PROSPECTS FOR IMPROVING NITROGEN FERTILISER USE EFFICIENCY WITH A NEW SOIL TEST AND AMMONIA VOLATILISATION MODEL

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Abstract

Sugarcane grown in the Southern African region is reliant on large inputs of fertiliser nitrogen (up to 200 kg N /ha/crop) for producing optimum sucrose yields. Urea is the preferred N fertiliser, mainly due to a high N concentration [46%] and a lower price per unit of N compared with its main competitors, limestone ammonium nitrate (LAN [28%]) and ammonium sulphate (AS [21%]). While LAN, AS and urea suffer similar field losses of NO_3-N by leaching and denitrification, urea is subject to additional NH_3-N losses by volatilisation from both acid and alkaline non-irrigated soils. A new laboratory method was developed to test grower soils for potential ammonia volatilisation from surface-applied urea. An empirical ammonia volatilisation model, based on soil buffer capacity, was developed from these new soil test data, requiring N-rate, soil pH, organic matter, and clay as inputs. The model was used to predict potential ammonia volatilisation losses from selected field trials and laboratory studies in South Africa and the USA. Good correlations between model predictions and experimental results, including sugar yield, highlighted the significance of the ammonia volatilisation process as a component of overall nitrogen fertiliser efficiency on many sugarcane soils. Possible management options which could improve N fertiliser efficiency on dryland South African sugarcane farms are discussed. These include use of the alternative N sources LAN or AS, broadcasting urea instead of banding, urea burying, fertiliser splitting, and liquid fertilisers.

Keywords: ammonia volatilisation, decision-support-tool, N-fertilisers, soil test, sucrose yield, urea

Introduction

Nitrogen (N) is undoubtedly the most influential plant nutrient required for profitable global sugarcane (*Saccharum* spp.) production. The complex behaviour of N fertiliser in the agricultural soil system must be understood for efficient deployment of soil-specific advice using Best Management Practices (BMP). Soil N is complicated mainly by the interaction and transformation between plant-available inorganic and unavailable organic fractions (mineralisation, immobilisation), three main loss pathways (denitrification, leaching, volatilisation), existence of at least seven N oxidation states (-3, 0, +1, +2, +3, +4, +5), and the variable competing requirements for N by soil microbes. Fertiliser N recovery by sugarcane is also lower than for many other crops (low N use efficiency), averaging 30 to 40% in South Africa (Wood, 1990).

Urea [$CO(NH_2)_2$; 46% N], which is the preferred N fertiliser in the SA sugar industry due to low price and high N concentration, is particularly prone to ammonia volatilisation losses caused by rapid generation of alkalinity from the urease enzyme catalysed hydrolysis of urea to ammonium bicarbonate (Equation 1).

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \quad (1)$$

While NH_4-N is non-volatile in aqueous solution at acid pH, the volatilisation losses increase exponentially with increasing pH due to transformation of NH_4^+ into the un-ionised and volatile $(NH_3)_{aq}$ form, which readily crosses the fluid-atmosphere boundary according to its partial vapour pressure to volatilise as $(NH_3)_g$ (Equation 2).

$$NH_4^+ \rightleftharpoons (NH_3)_{aq} + H^+ \rightleftharpoons (NH_3)_g \quad (2)$$

At pH 9.25 and 25°C, 50% of solution ammoniacal N is in the potentially volatile $(NH_3)_{aq}$ form, while at pH<7.0, risk of volatilisation is negligible (Figure 1). This useful equilibrium relationship describing the mole fraction of $NH_3/(NH_3+NH_4^+)$ as a function of pH and absolute temperature (T) of an aqueous solution is derived from the temperature-dependent dissociation constant for equation 2, and was presented in simplified form by Van der Molen et al. (1989) (Equation 3). Using this equation, Schumann and Mills (1996) demonstrated the ability to track and predict ammonia volatilisation after fertiliser application, using a closed system for measuring NH_3 gas emissions.

$$NH_3/(NH_3+NH_4^+) = 1/(1+10^{(0.09108+2729.92/T-pH)}) \quad (3)$$

Loss of NH_3-N volatilised from surface-applied urea can exceed 50%, and further losses of remaining N by leaching and denitrification may also occur. The main competing granular fertiliser products limestone ammonium nitrate [LAN] (28% N) and ammonium sulphate (21% N) do not undergo significant NH_3 volatilisation losses at acid pH (Figure 1), but do undergo similar denitrification and leaching. Urea is unique in that excess alkalinity generated by hydrolysis can increase pH sufficiently for NH_3 volatilisation to occur on acid soils. Despite these large demonstrated differences between N fertiliser sources, which were known since the introduction of urea into South African sugarcane fertiliser markets in the early 1960s (Anderson, 1962), practical soil-specific advice to counter inefficient N utilisation from urea is still lacking.

Early N fertiliser recommendations for South African sugarcane production were based on average growth response calibrations from extensive N rate trials. Fertiliser rates were mainly adjusted according to the crop (plant, or ratoon), and the expected yield of ratoon cane, although some cognisance was made of soil parent material differences (Wood, 1968). The first soil-specific N fertiliser advice was introduced in 1984, whereby soil N mineralising rates were related to soil groups (Meyer et al., 1983), and later, targeting of most economic N rates according to the soil N-mineralising potential of individual fields (soil

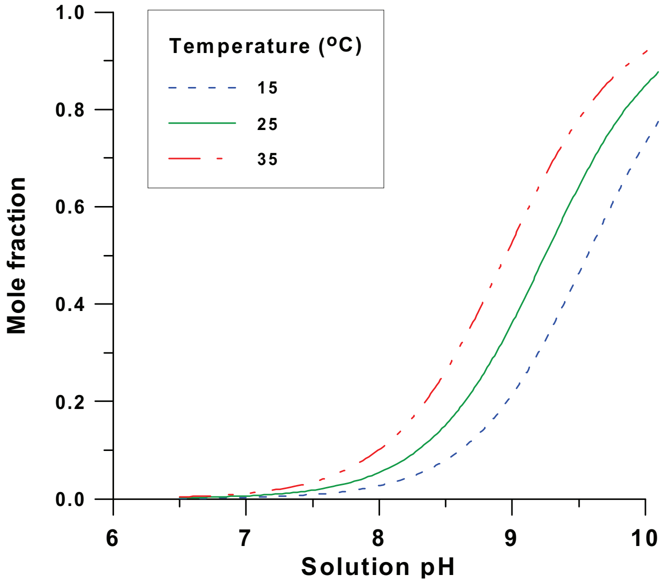

Figure 1. Relationship between the mole fraction of NH_3-N [$NH_3/(NH_3+NH_4^+)$] in aqueous solution and pH and temperature.

