

**AMMONIA VOLATILIZATION AND N-UPTAKE FROM UREA, UREA
AMMONIUM NITRATE (UAN) AND NITAMIN® (UREA-POLYMER)
APPLIED TO TALL FESCUE IN GEORGIA**

by

NICOLAS VAIO

(Under the Direction of Miguel L. Cabrera)

ABSTRACT

The use of urea-based fertilizers for grasslands in the southeastern U.S.A. is likely to increase as restrictions on animal manure applications are implemented. Surface application of these fertilizers commonly leads to gaseous losses of nitrogen (N), which results in low N recovery by plants. Thus, there is a need to improve the efficiency of urea-based fertilizers through new technologies, such as slow-release fertilizers. In this study, Nitamin® (slow-release urea-polymer), UAN (urea ammonium nitrate), and granular urea were tested for NH₃ volatilization losses. In addition, Nitamin® and UAN were evaluated for N use efficiency with respect to ammonium nitrate (AN). On average, urea lost significantly more ($p < 0.05$) NH₃ (25% of applied N) than UAN and Nitamin® (18%) under field and laboratory conditions. In addition, Nitamin® and UAN, were approximately 70% as effective as AN in promoting tall fescue N uptake.

INDEX WORDS: Urea-based fertilizers, Ammonia volatilization, Grasslands, Fertilizer, Nitamin®, Urea, Ammonium nitrate, Nitrogen uptake, Slow-release.

**AMMONIA VOLATILIZATION AND N-UPTAKE FROM UREA, UREA
AMMONIUM NITRATE (UAN) AND NITAMIN® (UREA-POLYMER)
APPLIED TO TALL FESCUE IN GEORGIA**

by

NICOLAS VAIO

Bs. Agronomy, Universidad Nacional de La Plata, 2002

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial
Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2006

© 2006

Nicolas Vaio

All Rights Reserved

**AMMONIA VOLATILIZATION AND N-UPTAKE FROM UREA, UREA
AMMONIUM NITRATE (UAN) AND NITAMIN® (UREA-POLYMER)
APPLIED TO TALL FESCUE IN GEORGIA**

by

NICOLAS VAIO

Major Professor: Miguel L. Cabrera

Committee: David E. Kissel

John G. Andrae

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
December 2006

DEDICATION

I would like to dedicate this thesis to my wife, family, friends, professors and all those people who were important in my life and education.

ACKNOWLEDGEMENTS

First of all, I would like to thank my committee of Drs. Miguel L. Cabrera, David E. Kissel, and John Andrae for helping me in my research, particularly Miguel for his permanent support and dedication during my time in the U.S. Also I would like to thank Mabel Elena Vazquez, for being the professor in Argentina who taught most of the important concepts of soil sciences. In addition, I would like to thank the staff of the Central Research and Education Center in Eatonton, especially Frank Newsome for his technical and spiritual support, Gerald Cathey, and Vaughn Calvert. I would like to thank my wife Carla for her support and patience, John A. Rema and the whole Rema family for being my family in the U.S., Dave Butler for his friendship and finally my parents for their trust and support.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	v
LIST OF TABLES.....	vii
LIST OF FIGURES.....	viii
INTRODUCTION	1
CHAPTERS	
1. LITERATURE REVIEW	3
2. AMMONIA VOLATILIZATION FROM NITAMIN® (UREA-POLYMER), UAN (UREA-AMMONIUM NITRATE), AND UREA APPLIED TO TALL FESCUE IN GEORGIA	19
3. EVALUATION OF THE AMMONIUM NITRATE EQUIVALENT VALUE OF UREA-POLYMER (NITAMIN®) AND UREA-AMMONIUM NITRATE (UAN) FOR TALL FESCUE PASTURES IN GEORGIA.....	44
4. CONCLUSIONS AND IMPLICATIONS.....	60
5. APPENDICES.....	61
A) DATA OF AMMONIA VOLATILIZATION STUDY UNDER FIELD CONDITIONS.....	62
B) DATA OF AMMONIA VOLATILIZATION STUDY UNDER LABORATORY CONDITIONS.....	64
C) DATA OF PLANT N UPTAKE STUDY.....	65

LIST OF TABLES

	Page
Table 2. 1. Total ammonia loss from urea-based fertilizers (Urea, UAN and Nitamin®) applied to tall fescue plots at 50 kg N ha ⁻¹ in fall 2004 (120 d), spring 2005 (69 d), fall 2005 (75 d), and spring 2006 (83 d).....	35
Table 3. 1. Fertilizer recovery for AN, UAN, and Nitamin® surface-applied to tall fescue plots in fall 2004, spring 2005, fall 2005, and spring 2006.....	54
Table 3. 2. Ammonium nitrate equivalent value of urea-based fertilizers (UAN and Nitamin®) applied to tall fescue plots in fall 2004, spring 2005, fall 2005, and spring 2006.....	55

LIST OF FIGURES

	Page
Figure 2. 1: a) Cumulative NH ₃ loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to tall fescue plots at 50 kg N ha ⁻¹ in fall 2004 (120 d) (bars are standard errors); b) Rainfall, relative humidity, critical relative humidity, and soil water content; and c) air temperature and wind speed measured during the experiment.....	36
Figure 2. 2: a) Cumulative NH ₃ loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to tall fescue plots at 50 kg N ha ⁻¹ in spring 2005 (69 d) (bars are standard errors); b) Rainfall, vapor pressure, and soil water content, and; c) air temperature and wind speed measured during the experiment.....	37
Figure 2. 3: a) Cumulative NH ₃ loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to tall fescue plots at 50 kg N ha ⁻¹ in fall 2005 (75 d) (bars are standard errors); b) Rainfall, vapor pressure, and soil water content, and; c) air temperature and wind speed measured during the experiment.....	38
Figure 2. 4: a) Cumulative NH ₃ loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to tall fescue plots at 50 kg N ha ⁻¹ in spring 2006 (84 d) (bars are standard errors); b) Rainfall, vapor pressure, and soil water content, and; c) air temperature and wind speed measured during the experiment.....	39

- Figure 2. 5. a) Cumulative NH_3 loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to fescue thatch at 100 kg N ha^{-1} in an 8-mo incubation study (bars are standard deviations); and b) Relative humidity (%), Critical relative humidity (%) during the first 30 d. Values followed by different letters are significantly different according to Fisher's LSD at $p=0.05$40
- Figure 2. 6. Daily time during which relative humidity was above urea's critical relative humidity during the first 30 d after fertilizer application for a) fall 2004, b) spring 2005, c) fall 2005, and d) spring 2006.....41
- Figure 2. 7. Nitrogen concentrations in lysimeters samples from plots treated with Nitamin®, urea, or UAN (a, b, and c) and rainfall and average soil water content (d) for spring 2005 (S05), fall 2005 (F05), and spring 2006 (S06) applications.....42
- Figure 2. 8. Average concentration of total N, nitrate-N, and ammonium-N in lysimeters samples taken from plots treated with Nitamin®, urea, or UAN in spring 2005, fall 2005, and spring 2006. Values followed by different letters are significantly different according to Fisher's LSD at $p=0.05$43
- Figure 3. 1. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) Surface-applied at 0, 35, and 70 kg N ha^{-1} , and from AN surface-applied at 0, 25, 50, and 100 kg N ha^{-1} to tall fescue plots in fall 2004.....56
- Figure 3. 2. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface-applied at 0, 35, and 70 kg N ha^{-1} , and from AN surface-applied at 0, 25, 50, and 100 kg N ha^{-1} to tall fescue plots in spring 2005.....57

Figure 3. 3. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface-applied at 0, 70, and 140 kg N ha⁻¹, and from AN surface-applied at 0, 50, 100, and 200 kg N ha⁻¹ to tall fescue plots in fall 2005.....58

Figure 3. 4. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface-applied at 0, 70, and 140 kg N ha⁻¹, and from AN surface-applied at 0, 50, 100, and 200 kg N ha⁻¹ to tall fescue plots in spring 2006.....59

INTRODUCTION

The use of urea and urea-based fertilizers has increased considerably over the past 15 years, currently accounting for approximately 51% of the world's agricultural N consumption. Urea is not only the solid fertilizer with the largest percentage of nitrogen at the present (Anonymous, 2006), but also is one of the least expensive sources of N for crop production.

Concerns have been raised about the economic and environmental impacts of ammonia (NH_3) loss through volatilization when urea-base fertilizers are surface applied. Ammonia losses from urea broadcast on pastures have been reported to be as high as 29% of the N applied (Eckard et al., 2003). Volatilized NH_3 is able to travel hundreds of kilometers from the site of origin and even low levels of NH_3 in the atmosphere can produce significant respiratory and cardiovascular problems (Gay and Knowlton, 2005).

Urea is an organic fertilizer that needs to be hydrolyzed by the enzyme urease before NH_3 can be volatilized. This hydrolysis of urea can be rapid under certain environmental conditions (Black et al., 1987).

Georgia Pacific Corporation has developed an alternative slow-release, urea-based fertilizer that has potential to reduce the amount of N loss through volatilization. This alternative fertilizer is a liquid urea polymer (Nitamin®) in which about 30% of the N is in the form of urea and 70% in the form of polymer-compounds. Theoretically, the polymer increases the number of bonds that urease must hydrolyze urea, decreasing the rate of conditions bore NH

applied on tall fescue *Lolium arundinaceum* (Schreb.) Darbysh. and (2) to evaluate the fertilizer equivalent value of Nitamin® and UAN for tall fescue when compared to ammonium nitrate (AN). UAN was compared to Nitamin®, because it is the most common liquid commercial source of N used for tall fescue in Georgia and ammonium nitrate was used as a reference because it does not undergo NH₃ losses.

References

- Anonymous. 2006. International fertilizer industry association [Online]. Available at www.fertilizer.org (accessed 29 August 2006) IFA, International Fertilizer Industry Association.
- Black, A.S., R.R. Sherlock, and N.P. Smith. 1987. Effect of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture-content. *J Soil. Sci.* 38:679-687.
- Eckard, R.J., D. Chen, R.E. White, and D.F. Chapman. 2003. Gaseous nitrogen loss from temperate perennial grass and clover dairy pastures in south-eastern Australia. *Aust. J. Agric. Res.* 54:561-570.
- Gay, S.W., and K.F. Knowlton. 2005. Ammonia emissions and animal agriculture [Online]. Online at www.ext.vt.edu/pubs/bse/442-110/442-110 (accessed 28 October 2006) Virginia Tech Cooperative Extension.

CHAPTER 1

LITERATURE REVIEW

Urea and urea-based fertilizers are extensively used in grasslands of the southeastern U.S.A. Urea-based fertilizers are generally chosen over other nitrogen (N) fertilizers because they are one of the most inexpensive sources of N and have a high N concentration. However, surface application of urea-based fertilizers on grasslands commonly leads to gaseous losses of N through ammonia (NH_3) volatilization.

Agriculture is the major source of NH_3 emission to the atmosphere, contributing 90% of the total emission in western Europe, according to recent estimates (Bussink and Oenema, 1998). Mahler and Hamid (1994) measured losses of NH_3 close to 30% of the total N applied when urea was surface applied to two northern Idaho soils, and Lightner et al. (1990) reported losses of 41% of the total applied N when granular urea was surface-applied to orchardgrass sod in West Lafayette, Indiana.

Ammonia volatilization is important for both agricultural and non-agricultural ecosystems because it is a direct loss of plant available N to farmers, and because it contributes to eutrophication in aquatic and low N input ecosystems through atmospheric transport and deposition (Asman et al., 1994).

Although several studies have been published on NH_3 volatilization losses from urea and urea-based fertilizers worldwide, there is a lack of information on NH_3 volatilization losses from urea-based fertilizers applied on tall fescue *Lolium arundinaceum* (Schreb.) Darbysh. grasslands in the southeastern U.S.

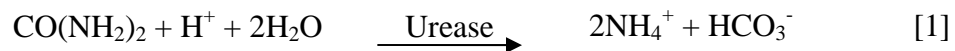
Process of Ammonia Volatilization from Urea

The process of NH_3 volatilization from urea could be divided into two steps. The first one is the hydrolysis of urea by the urease enzyme. The product of urea hydrolysis is ammonium (NH_4^+) that can remain in the soil solution or be retained by the soil. The second step is the chemical change from NH_4^+ in the soil solution to aqueous NH_3 [$\text{NH}_{3(\text{aq})}$], which in turn can diffuse from the soil solution to the atmosphere giving rise to NH_3 volatilization.

Urea Hydrolysis

The origin of urease enzyme is associated with two sources: saprophytic microorganisms and some plants. Frankenberger and Tabatabai (1985) found urease activity in 21 air-dried plant species and reported that graminaceous plants exhibited high urease activity. Most of the studies suggest that as organic matter increases, such as in no-tilled soils, urease activity increases (Kheyrodin and Antoun, 2002). Also saprophytic microorganisms that exist in the soil can colonize crop residues increasing their urease activity (Hartel et al., 2005).

