effect was less persistent in the July trials where NH₃ loss from NBPT-amended urea was measured by 5 DAF (1.1–9.2%), but was negligible until at least 8 DAF during the May trials (0.5–3.8%) (Fig. 1). The rate and extent of NH₃ loss from NBPT-treated urea was lower on the clay loam than the fine sandy loam soil, particularly in July when rate of loss from all treatments was accelerated

due to increased soil temperatures. In July, the various rates of NBPT reduced total NH₃ losses by about half as much on the fine sandy loam soil (29–49%) as on the clay loam soil (64–85%) in both years. Ammonia volatilization from NBPT-treated urea was highest for the 1997 July trial on the fine sandy loam where cumulative NH₃ loss from unamended (50.0%) and amended urea treatments (30–36%) did not differ significantly at $P < 0.05$ because of high variability between replicates, combined with relatively high rates of loss. Cumulative NH₃ loss at each rate of NBPT at the 1997 July trial on the fine sandy loam was at least two times the amount measured for the corresponding trial in 1996.

For each trial, the relationships between total NH₃ loss and NBPT rate and between cumulative NH₃ loss to 5 DAF and NBPT rate were best described by quadratic equations (Tables 3 to 5), where the magnitude of reduction in NH₃ loss decreased with increasing rate of NBPT above 0.05%

Table 5. Regression equations describing effect of NBPT rate on total N loss as percent of applied N for Newdale clay loam and Stockton fine sandy loam soil

	1996		1997	
	Quadratic equation	R^2	Quadratic equation	R^2
<i>Clay loam</i>				
May	$Y = 24.07 - 414.1x + 1890x^2$	0.84	$Y = 21.91 - 346.9x + 1581x^2$	0.94
July	$Y = 23.56 - 332.0x + 1594x^2$	0.72	$Y = 25.84 - 415.8x + 1852x^2$	0.94
<i>Fine sandy loam</i>				
May	$Y = 26.13 - 317.8x + 1444x^2$	0.86	$Y = 20.06 - 316.7x + 1382x^2$	0.89
July	$Y = 26.90 - 244.5x + 1196x^2$	0.46	$Y = 47.75 - 330.0x + 1455x^2$	0.53

wt/wt. Suppression of NH_3 volatilization tended to be slightly greater at the 0.10 and 0.15% rates than at the 0.05% rate for all trials. Ammonia volatilization throughout each study was very similar at the 0.10 and 0.15% rates. This relationship was not as well defined for the July trials on the fine sandy loam ($R^2 = 0.46, 0.53$) because of the high variability during this period.

DISCUSSION

Under field conditions, soil properties related to texture and pH establish the NH_3 volatilization potential for a soil while the extent of NH_3 loss depends on weather conditions around the time of fertilizer application (Hargrove 1988). For both soils, initial soil water content was suitable for granule dissolution and urea hydrolysis. When soil is initially moist, as soil temperature increases, the rate of urea hydrolysis also increases (Xu et al. 1993; Moyo et al. 1989), and equilibrium shifts in favour of NH_3 formation (Sherlock and Goh 1985). For coarse-textured soils such as the Stockton fine sandy loam, soil water is less closely associated with soil surfaces and is more susceptible to fluxes, so as temperature increased, NH_3 moved upwards with soil water to concentrate near the soil surface where it could easily be volatilized. Urease activity is positively correlated to organic carbon (Kissel and Cabrera 1988) and, therefore, should be higher on the clay loam soil, but the potential for NH_3 volatilization for this soil is lower because of higher retention capacity associated with higher CEC, greater water-holding capacity, and characteristically more complex pore matrix.

The pattern and magnitude of NH_3 loss from NBPT-treated urea varied more with soil type and date of trial than with rate of NBPT (0.05, 0.10 and 0.15% NBPT wt/wt). Total NH_3 volatilization at the 0 to 0.15% NBPT rates was lowest on the fine sandy loam soil in May 1997 where temperatures were exceptionally low, ranging from 5 to 15°C during the 19 DAF. Low soil temperatures slowed the rate of hydrolysis and limited water evaporation. The final water content at 79% of field capacity in the surface 5 cm at the end of this trial was the highest measured on this soil type. Ammonia losses were highest in 1997 on the fine sandy loam July trial for all treatments where high soil temperatures during the first 15 DAF (23–27°C) in combination with initially moist soil and low water-holding capacity of this coarse-textured soil would have been suitable for rapid granular dissolution and hydrolysis before urea could move deeper into the soil. Elevated soil temperature and high urea concentration like-

ly stimulated urease activity to more rapidly overcome the NBPT inhibitory effect. As water evaporated from the soil, NH_3 would have concentrated near the soil surface, creating a high gradient for NH_3 volatilization in the initial days of the study before sufficient downward movement of urea and hydrolysis products into the soil profile could proceed to decrease the potential for NH_3 loss. At the time of fertilizer application, the soil would have been at field capacity (19%) to a depth of about 3 cm, but by study end soil water content was only 10%. Ammonia would have been carried upward in the soil with evaporating soil water.