samples) became possible (Meyer et al., 1986). Additional methods for improving fertiliser N efficiency were investigated in South Africa and elsewhere, including the choice of N fertiliser (urea, ammonium sulphate, ammonium nitrate or LAN), timing, split application, and placement (banded, broadcast, buried, liquid). Significant yield responses were obtained in experiments from as early as the 1960s, but the quoted averages of the many often contradictory trial responses failed to provide definitive advice for specific soils. DuToit (1967) concluded from this work on forms of N fertiliser that "Until such time as we can specifically identify the conditions under which ammonium sulphate will outyield urea, it will be logical to recommend the cheapest and most convenient form." This conclusion on N fertiliser choice has remained, except where S fertilisation or acidification of alkaline soils from ammonium sulphate is desired, and no conclusive benefits were perceived from fertiliser placement (banded or broadcast), but split applications were recommended on poorly drained and very sandy soils (Meyer and Wood, 1994). Similar inconclusive yield trends were observed in Australia (Vallis and Keating, 1994), Hawaii, Mauritius, and Louisiana (Du Toit, 1967), despite the alarmingly high volatilisation losses measured from urea fertiliser in numerous laboratory and field experiments (Denmead et al., 1993; Denmead et al., 1990; Freney et al., 1991; Freney et al., 1992; Freney et al., 1994; Hagihara and Hilton, 1987; Kong et al., 1991; Prammanee et al., 1988; Prammanee et al., 1989; Wood et al., 1990). The apparent disparity between measurable N losses and sugarcane yield response may have hindered the rapid development of useful soil-specific recommendations for different types of N fertiliser.

Recently, to address this problem, the equilibrium relationships for aqueous ammonia (Equations 2-3) were exploited again in combination with Equation 1 to develop a new rapid soil test for estimating potential NH_3 volatilisation from surface applied urea. The test involves a 20-min reaction of a soil sample with specially formulated ammonium bicarbonate buffer representing the end product of complete urea hydrolysis (Equation 1). The soil + buffer pH measured at the end of this equilibration period is used to calculate potential NH_3 volatilisation from surface applied urea according to Equation 3. Essentially a comprehensive ammonia volatilisation model such as that of Rachpal-Singh and Nye (1986a) has been stripped down to the three most sensitive parameters pH, soil buffer capacity, and N rate (Rachpal-Singh and Nye,1986b). Details of this laboratory procedure and a directly coupled companion NH_3 volatilisation simulation model using N rate, soil pH, clay and organic matter (OM) inputs, will be published elsewhere since they are beyond the scope of this paper.

The soil test is being implemented by the Fertiliser Advisory Services (FAS) laboratory of the South African Sugar Association Experiment Station (SASEX) for all incoming soil samples, and will allow different N fertilisers and BMPs to be advised with confidence. The purpose of this paper is to validate the performance of the soil test and to explore prospects for improving N fertiliser use efficiency by applying the simulation model to a range of historical data from South Africa and abroad.

Materials and Methods

Ammonia volatilisation experiments

Two studies conducted in the USA (McInnes et al., 1986; Reynolds and Wolf,1987) published sufficient soil information (pH, clay, organic matter) for their measured results from surface application of urea to be tested with the simulation model (Table 1). Where other experimental conditions such as air humidity or soil moisture were varied as treatments, those with initially moist, drying soil were selected because they would best represent the conditions which were used for calibrating the model to predict potential NH_3 volatilisation. A Windows-based 'CN&S Utilities' decision-support program implementing the model (Figure 2) was developed and used to predict potential NH_3 volatilisation for the three soils, for comparison with measured volatilisation (Table 1).

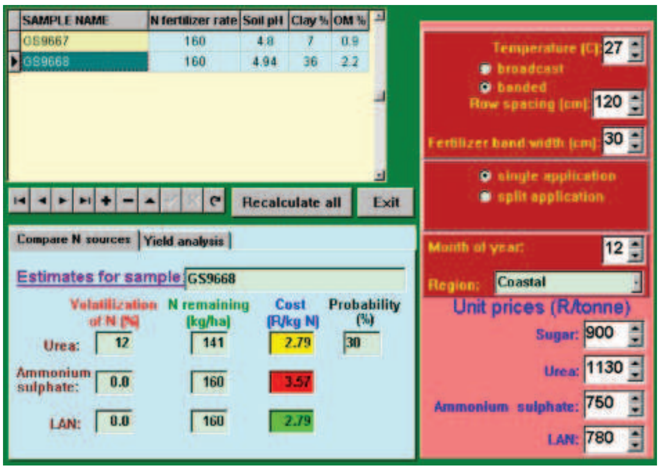

Figure 2. Nitrogen management module of the Windows-based CN&S Utilities program.

Regional assessment of volatilisation loss from urea in South African sugarcane soils

Potential NH_3 volatilisation was estimated for 54 502 representative soil sample data spanning the period 1980 to 1999 in the FAS database. Soil pH(H_2O), clay content, and recommended N fertiliser rate were used as inputs in a customised version of the CN&S Utilities model, using Genstat 5.0 (Anon, 1993). Soils were then classified according to 12 sugarcane extension areas, and 12 parent materials, reporting the percentage of samples with a potential NH_3 volatilisation above 15% (high), 5 to 15% (moderate) and less than 5% (low).

Sugarcane field trials

Information from seven sugarcane field trials conducted since 1980, comparing N fertilisers or placement of urea-N was extracted from the South African Sugar Industry Agronomist's Association archives (Table 2). The eighth experiment (FT24N) was established by the author in September 1999 at Kirkleyvale farm, KwaZulu-Natal, and constitutes a comprehensive 2^4 factorial design testing N fertiliser rate, source, placement, and splitting (Table 2). Scatter plots of sucrose yield, or 6-month stalk volume yield (FT24N) versus applied N fertiliser were prepared, and the linear correlations compared with scatter plots of yield versus N remaining after volatilisation, calculated with the CN&S Utilities program for all urea treatments. In banded treatments, a width of 40 cm and a row spacing of 120 cm was used in the model, unless specified otherwise. Improvement in the linear correlation between yield and remaining N, compared with the correlation between yield and applied N was used to estimate the significance of urea-N volatilisation in the overall fertiliser N efficiency of each soil. Leaf N concentration was similarly compared in experiments FT15N/78 and FTSL2/90 to correlate sucrose yield response with plant N sufficiency. Potential NH_3 volatilisation was also calculated with the CN&S Utilities program at a standard broadcast application of urea-N on these trial soils because this would be the new laboratory index to determine suitability of soils for surface application of urea (Table 2).