Urease is a nickel-containing enzyme (Fidaleo and Lavecchia, 2003) that can be classified as an extracellular enzyme (Klose and Tabatabai, 1998). Extracellular enzymes can be present in the soil solution, associated with organic-mineral compounds in the soil, or adsorbed onto clay surfaces that stabilize the enzyme against degradation (Hartel et al., 2005). The urease enzyme needs to be present and active to produce the hydrolysis of urea. The common urea hydrolysis reaction is as follows:



There are four major factors that affect the hydrolysis of urea: 1) soil water content, 2) temperature, 3) pH and 4) urea concentration.

1) Effect of soil water content on urea hydrolysis

Soil water content is one of the most important factors affecting the rate of urea hydrolysis. Because urea is a hygroscopic material, it can absorb water not only through contact with liquid water but also from the water-vapor in the air (Wahl et al., 2006). After granular urea is applied to the soil, the process of dissolution of urea starts almost immediately, because urea is a compound highly soluble in water (about 1080 g L⁻¹ can be dissolved at 20°C, Wahl et al., 2006). The solubility of urea increases as temperature increases (Wahl et al., 2006).

Black et al. (1987) found that when urea was applied to air-dry soil (0.06 g H₂O/g) the hydrolysis was slow and about 73± 14% of the urea remained 30 d after application. On the other hand, when urea was applied to a soil at field capacity, all of the urea was hydrolyzed four days after application. In addition, Vlek and Carter (1983) found that urease activity is generally greater near field capacity and declines as soil moisture decreases, but is still significant at the permanent wilting point. Finally, Yadav et al. (1987) found that the urea hydrolysis rate was not a linear function of moisture content. When expressed as a percentage of field capacity (FC) the rate of hydrolysis in the two soils used (sandy loam and clay loam) followed the order: 20% FC < 40% FC < 80% FC = 100% FC. In addition Yadav et al. (1987) reported that the added urea was completely hydrolyzed in 3 d at all moisture regimes except 20% FC.

2) *Effect of temperature on urea hydrolysis*

Temperature is an important factor affecting the process of urea hydrolysis.

Temperature can affect the rate of dissolution of a urea granule in water. Wahl et al. (2006) reported that as temperature increases the rate of dissolution of urea in water increases. In addition, Sadeghi et al. (1989) showed that urea hydrolysis is accelerated by increasing temperature in part because the rate of urea diffusion is positively correlated with temperature. A faster diffusion rate increases the rate of movement of urea toward the urease enzyme.

Furthermore, because urease is an extracellular enzyme produced by microorganisms, high temperatures can increase microorganism growth and urease production. Moyo et al. (1989) found that increasing temperature from 5 to 45 °C greatly increased urease activity. They also found that the mean energy of activation (E_a) for soil urease was about 51.5 kJ mol⁻¹. This value corresponds to a Q_{10} of approximately 2, which indicates that reaction rates of urea hydrolysis double for every 10 °C rise in temperature. Yadav et al. (1987) reported that the amount of urea remaining after 12 h of incubation was 64% at 10 °C and 27% at 35 °C. In addition, Lai and Tabatabai (1992) found that urease activity increases with temperature and reaches a maximum between 60 and 70 °C.

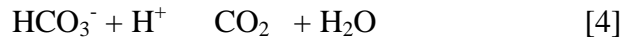
3) *Effect of pH on urea hydrolysis*

Soil pH is another major factor that can affect the rate of urea hydrolysis. The products of urea hydrolysis are NH_4^+ and one or more inorganic carbon (C) species depending on the soil pH. In a soil of near neutral pH the predominant C species will be HCO_3^- , whereas in a soil where $\text{pH} < 6.3$ the predominant C species will be H_2CO_3 (Ferguson et al., 1984).

The urea hydrolysis reactions can be represented as follows:



The HCO_3^- produced in equation [2] can react with another H^+ to maintain a chemical equilibrium in the system (Ferguson et al., 1984).



In most agricultural soils ($\text{pH} < 6.3$), the hydrolysis of urea is a process that consumes two protons for each mole of urea hydrolyzed. Therefore this reaction tends to increase the pH of the area surrounding the urea fertilizer, in turn causing an increase in the rate of urea hydrolysis (Ferguson et al., 1984).

Longo and Melo (2005) measured the rate of urea hydrolysis under laboratory conditions using a range of soil pH from 2.2 to 8.0. They found that as the soil pH increases the rate of urea hydrolysis increases almost exponentially. In addition, they found that the highest rate of urea hydrolysis was at pH 8.0. Similar results were found by Cabrera et al. (1991) where the rate of urea hydrolysis increased until a pH of 9.5.

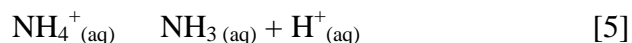
4) *Effect of urea concentration on urea hydrolysis*

Many studies have demonstrated that urea hydrolysis follows simple Michaelis-Menten kinetics, where an increase in substrate concentration increases the reaction rate until a concentration sufficient to saturate the enzyme is reached (Tabatabai and Bremner, 1972; Dalal, 1975). When urea fertilizers are applied to the soil, the concentration of the urea solution may range from very low at some distance from the granule or site of application to very high at the surface of the prill or centered at the application site. Cabrera et al. (1991) measured the hydrolysis of urea at urea concentrations ranging from

0.01 to 10 M. They found the possible existence of two reactions, one with high affinity and one with low affinity for urea. While the high affinity reaction was responsible for most of the hydrolysis at urea concentration lower than 0.1 M, its contribution at 8 M was smaller. In general, the urea-N concentration at which low and high affinity enzyme reactions contribute equally is 0.5 M. In addition, Cabrera et al. (1991) found that when urea concentration is > 6 M the rate of urea hydrolysis decreases, possible due to enzyme denaturation or substrate inhibition (Kistiakowsky and Rosenberg, 1952).

Ammonia Volatilization

After the process of urea hydrolysis has been completed, the NH_4^+ produced in the soil can follow different pathways, one of them being NH_3 volatilization. Ammonium derived from urea can be transformed to $\text{NH}_{3(\text{aq})}$, which can remain dissolved in the soil solution, or it can be lost to the atmosphere by the process of NH_3 volatilization. The total ammoniacal N in aqueous solution consists of two principal forms, NH_4^+ and $\text{NH}_{3(\text{aq})}$. The chemical equilibrium between these two forms is pH- and temperature-dependent (Körner et al., 2001), and can be described by the following equation:

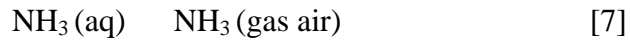


A substantial fraction of ammoniacal N remains in the NH_4^+ form in solution or adsorbed to the soil colloids. A quantitative indication of this strength is given by its base ionization constant (Clegg and Whitfield, 1995). The stoichiometric (or apparent) dissociation constant of NH_4^+ includes the value of the various activity coefficients and is defined according to the following equation:

$$K_a = (m \text{NH}_3)(m \text{H}^+) / (m \text{NH}_4^+) = 1.75 \times 10^{-5} \text{ at } 25^\circ\text{C} \quad [6]$$

where K_a (mol kg^{-1}) is the thermodynamic acid dissociation constant of the NH_4^+ , and m denotes molality (moles of solute per kg of pure water).

Once $\text{NH}_{3(\text{aq})}$ is present in the soil solution, the physical process of NH_3 transfer across a water surface in contact with the atmosphere is described by the simple reaction.



This process tends to restore the thermodynamic equilibrium, which is reached when the chemical potential (or fugacity) of NH_3 is equal in both phases (aqueous –air). This transfer basically depends on the bulk concentrations of $\text{NH}_{3(\text{aq})}$ in the water and NH_3 in the air, and is explained by Henry's law. According to Henry's law, the equilibrium ratio

measured the effect of soil pH on NH_3 volatilization losses when urea was uniformly surface applied at a rate of 200 mg N kg^{-1} . They found that NH_3 volatilization was minimal at pH 3.5 and maximum at pH 8.5.

Hydrogen ion (H^+) buffering capacity is another soil property that can affect NH_3 volatilization losses. Buffering capacity is defined as the ability of the soil to resist changes in pH. The H^+ buffering capacity of a soil is determined by its soil minerals and organic matter content, among other soil properties (Meisinger and Jokela, 2000). The ability of the soil to resist an increase in pH during urea hydrolysis affects the amount of NH_3 loss due to its effect on the ratio of NH_3 to NH_4^+ (Avnimelech and Laher, 1977). A soil with more H^+ supplying ability than another will have less potential for NH_3 volatilization provided all the other factors are equal (Ferguson et al., 1984). Ferguson et al. (1984) measured the effect of H^+ buffering capacity on NH_3 volatilization losses in two different soils, and they found that when soils were amended with a resin that increased the H^+ buffering capacity, the amount of N lost through volatilization was smaller compared to unamended soil.

2) *Effect of temperature on NH_3 volatilization*

Temperature is another major factor that can affect the rate of N loss through volatilization. The rate of NH_3 volatilization increases as the temperature increases (Olesen and Sommer, 1993). Temperature has a triple effect on the process of NH_3 volatilization. High temperature not only can increase urease activity and thus, NH_4^+ and OH^- in the soil solution (Lai and Tabatabai, 1992), but also can increase the conversion of NH_4^+ to NH_3 and the diffusion of NH_3 from the aqueous phase to the air phase increasing the process of volatilization (Sander, 1999). Staudinger and Robers (2001)

found that Henry's constant (K_H) is temperature dependent. Therefore, as temperature increases by 10 °C the diffusion of NH_3 from the aqueous phase to the air phase increases by a factor of 1.88 (an 88% increase).

McGarry et al. (1987) measured the effect of three soil temperatures (8°, 13° and 18°C) on NH_3 volatilization when a solution of urea was surface applied on pastures. They found that NH_3 losses increased with an increase in temperature.

Even though high temperatures have been shown to increase NH_3 volatilization losses, Steenhuis et al. (1979) found that NH_3 losses do not stop at near-freezing temperatures. Losses near freezing can occur because a lower, but still substantial rate, of volatilization occurs for a longer period of time (Sommer and Olesen, 1991).

3) Effect of cation exchange capacity (CEC) on NH_3 volatilization

The cation exchange capacity (CEC) of a soil is the amount of positively charged ions a soil can hold. Generally, texture is an important indicator of CEC and the greater the clay content and organic matter content, the greater the CEC of the soil (Havlin et al., 1998). A high CEC can reduce NH_3 loss principally by two ways: by restricting the pH changes or increasing the buffering capacity and by increasing the adsorption of NH_4^+ produced after the process of urea-hydrolysis is completed.

Ahmed et al. (2006) conducted a laboratory study showing the differences on NH_3 volatilization losses when urea-fertilizer was mixed with triple superphosphate (TSP), humic acid and zeolite materials having the property to enhance soil CEC. The results indicate that applying urea with humic acid and zeolite significantly reduces NH_3 volatilization losses from 48 to 18% of the total applied N when compared to urea without additives. In summary, the decreased loss of NH_3 from surface applied urea in

soils with high CEC is possibly due to a lower formation of NH_3 over NH_4^+ , a greater buffering capacity, and a greater retention of NH_4^+ ion within the soil (Ahmed et al., 2006).

4) *Effect of soil water content and rainfall on NH_3 volatilization*

Ammonia volatilization after surface application of urea is influenced by soil water content or water potential. Soil water content influences first the dissolution of urea applied in granular form, then the movement of urea into the soil, the urea hydrolysis process, and finally the movement of urea hydrolysis products into the soil (Ferguson and Kissel, 1986). Vlek and Carter (1983) suggest that at low water contents, the lack of free water in the soil might inhibit diffusion of urea, limiting the contact between urea and soil urease and causing a decrease in urea hydrolysis.

Soil water content is strongly influenced by rainfall events. Craig and Wollum (1982) found that if a light rainfall (< 15 mm) occurs and it is sufficient to moisten the soil but not leach urea to any substantial depth, NH_3 volatilization increases, most likely because an increase in the rate of urea hydrolysis. Van Der Weerden and Jarvis (1998) reported that the NH_3 emission after urea application was affected by 14 mm of rainfall, but because this event occurred 3 d after fertilizer application total losses were still about 20% of the total applied N. This was probably due to most of the urea being hydrolyzed in the first 3 d following application. Mugasha and Pluth (1995) found, in an forest study, that NH_3 volatilization losses decreased to background levels after 40 mm of rain that occurred 9 d after urea was surface applied. In addition, Bussink and Oenema (1996) reported reductions of NH_3 losses with 9 mm of rain following applications.

In a study conducted in a loblolly pine forest, Kissel et al. (2004) found that NH_3 volatilization losses increased after 4, 11 and 40 mm of simulated rainfall was applied 4 to 5 d after urea application. In contrast, simulated rainfall applied immediately after urea application reduced NH_3 volatilization losses to <1% of the applied urea. In a follow-up study, Cabrera et al. (2005) found that rain received after urea is dissolved on the forest floor increases NH_3 volatilization because it enhances the hydrolysis of urea that diffuse into pine needles after dissolution.

In summary, the effect of rainfall on NH_3 volatilization losses is not totally clear by the present studies. Ammonia volatilization losses may be more influenced by the intensity of rainfall than by the amount of rainfall, but additional studies are needed to verify this hypothesis.

5) *Effect of wind speed on NH_3 volatilization.*

Greater wind speeds contribute to higher NH_3 losses by increasing mass transfer and air exchange between the NH_3 in the soil surface and the NH_3 in the atmosphere. The effect of wind speed on NH_3 volatilization was clearly demonstrated by Fillery et al. (1984), who found that the rate of NH_3 loss from a flooded rice (*Oryza sativa* L.) field increased linearly with wind speed over the range of 0 to 8 m s^{-1} .