Increasing the rate of NBPT should increase the proportion of total enzyme active sites occupied by NBPT to inhibit urease activity to a greater degree. Only slightly greater inhibition was observed at 0.10 and 0.15% NBPT rates than at the 0.05% rate, but there was no significant difference in performance at these two higher rates. As soil temperature increased, the difference between rates diminished. The duration of NBPT activity is shorter at higher temperatures because of increased urease activity (Clay et al. 1990; Bremner et al. 1991). Under these conditions a greater concentration of NBPT is required to achieve a level of inhibition equivalent to when loss potential is low, such as when the soil is cool. At higher temperatures, the hydrolysis rate may surpass the rate of NBPT conversion to NBPTO, or the rate of inhibitor degradation may be more rapid. Enhanced loss at all rates of NBPT in the July trials relative to the May trials for both soils coincided with elevated soil temperatures. In our studies NBPT at all rates was most effective during the first week after fertilization, coinciding with periods of peak loss from unamended urea. Over time, the inhibitory effect lessened as the inhibitor degraded or was replaced by urea at the enzyme active sites. Hendrickson and Douglass (1993) found minimal amounts of NBPT and NBPTO remained at the conclusion of a 14 d laboratory experiment. Extending our study period by 9 d in 1997 showed NH_3 loss continued beyond 14 d for each soil and temperature regime, but only at very low rates.

According to these modified field studies, an appreciable quantity of NH_3 can volatilize even when conditions are not generally thought to be conducive to loss, such as on cool and moist fine-textured soils, making regular use of NBPT a more viable option. However, the design of our study interfered with drying of the surface soil layer, particularly for the clay loam soil. The moist polyfoam discs restricted air movement and elevated the humidity of the confined air while still removing volatilized NH_3 to maintain a gradient

for volatilization for a longer period than may occur in the field. Under normal field conditions wind movement and lower humidity would typically dry the surface layer of soil to create a barrier between the moist NH_3 -enriched soil and the atmosphere air to decrease the diffusion gradient and the duration of NH_3 volatilization (Bouwmeester et al. 1985). In the field the duration and magnitude of NH_3 loss would likely be lower on a fine-textured soil where lower soil water flux, greater water retention, and higher CEC would restrict NH_3 diffusion to the atmosphere once the surface layer of soil dried, relative to a coarse-textured soil. Ferguson and Kissel (1986) observed transport of urea from depth to the surface with evaporating water on a very fine sandy loam soil while Bouwmeester et al. (1985) found reduced NH_3 loss with drying of a soil with a clay content of 470 mg kg^{-1} at wind speeds approximating those present in the field.

Use of NBPT may be most beneficial when soil conditions are conducive to high NH_3 volatilization from urea such as warm, drying, coarse-textured soils with elevated urease activity, low CEC, and high pH (Hargrove 1988; Watson et al. 1994b). Under these conditions, downward diffusion of urea and NH_3 , and retention of NH_4^+ on the soil is limited, and NH_3 formation is rapid (Sherlock and Goh 1985). Treating urea with NBPT may slow hydrolysis until rainfall can move urea deeper into the soil to reduce further loss, but if rain does not occur within 1 to 2 wk, total volatilization losses from NBPT-amended urea could approach total losses from unamended urea on susceptible soils.

CONCLUSIONS

Ammonia loss from surface-applied urea was significantly reduced with use of NBPT at rates of 0.05, 0.10 and 0.15% for all trials. The greatest reduction in NH_3 loss occurred during the first week, when volatilization losses were greatest from unamended urea. The inhibitory effect of NBPT was less pronounced and persistent in July as warm soil temperatures would have induced rapid granular dissolution, elevated urease activity, and upward movement of urea and NH_3 to soil surface in the evaporation stream, resulting in high concentrations of NH_3 near the soil surface. Ammonia losses at this time were greater for the fine sandy loam soil, which is characterized by lower capacity for retention of NH_4^+ and larger particle size. The commercial rate of NBPT application to urea is 0.14% wt/wt but the 0.10 and 0.15% NBPT rates were similar in effectiveness for all trials, and only slightly lower at the 0.05% rate. This research indicates a lower rate of NBPT may be suitable for surface applications of urea under the Western Manitoba weather and soil conditions investigated. The inherent limitations of the study design related to environment modification restricted the findings to a relative basis and did not permit quantitative analysis. Also, removal of residue in the immediate area of fertilizer application restricted any potential effects of residue on NH_3 volatilization due to elevated urease activity of the residue.

The urease inhibitor may not significantly reduce NH_3 losses from urea every year as conditions for volatilization vary. Whether or not a benefit is realized depends on initial soil properties at time of fertilization and weather conditions

in the days following. While the producer has some control over when fertilizer is applied, predicting weather and soil conditions afterwards is a little more difficult. Using NBPT, even at a reduced rate can be viewed as a precautionary measure. Further field research is required to evaluate the performance of reduced NBPT rates with surface applications of urea to residue-covered soil and to determine the potential yield benefit at lower rates of NBPT in the context of economic feasibility.

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