Economic evaluation of ammonium sulphate and urea: the AECI trials

The decision to use urea instead of alternative N fertilisers such as LAN or ammonium sulphate is frequently based only on the listed difference in cost per unit of N at the factory. Obviously other important costs, such as transportation and application costs, and the gross profit from sucrose response to N at the current sugar price, must also be included in a more comprehensive economic assessment. This investigation used 26 sugarcane crops from a series of trials conducted in the 1960s on different soils and locations by African Explosives and Chemical Industries Ltd. (AECI) (Anon, 1967). The fertiliser division of AECI was later known as Kynoch Fertilizer (Pty) Ltd and recently (1999) merged with Norsk Hydro.

Soil information for these trials was inadequate for quantitative simulation of potential NH_3 volatilisation, but the soil parent material was used to tentatively group the trials into either high risk (H) or low risk (L) categories (Table 3). Only sucrose yield was considered because it accounts for some quality factors (sucrose concentration). Net profit was calculated on an annual basis (R/ha/y), using the sucrose yield response over the control, current sucrose price (R900 /t), crop age (Table 3), N fertiliser rate (Table 3), N content of the fertiliser (21% for ammonium sulphate; 46% for urea), fertiliser price (R750 /t for ammonium sulphate; R1130 /t for urea), fertiliser transport cost (R39.25 /t for a 60 km radius), and fertiliser application cost (R20 /ha). Mean net profit was then calculated for each group (14H, 12L), and for all 26 trials (Table 3).

Impact of limed acid soils on urea-N losses

The CN&S Utilities program was used to simulate potential NH_3 losses from a Kroonstad form soil (Table 2) over a range of increasing urea-N levels (50, 75, 100, 125, 150, 175, 200, 225, 250), and the remaining N was plotted against N applied to assess fertiliser efficiency. The simulation was repeated for broadcast, banded (40 cm), and split banded situations, both at the original soil pH (4.87), and an expected soil pH (5.87) after

Table 1. Measured and simulated ammonia volatilisation losses by surface-applied urea from studies located in the USA.

Reference	Method	Soil	pH	Clay (%)	OM (%)	Urea-N rate (kg/ha)	Temperature (°C)	Measured NH_3-N loss (%)	Simulated NH_3-N loss (%)
McInnes *et al.* (1986); Study 1	Micro-meteorological in-field	Muir silt loam	7	29	2.4	120	25	4	2
McInnes *et al.* (1986); Study 3	Micro-meteorological in-field	Haynie very fine sandy loam	6	7	0.8	120	25	17	19
Reynolds and Wolf (1987)	Laboratory	Captina silt loam	5	10	0.5	100	25	11	7

Table 2. Selected site, soil, crop and treatment information for eight nitrogen trials conducted in South Africa from 1980 to 1999.

Trial	Site	Region	Soil form	Soil pH	Clay (%)	OM (%)	Harvest age (months)	Rainfall (mm)	Crop	Treatments (kg N /ha)	NH_3 volat. test (%) for single urea rates
FT9NK/80	CFS (N, S)	North Coast	Hutton	7.9	12	0.92	16.6 (4/6/80 to 22/10/81)	1330	5th ratoon	Urea (0, 50, 100, 150, 200, 250) split, banded	13, 34, 52, 64, 73
FT9NK/80	CFS (N, S)	North Coast	Hutton	7.9	12	0.92	11.4 (22/10/81 to 5/10/82)	744	6th ratoon	Urea (0, 50, 100, 150, 200, 250) single, banded	13, 34, 52, 64, 73
FT9NK/80	CFS (N, S)	North Coast	Hutton	7.9	12	0.92	13.1 (5/10/82 to 8/11/83)	889	7th ratoon	Urea (0, 50, 100, 150, 200, 250) single, banded	13, 34, 52, 64, 73
FT15N/78	La Mercy farm	North Coast	Kroonstad	4.9	7	0.93	17.6 (2/6/83 to 20/11/84)	1771	3rd ratoon	Urea (0, 100, 150, 200) single; urea (150) split; ammonium sulphate (150) single [all banded]	4, 9, 14
N2/86/Sw	Volindi Estate	Northern irrigated (Swaziland)	D&E soil set	6.1	14	0.9	10.9 (20/10/87 to 16/9/88	not given	2nd ratoon	Urea (160) banded; banded + incorporated; broadcast; broadcast + incorporated; buried in interrow; no irrigation for 6 days after fertilising	12
FTSL 2/90	Hillhead Section, Tongaat-Hulett	North Coast	Hutton	8.4	8	1.96	15 (6/90 to 4/9/91)	1144	2nd ratoon	Liquid fertiliser (50, 100); LAN (50, 100); Urea (50, 100)	16, 40
FTSL 1/90	Hillhead Section, Tongaat-Hulett	North Coast	Milkwood	7.5	45	4.81	12 (1/9/90 to 5/9/91)	1008	8th ratoon	Liquid fertiliser (50, 100); LAN (50, 100); Urea (50, 100)	0, 1
FT24N	Kirkley-vale farm	North Coast	Cartref	4.6	13	2.06	Not harvested 12 (1/9/99 to ?/9/00)	966 (6 months)	5th ratoon	Urea, LAN (0, 90, 180) x (banded or broadcast) x (single or split); ammonium sulphate (180) single, banded	1, 3

Table 3. Available experiment details, sucrose yield, and calculated net profit from N fertiliser for 26 AECI trials comparing two N fertilisers