Thompson et al. (1990) found that wind speed had a positive effect on NH_3 volatilization, although the effect was small in relation to the total loss; increasing the wind speed from 0.5 to 3.0 m s^{-1} increased the total 5-d loss by a factor of 0.29. In this experiment, the effect of wind speed was also most pronounced in the first 24 h when much of the NH_3 loss took place. Sommer and Ersbøll, (1994) measured NH_3 volatilization from surface-applied urea, diammonium phosphate (DAP), and calcium

ammonium nitrate (CAN) using chambers through which air was drawn continuously. They found that NH_3 losses were related to the air flow rate. They estimated the transfer coefficient increased exponentially with the flow rate. At a flow rate above 3.9 L min^{-1} (20 volume exchanges min^{-1}) no further increase in NH_3 volatilization was observed.

Ammonia Volatilization from Urea-based Fertilizers Applied to Grasslands

Nitrogen loss through NH_3 volatilization from surface-applied, urea-based fertilizers is a potential problem affecting fertilizer efficiency. The reduction in the efficiency of N fertilizer due to NH_3 volatilization is a major concern in areas such as the north-central United States, where approximately 50% of the N fertilizer used is applied as urea or urea-based solutions (Berry and Hargett, 1990). However, little information is available on the extent of NH_3 volatilization from surface-applied urea-based fertilizers on grasslands under humid temperate climatic conditions. In a study conducted in Australia by Eckard et al. (2003), where urea was surface applied at 50 kg N ha^{-1} to temperate perennial grass during 3 yr in four different seasons, the total annual loss averaged 30% of the total N applied. In a two-year study conducted by Oberle and Bundy (1987), in Wisconsin (USA), NH

phosphate (DP), ammonium sulphate (AS), and calcium ammonium nitrate (CAN) surface applied to winter wheat and grassland at 100 kg N ha⁻¹. Mean cumulative NH₃ loss from plots receiving urea, DP, AS, and CAN were 25%, 14%, <5% and <2%, respectively, during a 15-20 d measuring period. In Brazil, Bueno Martha Júnior et al. (2004) estimated the NH₃ volatilization loss in a *Panicum maximum* pasture fertilized with urea during the summer. Urea was applied at 40, 80 and 120 kg N ha⁻¹. The accumulated NH₃ loss represented 48%, 41% and 42% of the applied N for 40, 80 and 120 kg/ha urea-N fertilization, respectively.

Published estimates of NH₃ volatilization losses from urea and urea-based fertilizers vary widely. Much of this variability may be due to the method of estimation used and the environmental conditions during the experiment such as, temperature, soil water content, wind speed, pH, and rainfall.

References

- Ahmed, O.H., H. Aminuddin, and M.H.A. Husni. 2006. Reducing ammonia loss from urea and improving soil- exchangeable ammonium retention through mixing triple superphosphate, humic acid and zeolite. *Soil Use. Manage.* 22:315-319.
- Asman, W.A.H., M.A. Sutton, and J.K. Schjorring. 1994. Ammonia: emission, atmospheric transport and deposition. *New Phytol.*:139:27-48.
- Avnimelech, Y., and M. Laher. 1977. Ammonia volatilization from soils - equilibrium considerations. *Soil Sci. Soc. Am. J.* 41:1080-1084.
- Berry, J.T., and N.L. Hargett. 1990. Fertilizer summary data 1990. National Fertilizer Development Center, TVA, Muscle Shoals, A1.
- Black, A.S., R.R. Sherlock, and N.P. Smith. 1987. Effects of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture content. *J. Soil Sci.* 38:679-687.
- Bussink, D.W., and O. Oenema. 1996. Differences in rainfall and temperature define the use of different types of nitrogen fertilizer on managed grassland in UK, NL and Eire. *Net. J. of Agri. Sci.*:317-339.
- Bussink, D.W., and O. Oenema. 1998. Ammonia volatilization from dairy farming systems in temperated area: a review. *Nutr. Cycl. Agroecosys.*:19-33.

- Cabrera, M.L., D.E. Kissel, and B.R. Bock. 1991. Urea hydrolysis in soil - effects of urea concentration and soil-pH. *Soil Biol. Biochem.* 23:1121-1124.
- Cabrera, M.L., D.E. Kissel, N. Vaio, J.R. Craig, J.A. Rema, and L.A. Morris. 2005. Loblolly pine needles retain urea fertilizer that can be lost as ammonia. *Soil Sci. Soc. Am. J.*:1525-1531.
- Clegg, S., and M. Whitfield. 1995. A chemical model of seawater including dissolved ammonia and the stoichiometric dissociation constant of ammonia in estuarine water and seawater from 2 to 40°C. *Geochim. Cosmochim.* 59:2403-2401.
- Craig, R., and A.G. Wollum. 1982. Ammonia volatilization and soil nitrogen changes after urea and ammonium nitrate fertilization of *Pinus-taeda* (L). *Soil Sci. Soc. Am. J.* 4:409-414.
- Fenn, L.B., and D.E. Kissel. 1973. Ammonia volatilization from surface applications of ammonium compounds on calcareous soils: I general theory. *Soil Sci. Soc. Am. J.* 37:855-859.
- Ferguson, R.B., and D.E. Kissel. 1986. Effect of soil drying on ammonia volatilization from surface-applied urea. *Soil Sci. Soc. Am. J.*:485-490.
- Ferguson, R.B., D.E. Kissel, J.K. Koelliker, and W. Basel. 1984. Ammonia volatilization from surface-applied urea - effect of hydrogen-ion buffering capacity. *Soil Sci. Soc. Am. J.* 48:578-582.
- Fidaleo, M., and R. Lavecchia. 2003. Kinetic study of enzymatic urea hydrolysis in the pH range 4-9. *Chem. En. J.* 17:311-318.
- Frankenberger, W.T., and M.A. Tabatabai. 1985. Characteristics of an amidase isolated from a soil bacterium. *Soil Biol. Biochem.* 17:303-308.
- Hartel, P.G., D.M. Sylvia, J.J. Fuhrmann, and D.A. Zuberer. 2005. Principles and applications of soil microbiology. Prentice Hall, Upper Saddle River, NJ.
- Havlin, J.L., T.L. Samuel, W.L. Nelson, and J.D. Beaton. 1998. Soil fertility and fertilizers: An Introduction to nutrient management. 6th ed. Prentice Hall, Upper Saddle River, NJ.
- He, Z.L., A.K. Alva, D.V. Calvert, and D.J. Banks. 1999. Ammonia volatilization from different fertilizer sources and effects of temperature and soil pH. *Soil Sci. Soc. Am. J.* 164:750-758.
- Kheyrodin, H., and H. Antoun. 2002. Effect of tillage and manure application on soil microbial biomass and respiration and on enzyme activities. Department of Soil Science and Agri-food Engineering, Laval University, Quebec, Canada. 17th WCSS, 14-21 August 2002, Thailand.
- Kissel, D., M. Cabrera, N. Vaio, J. Craig, J. Rema, and L. Morris. 2004. Rainfall timing and ammonia loss from urea in a loblolly pine plantation. *Soil Sci. Soc. Am. J.* 68:1744-1750.
- Kistiakowsky, G.B., and A.J. Rosenberg. 1952. The kinetics of urea hydrolysis by urease. *J. Am. Chem. Soc.* 74:5020-5025.
- Klose, S., and M.A. Tabatabai. 1998. Urease activity of microbial biomass in soils. *Soil Biol. Biochem.* 31:2005-211.
- Körner, S., S.K. D., D.S. Veenstra, and J.E. Vermaat. 2001. The effect of pH variation at the ammonium/ammonia equilibrium in wastewater and its toxicity to *Lemna gibba*. *Aquatic Botany* 71:71-78.

- Lai, C.M., and M.A. Tabatabai. 1992. Kinetics parameters of immobilized urease. *Soil Biol. Biochem.*:225-228.
- Lightner, J.W., D.B. Mengel, and C.L. Rhykerd. 1990. Ammonia volatilization from nitrogen fertilizer surface applied to orchardgrass sod. *Sci. Soc. Am. J.*:1478-1482.
- Longo, R.M., and W.J. Melo. 2005. Urea hydrolysis in oxisols: effects of substrate concentration, temperature, pH, incubation time and storage. *Rev. Bras. Ciênc. Solo* 24:651-657.
- Mahler, R.L., and A. Hamid. 1994. Evaluation of water potential, fertilizer placement and incubation-time on volatilization losses of urea in 2 northern Idaho soils. *Commun. Soil Sci. Plan.* 25:1991-2004.
- McGarry, S.J., P. Otoole, and M.A. Morgan. 1987. Effects of soil-temperature and moisture-content on ammonia volatilization from urea-treated pasture and tillage soils. *Irish J. Agr. Res.* 26:173-182.
- Meisinger, J., and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. In *Proceedings from Managing Nutrients and Pathogens from Animal Agriculture*, 334-354. Camp Hill, PA. March 28-30.
- Moyo, C.C., D.E. Kissel, and M.L. Cabrera. 1989. Temperature effects on soil urease activity. *Soil Biol. Biochem.* 21:935-938.
- Oberle, S.L., and L.G. Bundy. 1987. Ammonia volatilization from nitrogen fertilizers surface-applied to corn (*Zea mays*) and grass pasture (*Dactylis glomerata*). *Biol. Fert. Soils*:185-192.
- Olesen, J.E., and S.G. Sommer. 1993. Modeling effects of wind speed and surface cover on ammonia volatilization from stored pig slurry. *J. Agri. Sci.* 27:2567-2574.
- Sadeghi, A.M., D.E. Kissel, and M.L. Cabrera. 1989. Estimating molecular diffusion coefficients of urea in unsaturated soil. *Soil Sci. Soc. Am. J.* 53:15-18.
- Sander, R. 1999. Modeling atmospheric chemistry: interactions between gas-phase species and liquid cloud/aerosol particles. *Surv. Geophys.*:1-31.
- Sommer, S.G., and J.E. Olesen. 1991. Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry. *J. Environ. Qual.*:679-683.
- Sommer, S.G., and A.K. Ersbøll. 1994. Effect of air flow rate, lime amendments, and chemical soil properties on the volatilization of ammonia from fertilizers applied to sandy soils. *Biol. Fert. Soils*:53-60.

- Vlek, P.L.G., and M.F. Carter. 1983. The effect of soil environment and fertilizer modifications on the rate of urea hydrolysis. *Soil Sci Soc Am* 136:56-63.
- Vlek, P.L.G., and M.F. Carter. 1983. The effect of soil environment and fertilizer modifications on the rate of urea hydrolysis. *Soil Sci. Soc. Am. J.* 136:56-63.
- Wahl, M., R. Kirsch, U. Brockel, S. Trapp, and M. Bottlinger. 2006. Caking of urea prills. *Chem. Eng. Tech.* 29:674-678.
- Yadav, D.S., V. Kumar, M. Singh, and P.S. Relan. 1987. Effect of temperature and moisture on kinetics of urea hydrolysis and nitrification. *Aust. J. Soil Res.*:185-189.

CHAPTER 2**AMMONIA VOLATILIZATION FROM NITAMIN® (UREA-POLYMER),
UAN (UREA-AMMONIUM NITRATE), AND UREA APPLIED
TO TALL FESCUE IN GEORGIA**

¹N. Vaio, M.L. Cabrera, D.E. Kissel, J.A. Rema, and J.G. Andrae
To be submitted to *Soil Science Society of America*

Abstract

The use of urea-based fertilizers in grasslands is likely to increase as restrictions on manure applications are implemented. Concerns have been raised about the economic and environmental impacts of N loss from urea-based fertilizers through volatilization. This study evaluated NH₃ volatilization losses from Nitamin® (urea-polymer), urea ammonium nitrate (UAN) and granular urea applied to grazed, tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) pastures at 50 kg N ha⁻¹ in fall and spring during 2 yr. Fertilizers were applied in triplicate circular plots (30-m diameter) and NH₃ loss was measured by the modified passive flux method for approximately 70 d following application. In a separate laboratory study, NH₃ volatilization was measured using flow-through volatilization chambers. Nitamin®, UAN, and urea were surfaced applied on fescue thatch at 100 kg N ha⁻¹ and samples were incubated at 24°C and 90% relative humidity for 8 months. Under field conditions, in fall 2004, urea lost significantly more ($p < 0.05$) NH₃ (19% of applied N) than UAN and Nitamin® (6%). In contrast, in spring 2005 there were no significant differences in NH₃ volatilization losses among treatments ($p < 0.05$), with an average loss of 13% of the applied N. In fall 2005 urea lost significantly more ($p < 0.05$) NH₃ (44% of applied N) than UAN (32%) and Nitamin® (34%) and in spring 2006 there were no significant differences among treatments, with Urea, UAN and Nitamin® losing 21, 15 and 15% of applied N, respectively. Similar results as field conditions were found in the incubation study, where urea lost significantly more ($p < 0.05$) NH₃ (24% of applied N) than UAN (11%) and Nitamin® (8%).