								Sucrose yield (t/ha/crop)			Net profit (R/ha/y)		
Trial	Year	Age (months)	SOIL	Category†	SITE	N rate (kg/ha)	CV (%)	Control	Ammonium sulphate (AS)	Urea	AS	Urea	Difference (AS-urea)
AG141H	1966	18	NGS-ord	H	Doornkop	134	19	12.3	17.9	17.8	2996	3052	-55
AG141G	1967	16	Dwyka tillite	H	Zinkwazi, Huletts	134	15	7.3	10.3	10.3	1617	1694	-77
AG142E	1967	14	Granite	H	Empangeni	134	11	11.0	19.2	16.6	5874	4026	1849
AG141B	1967	15	NGS-ord	H	Kirkleyvale, Huletts	134	10	11.9	16.8	15.8	3064	2485	579
AG142F	1966	21	Granite	H	Reynolds Bros.	134	16	11.7	13.1	13.1	437	542	-105
AG141A	1967	14	Granite	H	Glendale Sug. Co.	134	16	10.7	16.1	15.5	3766	3388	378
AG174A	1967	20	NGS-ord	H	Goble, Kemfus Gate	134	16	11.1	14.8	13.0	1693	823	870
AG142C	1965	17	Alluvium	H	South Sec., Illovo	134	15	18.9	21.2	18.3	1052	-654	1706
AG142D	1966	21	Rec. sand red	H	Bellamont, Huletts	134	20	15.7	19.4	16.2	1578	35	1542
AG142D	1967	15	Rec. sand red	H	Bellamont, Huletts	134	32	9.0	11.5	9.9	1380	385	995
AG140F	1964	11	Alluvium	H	South Sec., Illovo	134	15	12.9	16.2	15.4	2660	2025	635
AG142E	1966	18	Granite	H	Empangeni	134	13	14.8	24.0	25.4	5187	6116	-929
AG141C	1967	24	Dwyka tillite	H	Zinkwazi, Huletts	112	12	15.1	16.2	15.3	273	-82	355
AG140D	1964	11	Alluvium	H	South Sec., Illovo	134	14	6.9	8.9	8.4	1406	1057	349
										MEANS:	**2356**	**1778**	**578**
AG141Z	1966	18	Dolerite	L	Tongaat Sec.	112	18	21.4	18.1	21.6	-2270	-55	-2214
AG141F	1967	17	NGS-mist	L	Langspruit, Doornkop	134	12	6.4	11.2	9.3	2680	1575	1106
AG140E	1964	17	PMB shale	L	South Sec., Illovo	134	14	11.9	13.2	13.0	426	442	-16
AG142B	1965	22	NGS-mist	L	Doornkop	134	15	10.1	18.3	15.8	3738	2629	1109
AG141Z	1967	15	Dolerite	L	Tongaat Sec.	112	11	16.8	20.2	18.3	2107	819	1288
AG140E	1967	20	PMB shale	L	South Sec., Illovo	134	18	10.7	12.7	11.3	761	85	676
AG140C	1964	20	NGS-mist	L	Island farm,, Huletts	134	17	17.0	19.6	20.0	1088	1392	-304
AG140H	1967	24	NGS-mist	L	Windy Hill Wattle. Co.	134	15	15.4	17.9	18.0	880	1026	-146
AG140B	1966	21	NGS-mist	L	Doornkop	134	19	7.9	13.0	12.0	2350	1913	436
AG142B	1967	19	NGS-mist	L	Doornkop	134	11	9.2	16.3	15.8	3692	3515	177
AG141F	1965	21	NGS-mist	L	Langspruit, Doornkop	134	10	8.1	15.9	14.9	3720	3284	436
AG140B	1968	15	NGS-mist	L	Doornkop	134	15	7.1	14.9	13.9	5257	4646	611
										MEANS:	**2036**	**1773**	**263**
									MEANS (all categories):		**2208**	**1775**	**433**

† H= high NH_3 volatilisation risk; L = low NH_3 volatilisation risk according to soil type

corrective lime treatment. The purpose of this exercise was to estimate the impact of liming poorly buffered acid soils on surface applied urea-N losses.

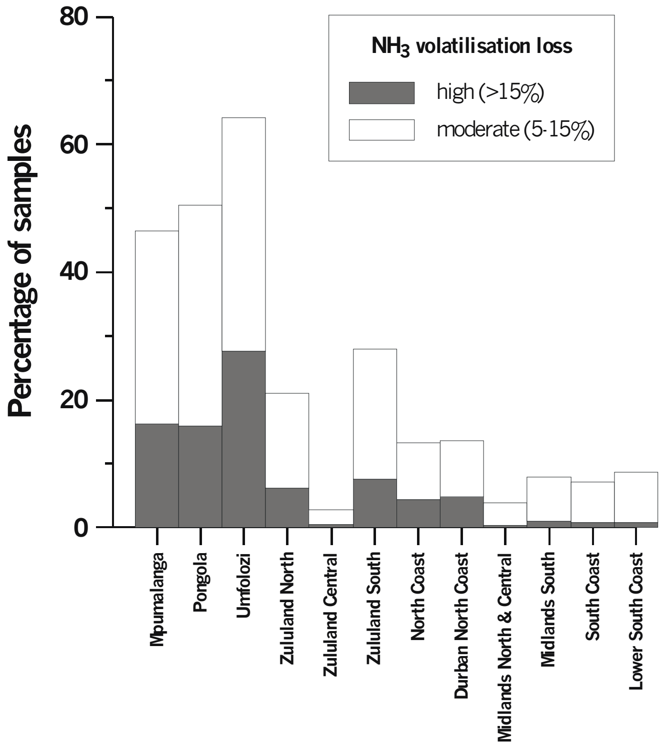

Figure 3. Relative abundance of FAS soil samples from 1980 to 1999 which are likely to encounter moderate or high NH_3 emissions from surface-applied broadcast urea in different extension regions.

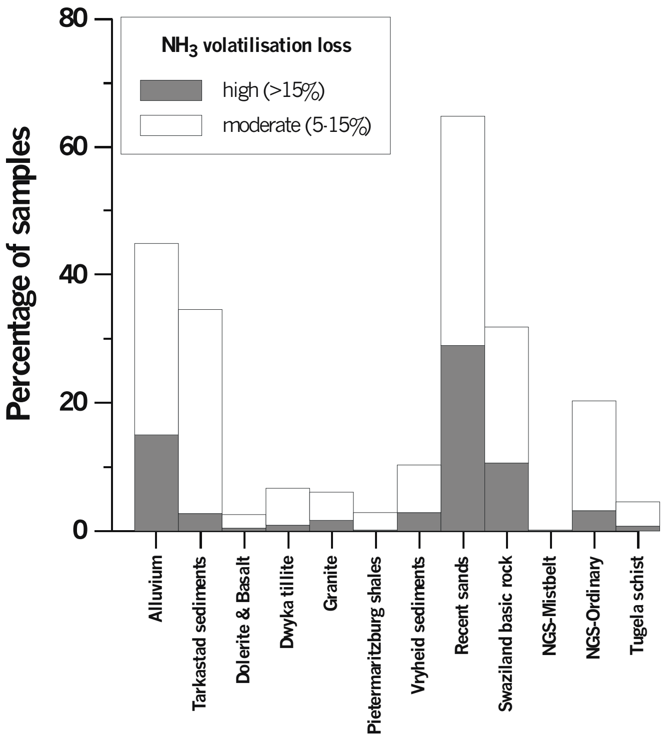

Figure 4. Relative abundance of FAS soil samples from 1980 to 1999 which are likely to encounter moderate or high NH_3 emissions from surface-applied broadcast urea on different soil parent materials

Results and Discussion

Ammonia volatilisation experiments

Agreement between simulated and measured NH_3 emissions in the three selected studies was satisfactory, demonstrating the importance of potential NH_3 volatilisation in classifying the average capabilities of a soil to volatilise a given dose of surface-applied urea (Table 1). Many environmental factors can modify the final result in practice, including wind, air humidity, sunshine hours, soil colour, temperature, rainfall and irrigation, but the simulated potential index is sufficient for decision making purposes, such as selecting management options which minimise urea-N losses.

Regional assessment of volatilisation loss from urea in South African sugarcane soils

Over all regions and soil parent materials,12% of soil samples were rated moderately susceptible to urea-N losses, and 3% were rated highly susceptible. Approximately 3 to 12% of the sugar industry soils and their sugarcane crops are therefore highly likely to benefit from a soil-specific test to determine the best N fertiliser type and management strategy. Figure 3 shows that regions most vulnerable to urea-N losses appear to be Umfolozi, Pongola, and Mpumalanga (high pH soils), followed by Zululand South, Zululand North, North Coast, and Durban North Coast (poorly buffered sandy soils). The lowest risk of urea-N losses can be expected in Midlands North and Central, and Zululand Central (acid, well buffered soils). Midlands South, and both South Coast areas show intermediate volatilisation risk, but much less than the northern regions.

Soil parent materials also showed large differences in potential urea-N losses (Figure 4). Recent sands, Alluvium, Tarkastad sediments, Swaziland basic rocks, and Natal Group sandstone [ordinary] (NGS- ord) indicated the greatest probability of low urea-N efficiencies, while NGS- mistbelt, Pietermaritzburg shales, Dolerite and Basalt were most likely to be urea-N efficient. Granite, Dwyka tillite, Vryheid sediments, and Tugela schist were intermediate (Figure 4).

Sugarcane field trials

Sucrose yield in field trials was significantly enhanced by N fertiliser (Figures 5,7,9,10,12) , with the exception of experiment FTSL1/90 (not shown). Lack of response in FTSL1/90 was attributed to high soil N mineralisation capacity (4.81 % organic matter; Table 2). Certain trends emerged from these experiments:

- on soils where N response was likely, yields were significantly lower with surface-applied urea than with the alternative surface-applied N fertilisers LAN, ammonium sulphate or liquid UAN-based formulations (Figures 7, 10, 12).
- The efficacy of urea fertiliser seemed to diminish rapidly with increasing application rates, so that the greatest differences between N fertiliser types were apparent at the highest N rate (Figures 7, 10, 12).
- Reduced fertiliser N efficiency from urea at high rates was dramatic enough to produce "false optima" in the yield versus N relationship of two trials (Figures 5 and 12).

- Closer inspection of the three ratoons from experiment FTNK/80 (Figure 5) revealed that in the one crop (7th ratoon) where urea applications were split, yields were improved by up to 25%, despite the relatively dry conditions that year (Table 2). This favourable response to urea splitting was repeated in experiments FT15N/78 (Figure 7), and FT24N (not shown).
- Placement of urea also strongly affected fertiliser efficiency and yield response. Buried urea performed better than broadcast urea, which in turn was better than banded urea (Figure 9) in experiment N2/86/Sw (Table 2) and experiment FT24N (not shown).
- In three experiments, leaf N concentrations fully supported the observed yield differences between fertiliser sources, urea splitting (Figures 8 and 11) and urea placement (FT24N, not shown), confirming that urea-N fertiliser inefficiencies were responsible.
- When urea-N volatilisation was accounted for by subtracting simulated estimates, the correlation between yield and fertiliser N improved dramatically (Figures 6,7,9,10,12), regardless of fertiliser type. Similar improvement was demonstrated in the correlation between leaf N and fertiliser N (Figures 8 and 11).
- Improvements of linear correlation (R^2) between yield and urea-N achieved by subtracting the potentially volatile NH_3 component, were positively related with the soil test index (Figure 13).

Economic evaluation of ammonium sulphate and urea: the AECI trials

Sucrose yields in the 26 sugarcane ratoon crops differed markedly, according to growing conditions at the different sites, crop age, fertiliser rate and N fertiliser type (Table 3). Net profit from N fertiliser addition however showed a fairly consistent advantage for ammonium sulphate over urea, with only one instance of a net loss from ammonium sulphate (R-2270 /ha/y) in experiment AG141Z (Table 3). Average trends looked more convincing, with an overall advantage of R433 /ha/y for ammonium sulphate over urea, despite the substantially higher N fertiliser cost. In soils of relatively higher urea-N volatilisation risk (H), the net profit margin of ammonium sulphate over urea was R578 /ha/y (Table 3). Finally, in soils considered to constitute a relatively lower risk to urea-N loss (L), the profit margin was still R263 /ha/y in favour of ammonium sulphate (Table 3). The overall maximum net profit from applying N fertiliser on all