Introduction

The use of urea accounts for approximately 51% of the world's agricultural N consumption (Anonymous, 2006) and for about 20% of the total N fertilizer consumed in the U.S.A. (Anonymous, 2006). Surface application of urea-based fertilizers on grasslands commonly leads to gaseous losses of N through NH_3 volatilization (Lightner et al., 1990). Because urea is an organic fertilizer it needs to be hydrolyzed to produce ammonium (NH_4^+) which can be converted to NH_3 , and lost to the atmosphere (Cabrera et al., 1991). Frankenberger and Tabatabai (1985) reported that graminaceous plants such as tall fescue *Lolium arundinaceum* (Schreb.) Darbysh. may exhibit high urease activity and thus, high potential for NH_3 volatilization losses. Batty et al. (1994) estimated that approximately 9.5% of the total NH_3 emission in the U.S. came from N fertilizer applications. Furthermore, Eckard et al. (2003) reported that losses of N through volatilization accounted for about 29% of total N applied when urea was broadcast on grasslands. Ammonia losses reported by Oberle and Bundy (1987), Catchpoole et al. (1983), Sommer and Jensen (1994), Lightner et al., (1990), and Bueno Martha Júnior et al. (2004) ranged from 14 to 48% of applied urea-N.

Ammonia volatilization losses are important for both agricultural and non-agricultural ecosystems because they represent a direct loss of plant available N and because they may contribute to eutrophication of aquatic and low N input ecosystems through atmospheric transport and deposition (Asman et al., 1994). Furthermore, volatilized NH_3 is able to travel hundreds of kilometers from the site of origin and even low levels of NH_3 in the atmosphere can produce significant respiratory and cardiovascular problems (Gay and Knowlton, 2005).

About 36% of the total agricultural land in Georgia is used as grassland, for grazing or hay production (USDA, 2002). At the present, approximately 40% of these grasslands are fertilized with broiler litter (Starkey, 2003), but the use of urea-based fertilizers is likely to increase as restrictions on animal manure applications are implemented.

Georgia Pacific Corporation has developed an alternative slow-release, urea-based fertilizer that has the potential to reduce the amount of N lost through NH_3 volatilization. This alternative fertilizer is a liquid urea-polymer (Nitamin®) in which about 30% of the N is in the form of urea and 70% in the form of polymer-compounds. Theoretically, the polymer present in the fertilizer decreases the rate of urea hydrolysis, thereby reducing losses through volatilization.

Even though several studies have been published on NH_3 volatilization losses from urea and urea-based fertilizers worldwide, there is a lack of information on NH_3 volatilization losses from urea-based fertilizers applied to tall fescue grasslands in the southeastern U.S.A. The objective of this study was to measure NH_3 volatilization losses from Nitamin®, urea ammonium nitrate (UAN), and traditional granular urea when surface-applied to tall fescue pastures in Georgia (USA). For this purpose, field and laboratory studies were conducted.

Materials and methods

Ammonia volatilization under field conditions

This study was conducted at the Central Research and Education Center of the University of Georgia located near Eatonton, GA (Latitude 33 ° 24' N, Longitude 83 ° 29'

W, elevation 150 m). The area can be described as a tall fescue and bermudagrass (*Cynodon dactylon* L.) temperate grassland surrounded by forest. The soils have been classified as Iredell sandy loam (Fine, montmorillonitic, thermic, Typic Hapudalfs) and Mecklenburg sandy loam and sandy clay loam (Fine, mixed thermic Ultic Hapludalfs) (Perkins et al., 1987). The surface soil (0 – 10cm) has a pH of 4.8 (1 soil: 1 CaCl₂, equivalent to 5.4 in water), 2.0 g total N kg⁻¹, and 24.1 g C kg⁻¹.

Treatments of Nitamin®, UAN, and granular urea fertilizer were surface applied at an approximate rate of 50 kg N ha⁻¹. Liquid fertilizers Nitamin® and UAN were surface applied using a device consisting of a pressure tank connected to a 1.5-m metallic boom in which nozzles (Spraying Systems Co., CP4916-24) (Wheaton, IL) were placed 25 cm apart to deliver a broadcast application. The solid granular urea was applied using a 1.5-m wide 6500 series spreaders, (Gandy, Owatonna, MN). Both devices were accurately calibrated to deliver the correct rate. The N concentration for Nitamin®, UAN and urea was, 25, 28, and 46% respectively. Fertilizers were applied in triplicate to circular plots (30-m diameter) which were separated from each other by approximately 100 m to avoid possible contaminations with NH₃ from nearby plots. Also, two controls were added, with no fertilizer addition.

on the inside with oxalic acid to trap the NH_3 . The tube facing the wind had a nozzle connected through a piece of silicone tubing. The nozzle consisted of a 2.3-cm glass tube with a stainless steel disk glued to it. The disk had a 1-mm hole at its center. The mast had a vane that kept the samples always pointing towards the direction of the wind source. The sampling tubes were changed periodically depending on the weather conditions to allow for enough concentration of NH_3 to be detected in the tubes. Each sampling tube was extracted with 3 mL of DI water for 30 min and the extract was analyzed colorimetrically for NH_4 (Crooke and Simpson, 1971).

Two Campbell Scientific weather stations (Logan, UT) were placed in the study area to measure rainfall, air temperature, air humidity, wind speed and direction (Campbell 215, 8161), air temperature

water to a manifold with 21 hypodermic needles (22 Gauge x 37.5 mm long) (Franklin Lakes, NJ) arranged in a circle with a 4.45-cm diameter. The needles generated 10.39-mg droplets and the manifold delivered a total flow rate of about 1.09-mL min^{-1} . During the rainfall simulation, the experimental units were rotated to obtain uniform distribution of water over the sample surface. After that, the experimental units were left overnight to allow for moisture equilibration.

After overnight equilibration, three treatments (Nitamin®, UAN, and regular urea) were surface applied to the experi

M KCL for 30 min, the extract was filtered (filter paper Whatman N° 1, 5.5-cm diameter), and analyzed colorimetrically for inorganic N (Crooke and Simpson, 1971; Mulvaney, 1996)

Statistical Analysis

Losses of NH₃ through volatilization under field and laboratory conditions were subjected to an analysis of variance (SAS, Institute, 1999) and the means were tested with Fisher's LSD at a 0.05 probability level.

Results and Discussion

Field conditions

Ammonia volatilization losses from urea-based fertilizers varied greatly among seasons. Differences in weather conditions during each season may have affected differently the amount of NH₃ lost after fertilizer application.

In fall 2004, in spite of 51 mm of rain that occurred 8 d after fertilizer application, urea lost significantly more ($p < 0.05$) NH₃ (19% of applied N) than UAN and Nitamin® (6%). (Fig. 2.1a, b and Table 2.1). Similar results were found by Kissel et al. (2004) where NH₃ losses increased after 4, 11 and 40 mm of simulated rainfall was applied to a forest floor on days 4 to 5 after urea application. In addition, Cabrera, et al. (2005) found that when urea is surface applied on forest floor, it can diffuse into the pine needles which then can greatly reduce urea-leaching by rainfall and enhance NH₃ losses. A similar mechanism may be operating on grasslands. In addition, in spite of the low average temperature (10 °C) during the first 30 d after fertilizer application (Fig 2.1 c), approximately 80% of the total losses occurred during the first month. Steenhuis et al.

(1979) found that NH_3 losses do not stop at near-freezing temperatures and Sommer and Olesen, (1991) found that losses near freezing temperatures occur because a lower, but still substantial rate of volatilization can occur for a longer period of time.

In spring 2005, however, no significant differences in NH_3 volatilization losses ($p < 0.05$) were observed among fertilizers, when losses ranged from 12 to 14% of the total applied N (Fig. 2.2a, Table 2.1). The lack of differences among fertilizers in spring 2005 may have been caused by 40 mm of rainfall that occurred 2 d after fertilizers application (Fig 2.2b and 2.7 d). The rainfall may have increased downward leaching of fertilizers (Fig 2. 7) or runoff outside the plots reducing N losses. Lysimeters samples collected during 69 d after fertilizers application showed elevated levels of NO_3^- and total N, indicating that infiltrating rain leached some of the fertilizer. Furthermore lysimeter samples taken from the plots treated with Nitamin®, concentrations of total-N, NO_3^- , and NH_4^+ were significantly greater ($P < 0.05$) than plots treated with UAN and urea (Fig. 2.8). Furthermore, losses from leaching were greater in fall 2005 compared with the other seasons indicating that most of the fertilizer applied in fall 2005 may have been leached into the soil reducing ammonia losses (Fig. 2.7abc). Similar results were found by Kissel et al. (2004) in a forest floor where NH_3 losses were reduced to $< 1\%$ of the total applied N when simulated rainfall was applied immediately after urea application. If the same mechanism of urea diffusion explained by Cabrera et al. (2005) is assumed to occur in tall fescue grasslands, it is possible that because rain occurred 2 d after application there may not have been enough time for urea to diffuse into the thatch and be retained against leaching by rain.

In fall 2005 urea lost significantly more ($p < 0.05$) NH_3 (46% of applied N) than UAN (33%) and Nitamin® (34%) (Fig. 2.3a Table 2.1). The large amount of NH_3 lost from all treatments during fall 2005 may have been caused by the high relative humidity (RH) (Fig. 2.3.b), and temperature, and by the lack of rainfall during the first 18 d following fertilizer application (Fig. 2.3 a, b, c, Table 2.1). Wahl et al. (2006) found that the critical relative humidity (CRH), which is the humidity of the atmosphere above which urea will absorb moisture, decreases from 80 to 70% as the air temperature increases from 20 to 40°C. In addition, Wahl et al. (2006) found that the solubility of urea in water increases from 1.08 to 1.65 g g⁻¹ as the air temperature increases from 20 to 40°C. The high average temperature for the first 30 d in fall 2005 (23°C) (Fig. 2.3.c) decreased the CRH and increased the solubility of urea, allowing the fertilizers to dissolve and urea hydrolysis to proceed. It can be seen from Figures 2.3 b and 2.6 c that in the first 30 d of this experiment, the RH was above the urea CRH 63% of the time, allowing most of the fertilizers to be dissolved, hydrolyzed, and eventually lost as NH_3 . In addition, the low average value of soil water content (0.07 g g⁻¹) during that period could have reduced the diffusion of urea into the soil enhancing even more NH_3 losses. Vlek and Carter (1983) suggest that at low water contents, the lack of free water in the soil might inhibit diffusion of urea. Therefore, most of the NH_4^+ produced after urea hydrolysis may have remained on the soil surface and was therefore lost as NH_3 to the atmosphere. Similar results of high NH_3 volatilization losses were found in West Lafayette, Indiana by Lightner et al. (1990) where losses from urea surface-applied to orchardgrass reached 41% of the total applied N.

may have limited the rate of NH_3 diffusion from the soil surface to the air inside the chamber (Sommer and Ersbøll, 1994).

Results observed in the laboratory study are similar to those under field conditions in fall 2004 and spring 2006 (Fig. 2.1a, 2.2a and Table 2.1). These similarities may have occurred because in both cases (field and laboratory conditions) the average soil water contents for the first 10 d after fertilizer application were 0.17 g g^{-1} for fall 2004, 0.15 g g^{-1} for spring 2006 and 0.18 g g^{-1} for the incubation study. If one takes into account that in the laboratory study fertilizers were surface applied after a simulated rainfall applied on top of the fescue thatch (equilibrated to the soil water content at field capacity 0.18 g g^{-1}) it can be assumed that part of the fertilizers diffused into the soil, giving similar conditions for volatilization to those that occurred in fall 2004 and spring 2006 (Fig 2.1ab, 2.4ab and 2.5a).

Conclusion

The results of these studies demonstrate the importance of reducing NH_3 volatilization losses from urea-based fertilizers when they are surface-applied to tall fescue grasslands in the southeastern U.S. Field and laboratory measurements of NH_3 volatilization showed that urea lost significantly more NH_3 than UAN and Nitamin®. However, all three N sources (urea, UAN, and Nitamin®) showed a great potential to lose NH_3 under optimum weather conditions for volatilization. Furthermore, the extent of NH_3 loss from urea-based fertilizers was markedly affected by the timing of rainfall, temperature, and relative humidity during the first two weeks following fertilizer application.

On average, Nitamin® lost approximately 30% less NH₃ than urea, indicating its potential to reduce NH₃ volatilization losses when it is surface-applied on tall fescue. Additional studies from slow-release, urea-based fertilizers are needed to better understand how to reduce NH₃ volatilization losses and increase N fertilizer effectiveness for grasslands.

Acknowledgements

Authors would like to thank the staff of the Central Research and Education Center in Eatonton, including Gerald Cathey, Vaughn Calvert, and especially Frank Newsome for his technical support and permanent collaboration during this study. Authors also extend their appreciation to Krystal Kerr for laboratory assistance during this study.

References

- Anonymous. 2006. International fertilizer industry association [Online]. Available at www.fertilizer.org (accessed 29 August 2006) IFA, International Fertilizer Industry Association.
- Asman, W.A.H., M.A. Sutton, and J.K. Schjorring. 1994. Ammonia: emission, atmospheric transport and deposition. *New Phytol.*:139:27-48.
- Bremner, J.M. 1996. Nitrogen-Total. p. 1185-1121. D.L. Sparks et al. (ed.) *Methods of soil analysis-Part 3. Chemical methods*. SSSA Book Ser. No. 5. SSSA and ASA, Madison, WI.

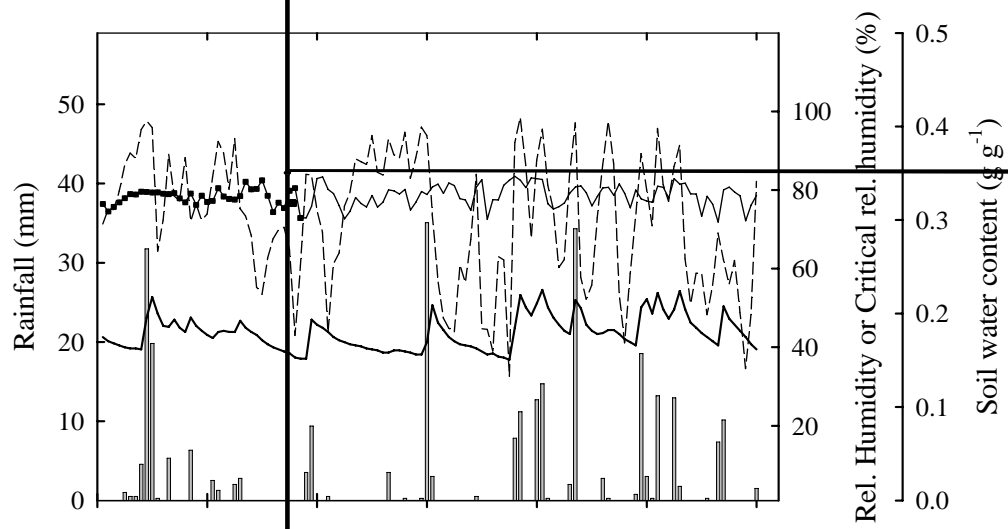
- Catchpoole, V.R., D.J. Oxenham, and L.A. Harper. 1983. Transformation and recovery of urea applied to a grass pasture in south-eastern Queensland. *Awt.I. Exb. Apric. Anim. Hwb.*:80-86.
- Crooke, W.M., and W.E. Simpson. 1971. Determination of ammonium in Kjeldahl digests of crops by an automated procedure. *J. Sci. Food Agric.*:47-64.
- Eckard, R.J., D. Chen, R.E. White, and D.F. Chapman. 2003. Gaseous nitrogen loss from temperate perennial grass and clover dairy pastures in south-eastern Australia. *Aust. J. Agric. Res.* 54:561-570.
- EPA. 1983. *Methods for Chemical Analysis of Water and Wastes*, U.S. Environmental Protection Agency, EPA 600/4-79-020:365.1.
- Fenn, L.B., and D.E. Kissel. 1973. Ammonia volatilization from surface applications of ammonium compounds on calcareous soils: I general theory. *Soil Sci. Soc. Am. J.* 37:855-859.
- Franklin. Lakes, NJ. Becton, Dickinson and Co. [Online]. Available at www.bd.com/ca/safety/products/injection/syringes_needles/ (accessed 29 November 2006) Becton, Dickinson and Co.
- Franklin, D.H., M.L. Cabrera, J.L. Steiner, D.M. Endale, and W.P. Miller. 2001. Evaluation of percent flow captured by a small in-field runoff collector. *Trans. ASAE*, 44, 551, 2001.:551-554.
- Gay, S.W., and K.F. Knowlton. 2005. Ammonia emissions and animal agriculture [Online]. Online at www.ext.vt.edu/pubs/bse/442-110/442-110 (accessed 28 October 2006) Virginia Tech Cooperative Extension.
- Kissel, D., M. Cabrera, N. Vaio, J. Craig, J. Rema, and L. Morris. 2004. Rainfall timing and ammonia loss from urea in a loblolly pine plantation. *Soil Sci. Soc. Am. J.* 68:1744-1750.
- Le Cadre, E., S. Genermont, C. Decuq, S. Recous, and P. Cellier. 2005. A laboratory system to estimate ammonia volatilization. *Agron. Sustain. Dev.*:101-107.
- Leuning, R., J.R. Freney, O.T. Denmead, and J.R. Simpson. 1985. A sampler for measuring atmospheric ammonia flux. *Atmos. Environ.*:1117-1124.
- Lightner, J.W., D.B. Mengel, and C.L. Rhykerd. 1990. Ammonia volatilization from nitrogen fertilizer surface applied to orchardgrass sod. *Sci. Soc. Am. J.*:1478-1482.
- Logan. UT. Campbell Scientific, Inc [Online]. Available at www.campbellsci.com/custom-weather-station

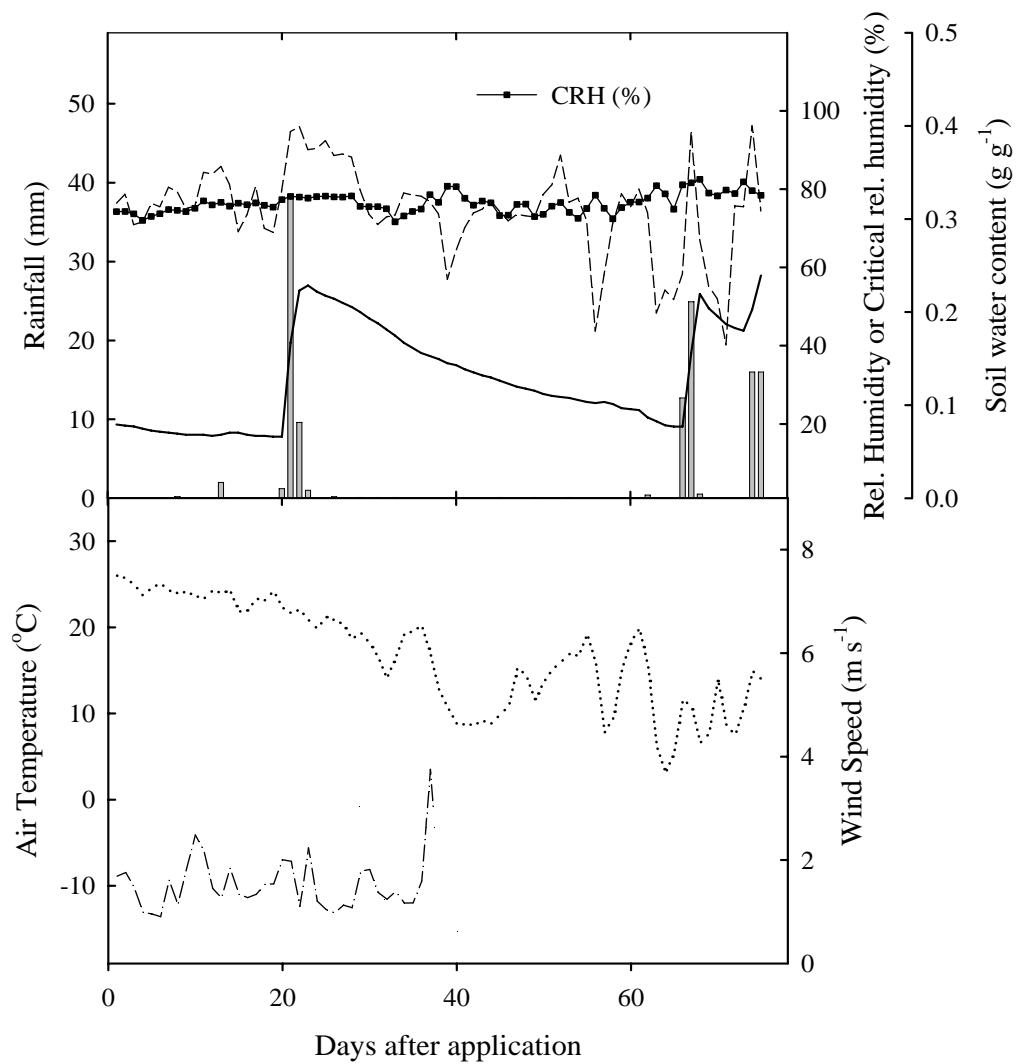
- Perkins, H.F., N.W. Barbour, and C.G. V. 1987. Soils of the Central Georgia Branch. Experiment Station. Univ. of Georgia, Athens, GA.:1-49.
- Rawlins, S.L., and G.S. Campbell. 1986. Water potential: thermocouple psychrometry. In: Methods of Soil Analysis - part 1: Physical and Mineralogical Methods. Monograph Number 9 (2nd Edn) (Klute A, ed) ASA, Madison, WI, USA.:597-618.
- SAS. Institute. 1999. SAS/STAT user's guide. v. 8. SAS Inst., Cary, NC.
- Sommer, S.G., and J.E. Olesen. 1991. Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry. *J. Environ. Qual.*:679-683.
- Sommer, S.G., and A.K. Ersbøll. 1994. Effect of air flow rate, lime amendments, and chemical soil properties on the volatilization of ammonia from fertilizers applied to sandy soils. *Biol. Fert. Soils*:53-60.
- Sommer, S.G., and C. Jensen. 1994. Ammonia volatilization from urea and ammoniacal fertilizers surface-applied to winter-wheat and grassland. *Fertil. Res.* 37:85-92.
- Starkey, J. 2003. Georgia's response to the new federal CAFO rule. *Poultry Tech* 15(2) [\[http://atrp.gatech.edu/pt15-2/15-2_p3.html\]](http://atrp.gatech.edu/pt15-2/15-2_p3.html)

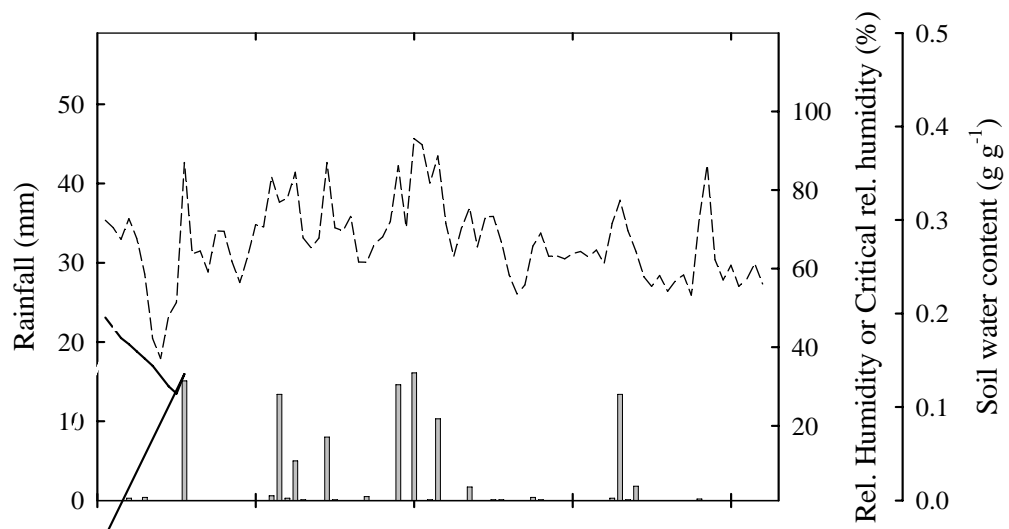
Table 2. 1. Total ammonia loss from urea-based fertilizers (Urea, UAN and Nitamin®) applied to tall fescue plots at 50 kg N ha⁻¹ in fall 2004 (120 d), spring 2005 (69 d), fall 2005 (75 d), and spring 2006 (83 d).

Treatment	Fall 2004	Spring 2005	Fall 2005	Spring 2006	Average
-----Ammonia loss (% of applied N)-----					
Urea	19 a†	12 a	46 a	21 a	25 a
UAN	6 b	13 a	33 b	15 a	17 b
Nitamin®	6 b	14 a	34 b	15 a	17 b

†Within a column, values followed by the same letter are not significantly different according to Fisher's LSD at p=0.05.