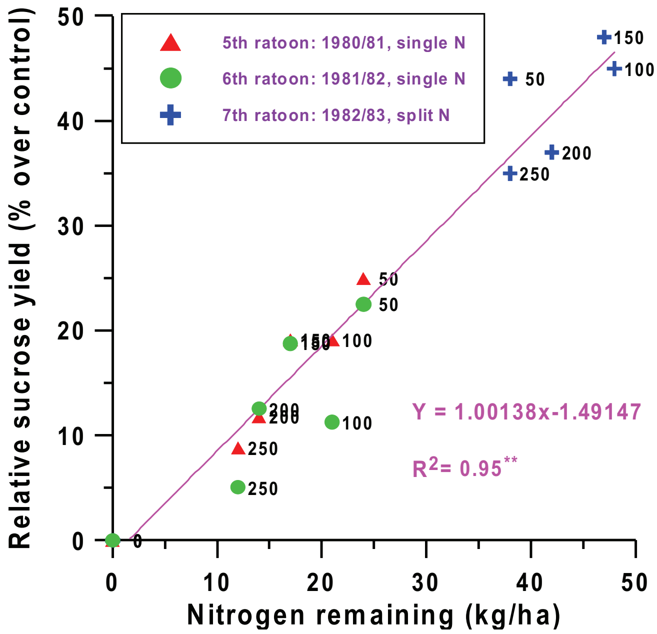

Figure 6. Relative sucrose yield response of three sugarcane ratoons in experiment FT9NK/80 to estimated urea-N fertiliser remaining after NH_3 volatilisation. Linear correlation (R^2) = 0.95.

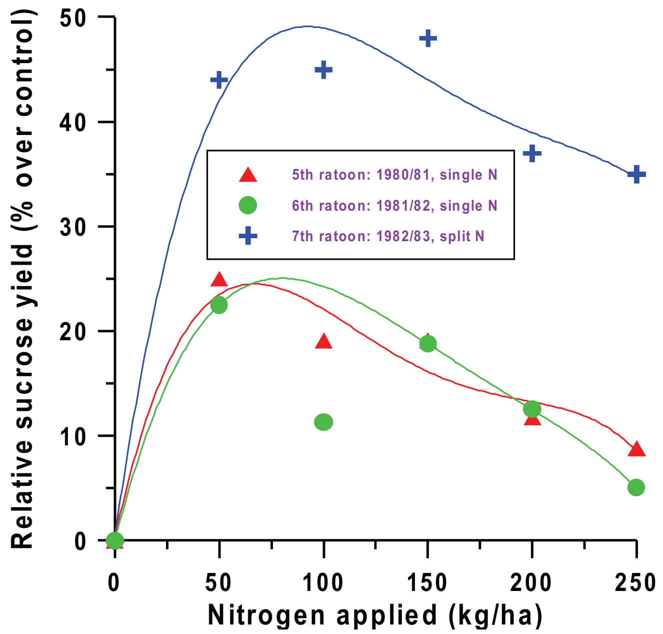

Figure 5. Relative sucrose yield response of three sugarcane ratoons in experiment FT9NK/80 to applied urea-N fertiliser, ignoring the probability of NH_3 emissions. Linear correlation (R^2) = 0.03.

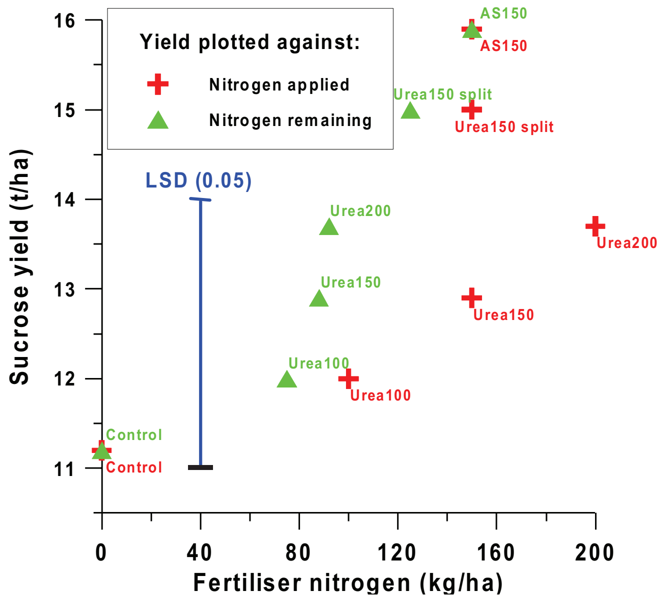

Figure 7. Sucrose yield of third ratoon sugarcane in experiment FT15N/78 at different N fertiliser treatments, without accounting for NH_3 volatilisation from urea (R^2 = 0.47), and after removing volatilised N (R^2 = 0.87).

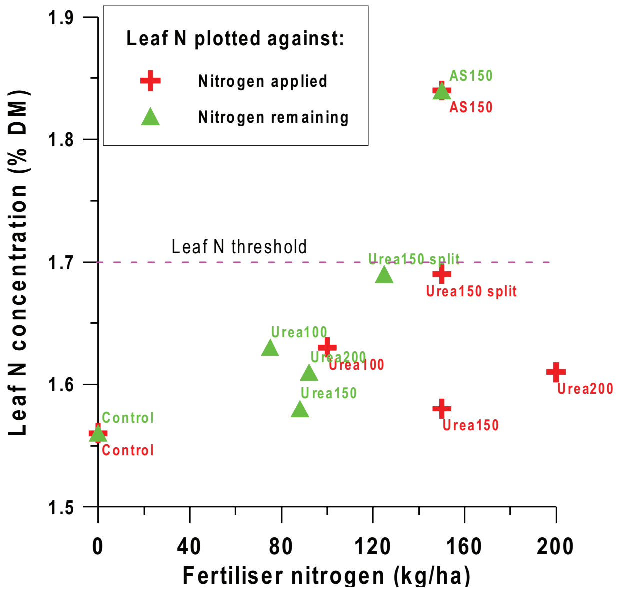

Figure 8. Leaf N concentration at 6.8 months of third ratoon sugarcane in experiment FT15N/78 at different N fertiliser treatments, without accounting for NH_3 volatilisation from urea (R^2 = 0.13), and after removing volatilised N (R^2 = 0.65).

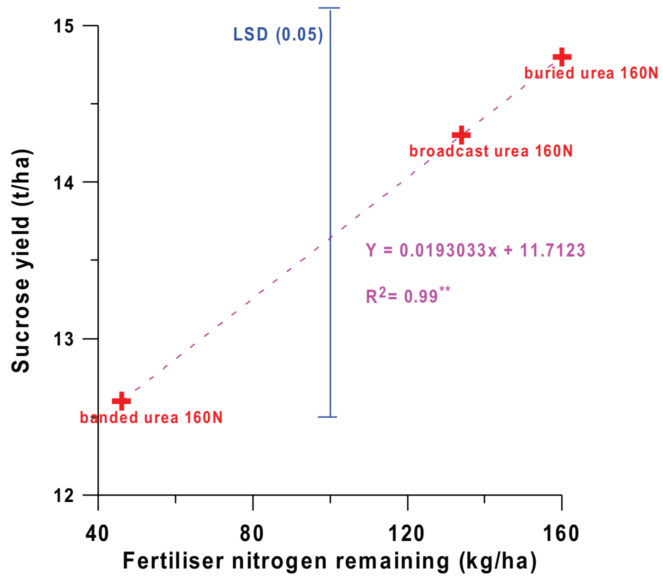

Figure 9. Sucrose yield of second ratoon sugarcane in experiment N2/86/Sw at different N fertiliser treatments, after removing volatilised N (R^2 = 0.99).

these soils was an impressive R2208 /ha/y, despite the fairly moderate fertiliser rates (112 to 134 kg N/ha).

Impact of limed acid soils on urea-N losses

Since soil pH is the most sensitive soil parameter regulating the equilibrium of ammoniacal-N in soil solution, the simulated response of urea-N losses to an increase from pH 4.87 to 5.87 by lime was significant on the sandy Kroonstad form soil (Figure 14). Many Southern African sugarcane soils fall into this category, where low clay and organic matter content, high rainfall, and rapid artificial acidification from N-fertilised monoculture necessitate periodic lime applications. Soils derived from Recent sands, NGS-ordinary, Alluvium, and Granite are particularly susceptible (Figure 4). Low buffering capacity of such soils makes them vulnerable to relatively large initial pH in-

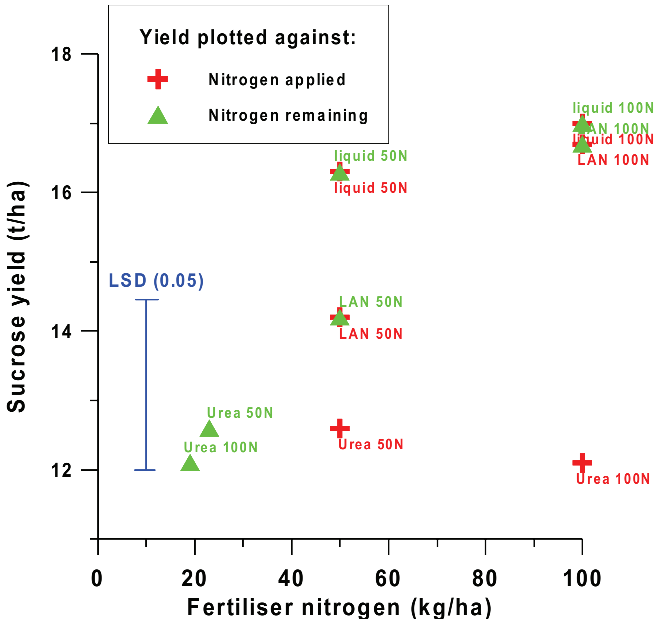

Figure 10. Sucrose yield of second ratoon sugarcane in experiment FTSL 2/90 at different N fertiliser treatments, without accounting for NH_3 volatilisation from urea (R^2 = 0.05), and after removing volatilised N (R^2 = 0.81).

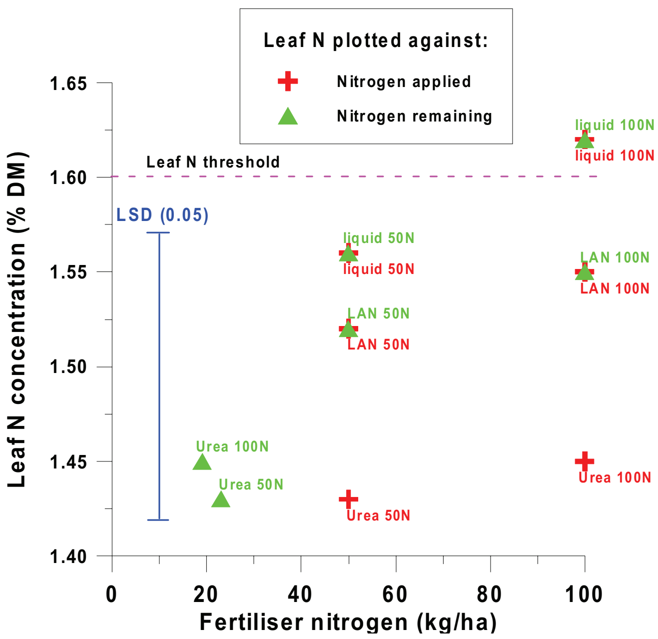

Figure 11. Leaf N concentration of second ratoon sugarcane in experiment FTSL 2/90 at different N fertiliser treatments, without accounting for NH_3 volatilisation from urea (R^2 = 0.01), and after removing volatilised N (R^2 = 0.75).

creases after liming, which in turn can dramatically reduce the efficiency of surface-applied urea, especially in single banded doses (Figure 14).

Conclusions

The satisfactory performance of the new soil test for urea was shown on a number of soils, seasons and sites. While the method is clearly confined only to "potential" urea-N losses by NH_3 volatilisation, it is fortuitous that other important N fertiliser loss mechanisms such as leaching and denitrification are highly probable in the same soils as those where NH_3

volatilisation is predicted. This implies that overall N fertiliser use efficiency is low on such soils, but that urea will be worst affected because it alone undergoes significant volatilisation losses on acid soils.

The calibrated simulation model developed from the soil test can correctly predict the relative increases in urea-N losses which occur from increasing surface-applied urea rates, and is also able to estimate the increased volatilisation loss from band-applied fertiliser or decreased loss from split application. Useful comparisons between the different N sources can therefore be simulated over different soils, allowing selection of the best management practice for urea or an alternative N fertiliser. Results presented in this paper clearly show that because losses of urea-N on certain sandy soils can exceed 50%, further increases of applied urea to rectify the situation tend to promote increased N losses and this alone cannot solve the problem of inadequate N supply.