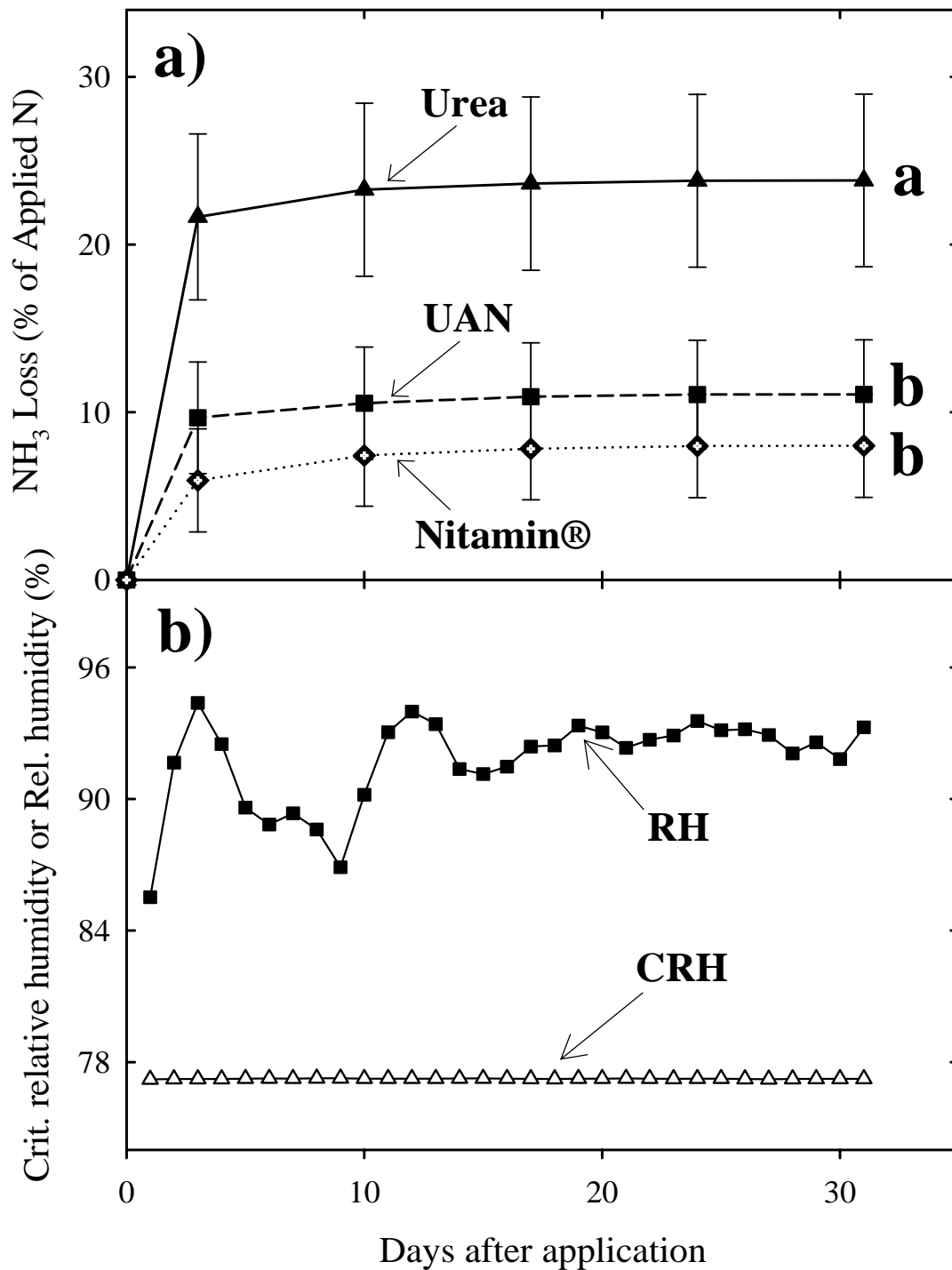
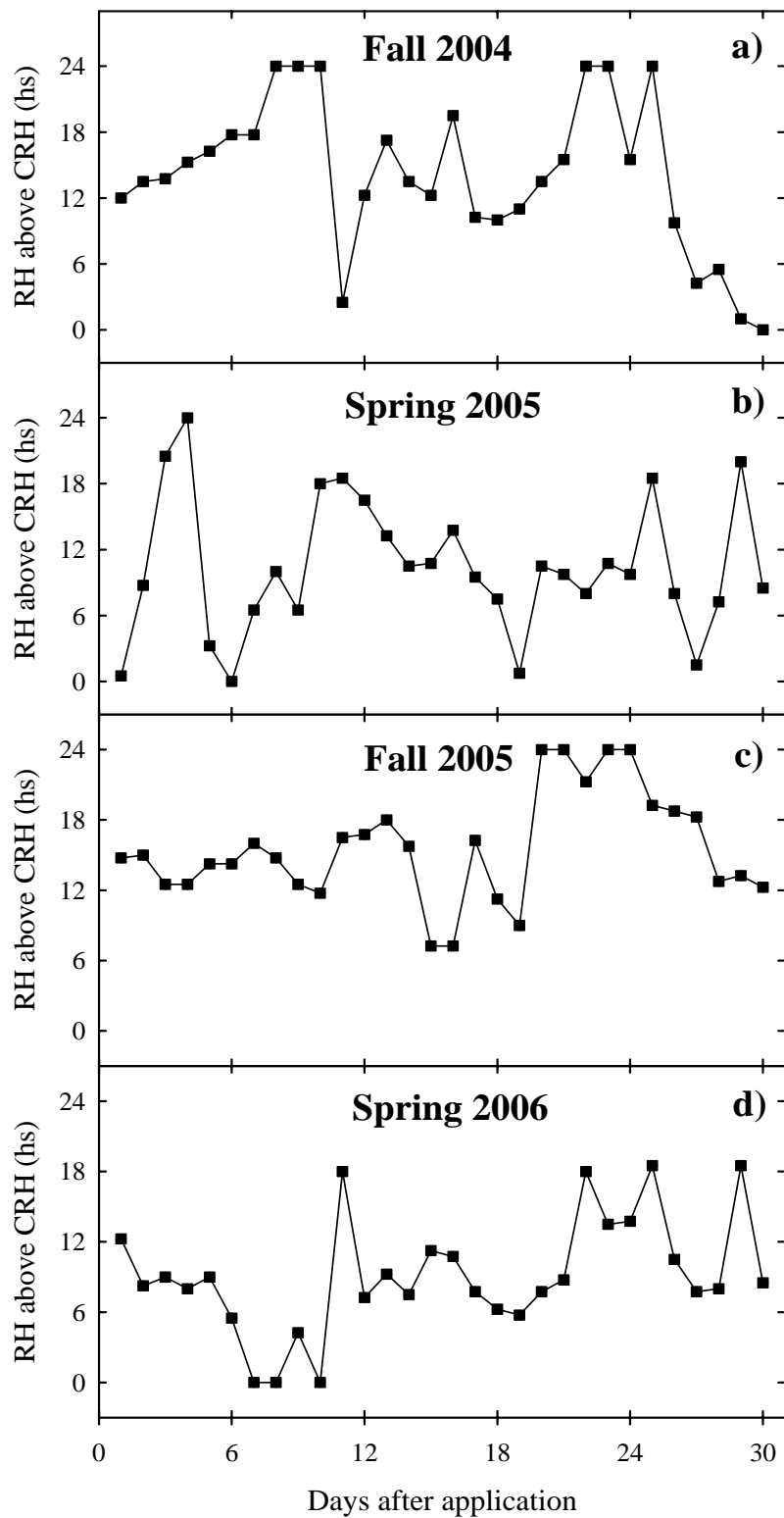
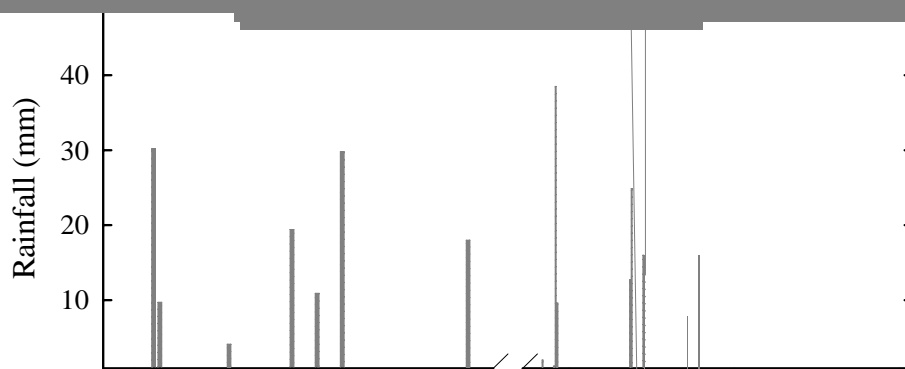


Figure 2. 5. a) Cumulative NH₃ loss from urea-based fertilizers (Urea, UAN, and Nitamin®) applied to fescue thatch at 100 kg N ha⁻¹ in an 8-mo incubation study (bars are standard deviations); and b) Relative humidity (%), Critical relative humidity (%) during the first 30 d. Values followed by different letters are significantly different according to Fisher's LSD at p=0.05.





CHAPTER 3**EVALUATION OF THE AMMONIUM NITRATE EQUIVALENT VALUE OF
UREA-POLYMER (NITAMIN®) AND UREA-AMMONIUM NITRATE
FOR TALL FESCUE PASTURES IN GEORGIA**

¹N. Vaio, M.L. Cabrera, D.E. Kissel, J.A. Rema, and J.G. Andrae
To be submitted to *Agronomy Journal*

Abstract

Tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) is one of the most

Introduction

Tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) is one of the most important cool- season forages used in the southeastern U.S.A. It is a perennial grass, with greatest production during spring and fall. Tall fescue can be adapted to a wide range of conditions but grows best on fertile, well-drained soils with a soil pH of 5.5 to 6.5 (Landry, 2006).

Over 36% of the total agricultural land in Georgia is used as grasslands (USDA, 2002) and approximately 40% of these grasslands are fertilized with broiler litter (Starkey, 2003). The use of urea-based fertilizers in these pastures is likely to increase as restrictions on animal manure applications are implemented. Surface application of urea-based fertilizers on grasslands commonly leads to gaseous losses of nitrogen (N) through ammonia (NH₃) volatilization (Lightner et al., 1990), sometimes to leaching losses (Wang and Alva, 1996), and immobilization by microorganisms (Raczkowski and Kissel, 1989). As a result, N recovery by plants is approximately 50% of the total N applied (Shaviv and Mikkelsen, 1993). This represents not only an economic loss but also a potential danger for environmental contamination. Improving the efficiency of N fertilizers through new technologies, such as controlled release fertilizers (CRF), is needed and may be used as an effective alternative to control environmental contamination and economic loss from N fertilizer applications.

Mikkelsen et al. (1993) conducted laboratory and field studies to determine if the addition of gel-forming, hydrophilic polymers to UAN solutions could reduce N leaching losses and increase plant uptake of N on tall fescue. They found that compared to UAN alone, N leaching losses were reduced from 0 to 45% due to polymer addition, whereas

the growth of tall fescue was increased by 40% and N accumulation by 50%. In Colorado, U.S.A., Shoji et al. (2001) conducted a study using controlled-release fertilizers (polyolefin coated urea) and a nitrification inhibitor (dicyandiamide) to increase N efficiency on irrigated barley. They found a reduction of N losses through volatilization to 12% of the total applied N and demonstrated the greatest potential to increase N use efficiency through the use of controlled-release fertilizers during the growing season of irrigated barley. Mikkelsen et al. (1994) evaluated N leaching losses and plant growth following two applications of six coated and noncoated controlled-release N fertilizers. They found that coated fertilizers generally out-performed the noncoated fertilizers in reducing N leaching losses, stimulating plant growth, and increasing tissue N concentrations. Similarly, Dou and Alva (1998) conducted a study to measure the growth and N uptake of two citrus rootstock seedlings after application of two controlled-release N fertilizers (polyolefin resin-coated (PRC), sulfur-coated urea (SCU)), and traditional urea. The study demonstrated that the total N uptake by seedlings was greater for the controlled release fertilizers compared to traditional urea. The ranking of the N fertilizers sources with respect to the total N uptake by seedlings was PRC>SCU>urea.

Understanding the fate of different forms of N fertilizers applied to crops is an important step in enhancing N use efficiency and minimizing N losses. When comparing N fertilizers, ammonium nitrate (AN) is commonly used as a reference because it does not undergo losses through NH_3 volatilization in soils with $\text{pH} < 6.3$ (Oberle and Bundy, 1987). Georgia Pacific Corporation has developed an alternative slow-release, urea-based fertilizer that has the potential to reduce the amount of N loss through volatilization and

increase N uptake. This alternative is a liquid slow-release urea-polymer (Nitamin®) in which about 30% of the N is in the form of urea and 70% in the form of polymer-compounds. The objective of this study was to evaluate the ammonium nitrate equivalent value (ANEV) of Nitamin® and UAN as tall fescue fertilizers. The ANEV of a fertilizer indicates the effectiveness of a fertilizer, in increasing yield or N uptake when compared to AN. It is a value that may range from 0 to more than 100%, with 100% indicating that the fertilizer is as effective as AN.

Materials and methods

In fall 2004 and spring 2005 a study was conducted at the Central Research and Education Center of the University of Georgia (Eatonton, GA; Latitude 33 ° 24' N, Longitude 83 ° 29' W, elevation 150 m). The area can be described as a tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) temperate grassland. The soils have been classified as Mecklenburg sandy loam and sandy clay loam (Fine, mixed thermic Ultic Hapludalfs) (Perkins et al., 1987). The surface soil (0 – 10 cm) had a pH of 5.1 (1 soil: 1 CaCl₂, equivalent to 5.7 in water).

In fall 2005 and spring 2006 another study was conducted at the Plant Sciences Farm of the University of Georgia, (Watkinsville, GA; Latitude 33° 52' N, Longitude 83° 32' W, elevation 260 m). The area can be described as a tall fescue temperate grassland and the soil has been classified as a Pacolet sandy clay loam (Hill et al., 1997). The surface soil (0 – 10 cm) had a pH of 5.7 (1 soil: 1 CaCl₂, equivalent to 6.3 in water), 0.5 g total N kg⁻¹, and 6.1 g C kg⁻¹.

Treatments consisted of a control (no fertilizer) and rates of ammonium nitrate (AN), Nitamin®, and urea-ammonium nitrate (UAN) fertilizers surface applied in a randomized complete block design. The plots were 1.5 x 3 m (4.5 m²) and each treatment was replicated four times, for a total of 60 plots.