The profitability of N fertilisation for sugarcane, and of using more expensive alternatives to urea, or using more expensive management options where indicated by the soil test, should no longer be in doubt. At today's sugar price (R900 /t) and fertiliser prices, a sucrose yield advantage of only 0.2 t/ha is required to justify using the more expensive LAN or ammonium sulphate fertiliser rather than the cheaper urea. Splitting, broadcasting or burying of urea is even more readily justified. Tentative thresholds for the soil index to be applied immediately in the FAS laboratory are:

- >15% - change from urea to a different N source such as LAN. Ammonium sulphate can be recommended where S is needed or where mild soil acidification is desirable, but definitely not on acid sandy soils.
- 5 to 15% - improve urea-N efficiency by adopting the best possible management practice.
- <5% - no special advice given for the use of urea, which is the preferred source.

In green-harvested cane, special efforts should be made to incorporate urea, as described below. Where N fertiliser can only be applied onto cane trash, urea should be avoided and LAN or ammonium sulphate would be preferable.

Possible best management practices for urea (at least one should be selected), in approximate order of importance are:

- burying the urea to a depth of about 7.5 cm
- incorporating the urea with immediate irrigation of ~25 mm
- splitting the N application
- applying dissolved urea in solution with KCl and P fertilisers. Dissolved urea alone does not usually have much benefit, but the benefits of KCl and other salts on inhibiting volatilisation are well documented (Anderson, 1962; Hagihara and Hilton, 1987; Kong et al., 1991)
- broadcasting rather than banding the fertiliser on the soil surface

The potential impact of maintenance liming on urea losses in poorly buffered (coastal) acid soils was demonstrated. Shallow

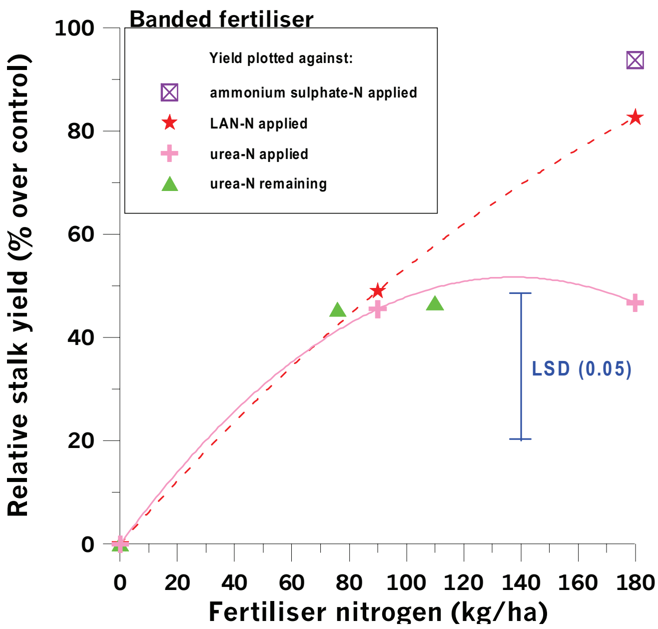

Figure 12. Relative sugarcane yield of experiment FT24N at six months using three N fertiliser sources, without accounting for NH_3 volatilisation from urea (R^2 = 0.76), and after removing volatilised N (R^2 = 0.96).

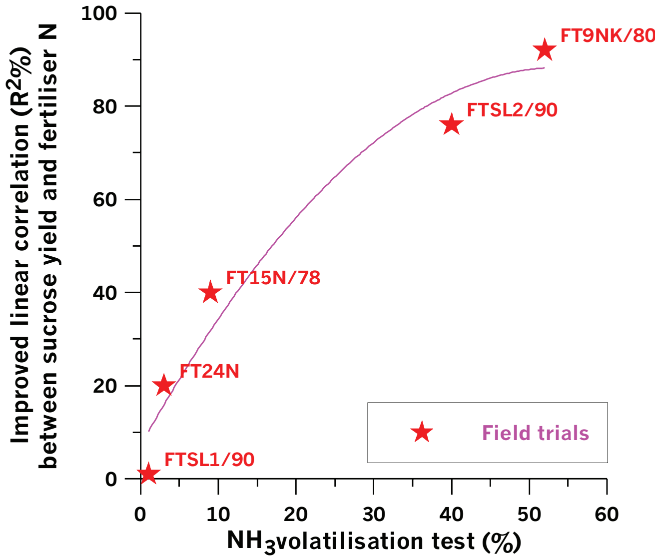

Figure 13. Relationship between the improved linear regression (R^2 %) describing yield-N correlations when estimated N losses are accounted for, and the new soil test for urea-N volatilisation.

liming of ratoon crops is particularly risky if urea is to be used. It may be safest to recommend LAN for the first crop after liming.

The new soil test developed at SASEX and implemented in the FAS laboratory will permit field-specific advice on correct choice, rates and management for N fertiliser to growers. Historic soil data show that up to 25% of Grower soils in some extension areas and 3% overall would benefit from the use of LAN or ammonium sulphate instead of urea, while on average, up to 12% of Grower soils would benefit from best management practices for urea.

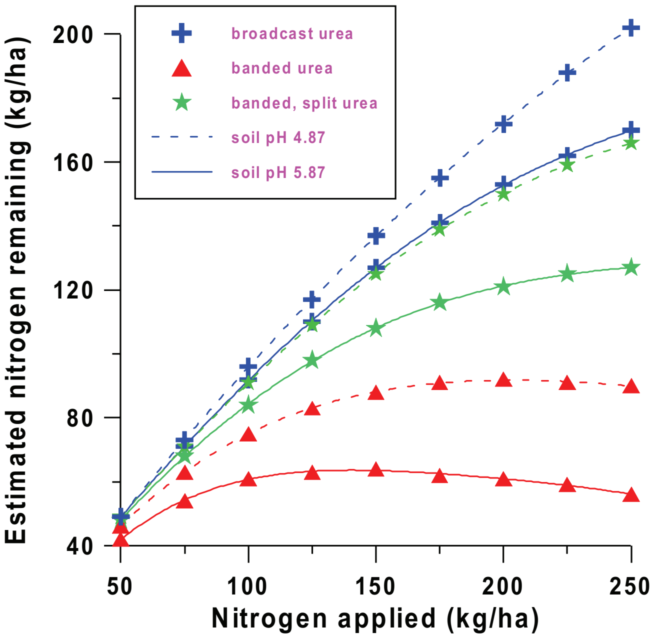

Figure 14. Estimated fertiliser N efficiency after simulated NH_3 volatilisation on a Kroonstad soil (experiment FT15N/78) from surface-applied urea, before or after liming to pH 5.87.

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