In fall 2004 (October 12) and spring 2005 (April 18), Nitamin® and UAN, were surface applied at approximate rates of 35 and 75 kg N ha⁻¹ and AN was applied at 0, 25, 50 and 100 kg N ha⁻¹. In fall 2005 (October 21) and spring 2006 (April 5), Nitamin® and UAN were surface applied at 70 and 150 kg N ha⁻¹ and AN was applied at 0, 50, 100 and 200 kg N ha⁻¹. Treatments in fall and spring were applied to different plots. Liquid fertilizers (Nitamin® (25% of N) and UAN (28% of N)) were applied using a device consisting of a peristaltic pump located on top of a cart, which was pulled by an electric motor at 5.7 m s⁻¹. The cart was supported and guided by a frame (3.65 m x 1.82 m) that was moved from plot to plot. The peristaltic pump was connected to five silicon tubes which delivered the fertilizer from the container to hypodermic needles (22 Gauge x 37.5 mm long) located 25 cm apart, resulting in a dribble application. The speed of the peristaltic pump and electric motor was accurately calibrated to deliver the fertilizer at the correct rate. For dry matter yield determination, a center swath (3 x 0.81m) with an area of approximately 2.43 m² was harvested regularly from each plot using an Auburn small-plot forage harvester (McCormick and Hoveland, 1971). The harvested material was dried at 65°C for 48 h, weighed, and a sub sample was ground and analyzed for total N by dry combustion (Bremner, 1996) to calculate plant N uptake. Nitrogen uptake from control plots was subtracted from all other plots to obtain the net N uptake derived from the applied fertilizer. Net N uptake from each fertilizer was plotted against N rate and a

straight line without intercept was fit to the data. The slope of the lines indicated the N uptake efficiency for each fertilizer. The slopes of UAN and Nitamin® were divided by the slope of AN to obtain the AN equivalent value (ANEV) of Nitamin® and UAN.

Statistical Analysis

Differences in N uptake among fertilizers were subjected to an analysis of variance (SAS, Institute, 1999) and the means were tested with Fisher's LSD at a 0.05 probability level.

Results and Discussion

The results from this study indicated that dry matter yield as well as N uptake from tall fescue was influenced by the source of N used. It can be seen from Figures 3.1,

Results and Discussion of the 2.3 AS, Inst

yield with increasing N rates, and differences among fertilizers were small at low fertilizers rates.

In spring 2005, significant differences were found in N uptake ($P < 0.05$) between AN versus Nitamin® and UAN (Table 3.1.). In addition significant differences in N recovery were found between AN and Nitamin® in fall 2005 (Table 3.1). In both cases AN had a larger N recovery than UAN and Nitamin® for tall fescue. In contrast, no significant differences were found between Nitamin® and UAN (Table 3.1) in spring and fall 2005. There were no significant differences ($P < 0.05$) among fertilizers in fall 2004 and spring 2005.

The greater recovery obtained with AN in this study may have occurred because AN does not undergo NH_3 losses (Oberle and Bundy, 1987). In a previous study conducted on tall fescue (Chapter 2, this thesis), we found that under optimum weather conditions for volatilization, surface-applications of UAN and Nitamin® lost approximately 30% of the total applied N by volatilization.

When ANEV was used to evaluate fertilizer effectiveness, no significant differences ($P < 0.05$) were found between UAN and Nitamin® in any of the seasons (Table 3.1). The effectiveness of both fertilizers, with respect to AN was between 47 to 98%, with an average of 73% for UAN and 68% for Nitamin®. On average, the values of ANEV for UAN and Nitamin® we

Conclusion

- Landry, G.J. 2006. Tall Fescue Managements [Online]. Available at <http://pubs.caes.uga.edu/caespubs/pubcd/L354.htm>. UGA, Cooperative of Extension, CAES.
- Lightner, J.W., D.B. Mengel, and C.L. Rhykerd. 1990. Ammonia volatilization from nitrogen fertilizer surface applied to orchardgrass sod. *Sci. Soc. Am. J.*:1478-1482.
- McCormick, R.F.J., and C.S. Hoveland. 1971. The Auburn small-plot forage harvester. *Agron. J.*:951-952.
- Mikkelsen, R.L., B. A.D.J., and H.M. Williams. 1993. Addition of gel-forming hydrophilic polymers to nitrogen fertilizer solution. *Fert. Res.*:55-61.
- Mikkelsen, R.L., A.D.J. Behel, and H.M. Williams. 1994. Nitrogen leaching and plant uptake from controlled-release fertilizers. *Fert. Res.*:43-50.
- Oberle, S.L., and L.G. Bundy. 1987. Ammonia volatilization from nitrogen fertilizers surface-applied to corn (*Zea mays*) and grass pasture (*Dactylis glomerata*). *Biol. Fert. Soils*:185-192.
- Perkins, H.F., N.W. Barbour, and C.G. V. 1987. Soils of the Central Georgia Branch. Experiment Station. Univ. of Georgia, Athens, GA.:1-49.
- Raczkowski, C.W., and D.E. Kissel. 1989. Fate of subsurface-banded and broadcast nitrogen applied to tall fescue. *Sci. Soc. Am. J.*:566-570.
- SAS. Institute. 1999. SAS/STAT user's guide. v. 8. SAS Inst., Cary, NC.
- Shaviv, A., and R.L. Mikkelsen. 1993. Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation - A review. *Nutr. Cycl. Agroecosys.*:1-12.
- Starkey, J. 2003. Georgia's response to the new federal CAFO rule. *Poultry Tech* 15(2) [http://atrp.gatech.edu/pt15-2/15-2_p3.html] Accessed 8/31/06.
- Teutsch, C.D., J.H. Fike, G.E. Groover, and S. Aref. 2005. Nitrogen rate and source effects on the yield and nutritive value of tall fescue stockpiled for winter grazing [Online]. *Forage and Grazinglands* doi:10.1094/FG-2005-1220-01-RS.
- USDA. 2002. National Agricultural Statistics Service [Online]. Available at www.nass.usda.gov/census/census02/volume1/ga/index1 (accessed 3 September 2006). USDA-NASS, Washington D.C.
- Wang, F.L., and A.K. Alva. 1996. Leaching of nitrogen from slow-release urea sources in sandy soils. *Soil Sci. Soc. Am. J.*:1454-1458.
- Whitehead, D.C. 1995. *Grassland nitrogen*. CAB Int. Wallingford, UK.

Table 3. 1. Fertilizer recovery for AN, UAN, and Nitamin® surface-applied to tall fescue plots in fall 2004, spring 2005, fall 2005, and spring 2006.

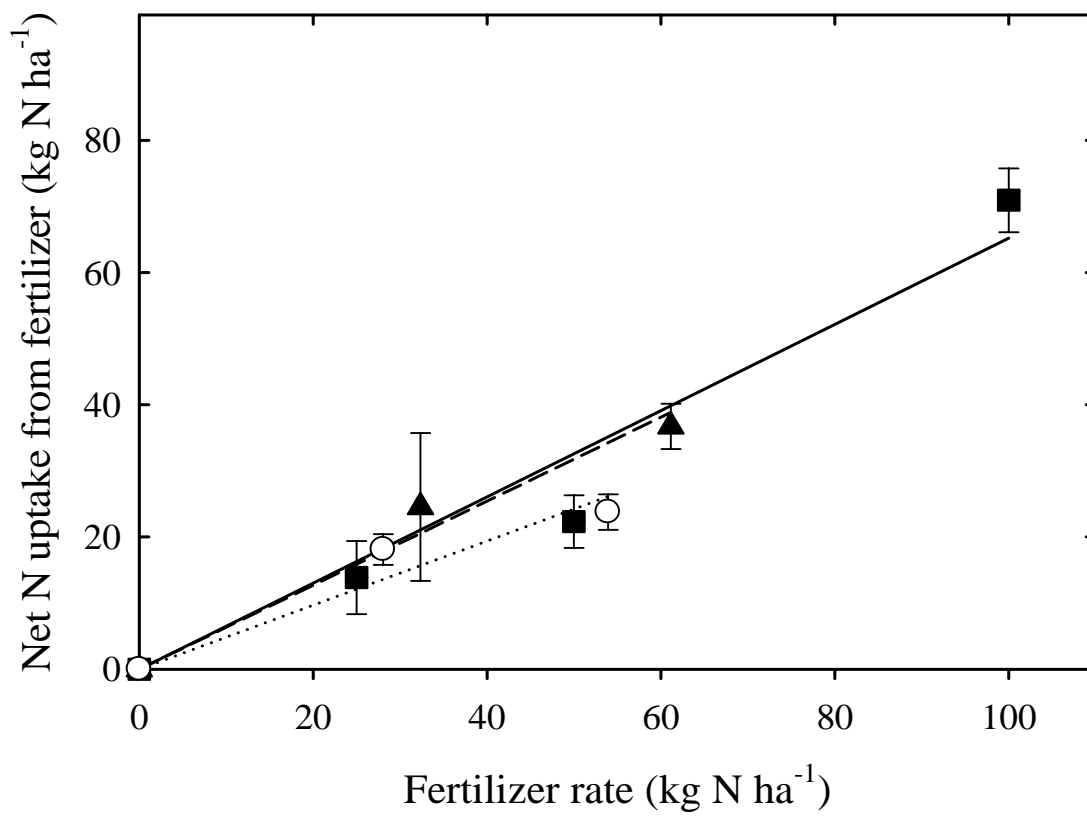
Treatment	Fall 2004	Spring 2005	Fall 2005	Spring 2006
	----- N recovery (kg N uptake / kg N applied) -----			
AN	0.65a†	0.68a	0.45a	0.38a
UAN	0.64a	0.37b	0.28a	0.29a
Nitamin®	0.48a	0.32b	0.32b	0.30a

†Within a column, values followed by the same letter are not significantly different according to Fisher's LSD at p=0.05.

Table 3. 2. Ammonium nitrate equivalent value of urea-based fertilizers (UAN and Nitamin®) applied to tall fescue plots in fall 2004, spring 2005, fall 2005, and spring 2006.

Treatment	Fall 2004	Spring 2005	Fall 2005	Spring 2006
	-----Ammonium nitrate equivalent value (%)-----			
UAN	98a†	54a	62a	76a
Nitamin®	74a	47a	71a	79a

†Within a column, values followed by the same letter are not significantly different according to Fisher's LSD at p=0.05.



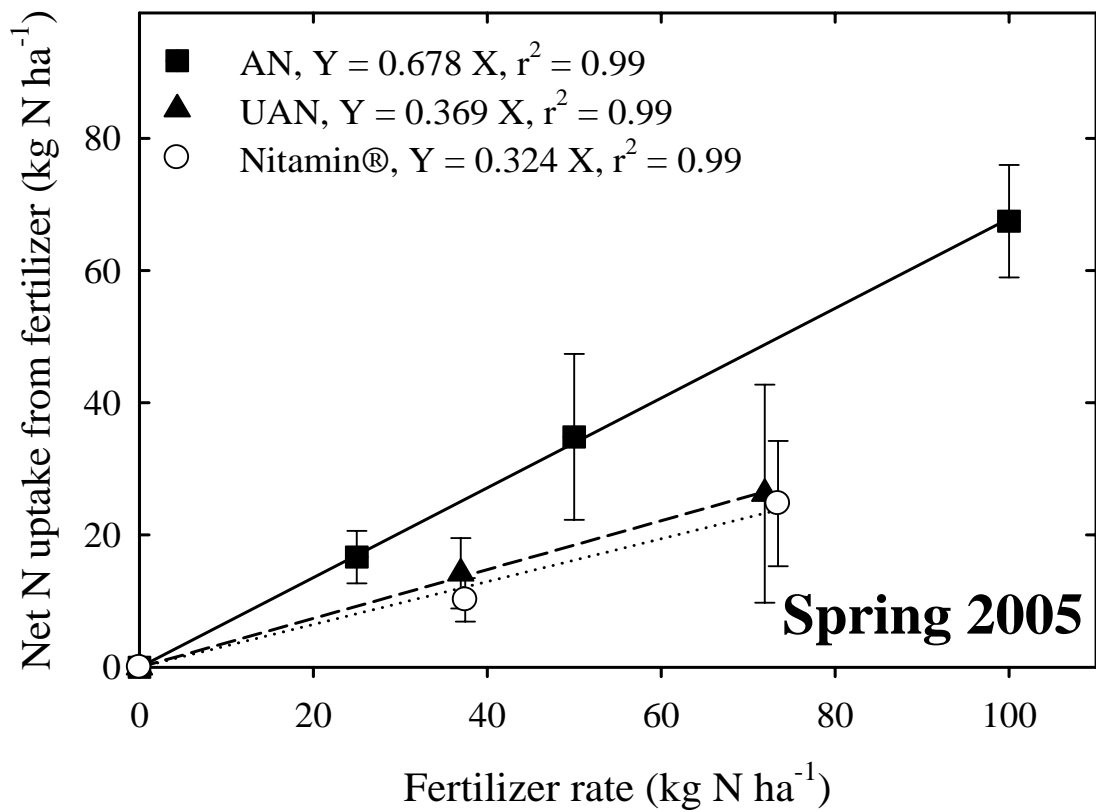


Figure 3. 2. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface applied at 0, 35, and 70 kg N ha⁻¹, and from AN surface-applied at 0, 25, 50, and 100 kg N ha⁻¹ to tall fescue plots in spring 2005.

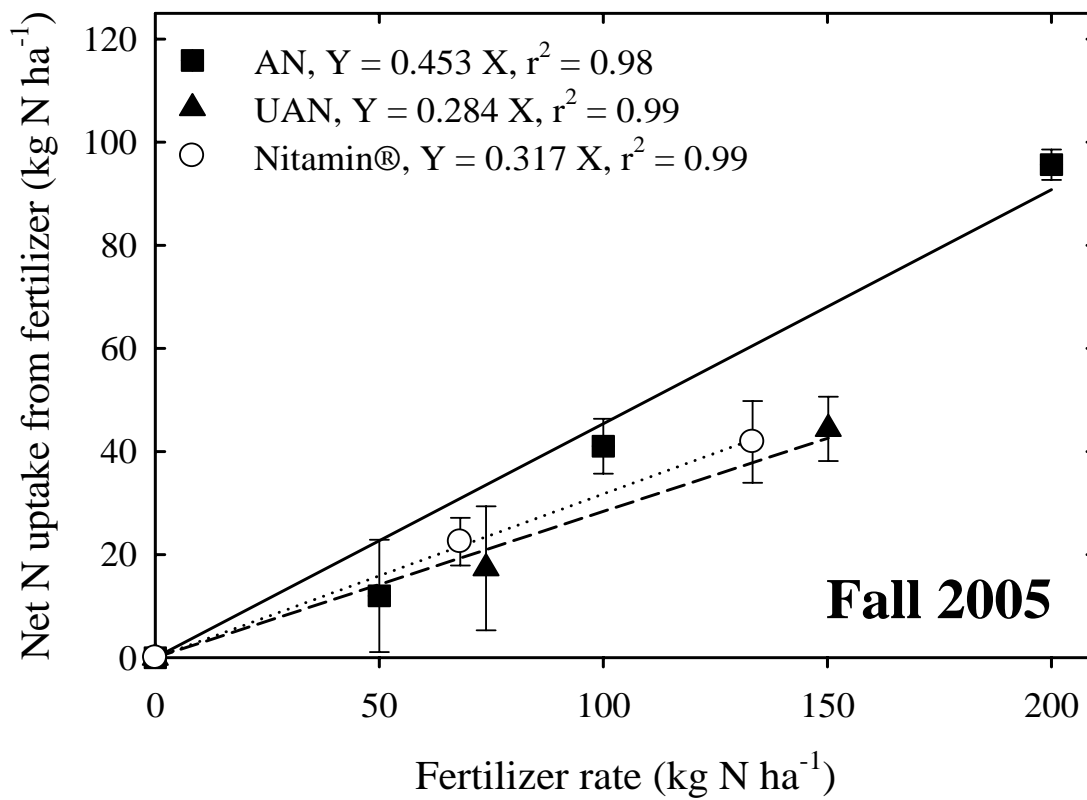


Figure 3. 3. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface applied at 0, 70, and 140 kg N ha⁻¹, and from AN surface-applied at 0, 50, 100, and 200 kg N ha⁻¹ to tall fescue plots in fall 2005.

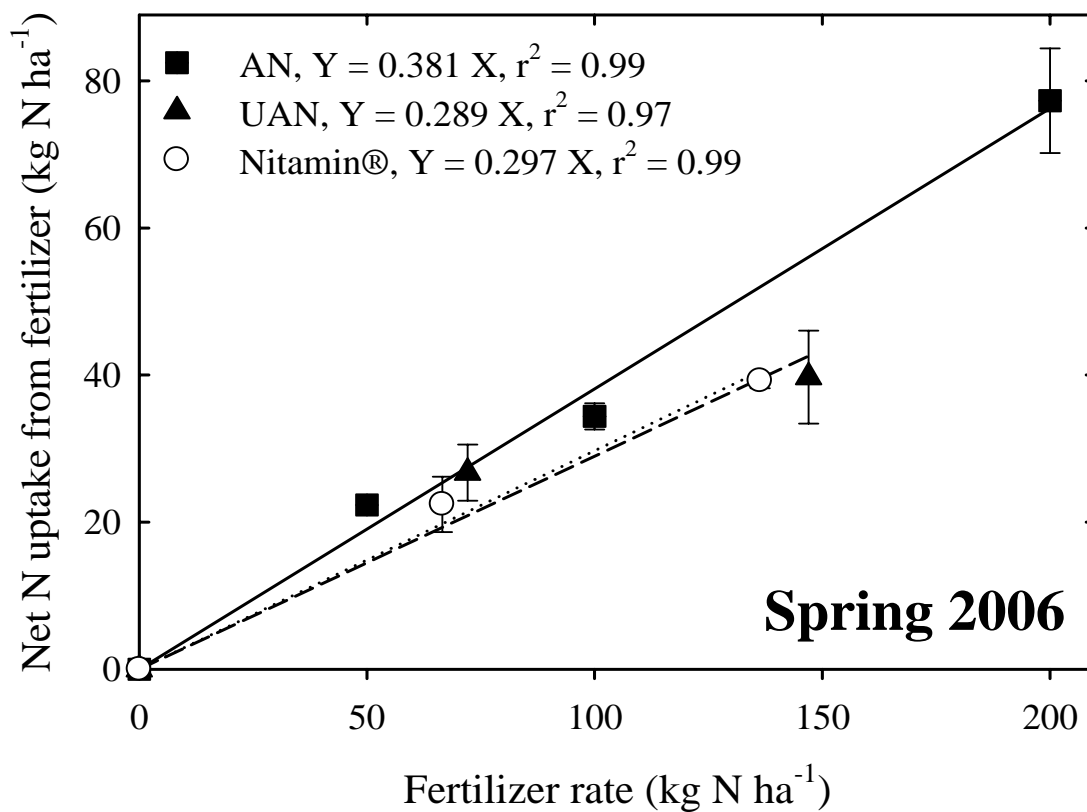


Figure 3. 4. Net nitrogen uptake from urea-based fertilizers (UAN, and Nitamin®) surface applied at 0, 70, and 140 kg N ha⁻¹, and from AN surface-applied at 0, 50, 100, and 200 kg N ha⁻¹ to tall fescue plots in spring 2006.

CONCLUSIONS AND IMPLICATIONS

The results of this study demonstrated the importance of reducing NH_3 volatilization losses from urea-based fertilizers when they are surface-applied to tall fescue grasslands in the southeastern U.S.A. It was determined that Nitamin® (slow-release urea-based fertilizer) could be effectively used as an alternative source to urea to reduce NH_3 volatilization losses. However, urea as well as Nitamin® and UAN showed great potential for N losses through volatilization when optimum weather conditions for volatilization were present. In fall 2005, under field conditions, NH_3

APPENDIX A

DATA OF AMMONIA VOLATILIZATION STUDY UNDER
FIELD CONDITIONS

Fall 2004			
Plot	Treatment	Fertilizer rate (kg N ha⁻¹)	NH₃ loss (% applied N)
1	UAN	48	6.8
2	Urea	54	21.1
3	Nitamin®	55	7.5
4	UAN	50	7.8
5	Urea	52	23.9
6	Nitamin®	55	6.0
7	Nitamin®	55	3.8
8	Urea	52	13.3
9	UAN	47	3.9

Spring 2005			
Plot	Treatment	Fertilizer rate (kg N ha⁻¹)	NH₃ loss (% applied N)
1	UAN	40	14.9
2	Urea	52	11.4
3	Nitamin®	49	12.2
4	UAN	39	15.5
5	Urea	49	11.4
6	Nitamin®	47	14.3
7	Nitamin®	48	15.1
8	Urea	50	11.9
9	UAN	42	9.0

Fall 2005			
Plot	Treatment	Fertilizer rate (kg N ha⁻¹)	NH₃ loss (% applied N)
1	UAN	52	33.5
2	Urea	52	54.0
3	Nitamin®	55	40.2
4	UAN	53	41.1
5	Urea	51	49.2
6	Nitamin®	56	39.7
7	Nitamin®	60	21.8
8	Urea	50	33.7
9	UAN	56	24.0

Spring 2006			
Plot	Treatment	Fertilizer rate (kg N ha⁻¹)	NH₃ loss (% applied N)
1	UAN	46	22.3
2	Urea	58	27.6
3	Nitamin®	51	18.4
4	UAN	46	16.6
5	Urea	58	24.5
6	Nitamin®	45	18.7
7	Nitamin®	48	17.8
8	Urea	54	20.6
9	UAN	47	16.0

APPENDIX B

DATA OF AMMONIA VOLATILIZATION STUDY UNDER
LABORATORY CONDITIONS

Samples	Treatment	Extraction time (Weeks)	Fertilizer rate (kg N ha⁻¹)	NH₃ loss (% of applied N)
1	Urea	4	98	20.1
2	Urea	4	101	18.8
3	Urea	8	101	21.5
4	Urea	8	98	25.8
5	Urea	16	100	23.5
6	Urea	16	97	27.7
7	Urea	32	97	21.4
8	Urea	32	97	20.9
9	Urea	4	100	31.6
10	Urea	8	97	29.9
11	Urea	16	101	30.9
12	Urea	32	101	15.6
13	UAN	4	106	16.9
14	UAN	4	106	10.6
15	UAN	8	106	12.4
16	UAN	8	106	9.4
17	UAN	16	106	12.3
18	UAN	16	106	6.5
19	UAN	32	106	11.4
20	UAN	32	106	13.0
21	UAN	4	106	4.9
22	UAN	8	106	13.8
23	UAN	16	106	9.6
24	UAN	32	106	12.7
25	Nitamin®	4	90	4.1
26	Nitamin®	4	90	4.3
27	Nitamin®	8	90	4.6
28	Nitamin®	8	90	9.4
29	Nitamin®	16	90	8.7
30	Nitamin®	16	90	11.0
31	Nitamin®	32	90	9.2
32	Nitamin®	32	90	7.6
33	Nitamin®	4	90	10.8
34	Nitamin®	8	90	2.6
35	Nitamin®	16	90	7.6
36	Nitamin®	32	90	7.5

APPENDIX C

DATA OF PLANT N UPTAKE STUDY

(AVERAGE VALUES)

Fall 2004			
Treatment	Target rate (kg N ha⁻¹)	Fertilizer applied (kg N ha⁻¹)	Net N uptake (kg N ha⁻¹)
UAN	35	32.3	24.5
UAN	70	61.1	36.7
Nitamin®	35	28.1	18.1
Nitamin®	70	53.9	23.8
AN	25	25	13.9
AN	50	50	22.3
AN	100	100	71.0

Spring 2005			
Treatment	Target rate (kg N ha⁻¹)	Fertilizer applied (kg N ha⁻¹)	Net N uptake (kg N ha⁻¹)
UAN	35	36.9	14.2
UAN	70	71.9	26.3
Nitamin®	35	37.5	10.2
Nitamin®	70	73.4	24.8
AN	25	25	16.7
AN	50	50	34.8
AN	100	100	67.5

Fall 2005			
Treatment	Target rate (kg N ha⁻¹)	Fertilizer applied (kg N ha⁻¹)	Net N uptake (kg N ha⁻¹)
UAN	70	73.8	17.3
UAN	140	150.2	44.4
Nitamin®	70	68.1	22.5
Nitamin®	140	133.3	41.8
AN	50	50	12.0
AN	100	100	45.0
AN	200	200	95.6

Spring 2006			
Treatment	Target rate (kg N ha⁻¹)	Fertilizer applied (kg N ha⁻¹)	Net N uptake (kg N ha⁻¹)
UAN	70	72.1	26.7
UAN	140	147.0	39.7
Nitamin®	70	66.6	22.4
Nitamin®	140	136.3	39.2
AN	50	50	22.4
AN	100	100	34.4
AN	200	200	77.3

DATA OF PLANT N UPTAKE STUDY

(RAW DATA)

Fall 2004 Harvest 1					
Treatment	Target rate (kg N ha ⁻¹)	Fert. applied (kg N ha ⁻¹)	Harvest	Replication	N uptake (kg N ha ⁻¹)
AN	25	25	Harvest 1	Rep 1	23.9
AN	25	25	Harvest 1	Rep 2	13.0
AN	25	25	Harvest 1	Rep 3	6.7
AN	25	25	Harvest 1	Rep 4	8.7
AN	25	25	Harvest 2	Rep 1	13.0
AN	25	25	Harvest 2	Rep 2	9.0
AN	25	25	Harvest 2	Rep 3	9.1
AN	25	25	Harvest 2	Rep 4	6.2
AN	25	25	Harvest 3	Rep 1	6.9
AN	25	25	Harvest 3	Rep 2	3.2
AN	25	25	Harvest 3	Rep 3	3.9
AN	25	25	Harvest 3	Rep 4	2.6
AN	25	25	Harvest 4	Rep 1	59.5
AN	25	25	Harvest 4	Rep 2	26.3
AN	25	25	Harvest 4	Rep 3	40.0
AN	25	25	Harvest 4	Rep 4	18.3
AN	50	50	Harvest 1	Rep 1	20.0
AN	50	50	Harvest 1	Rep 2	30.7
AN	50	50	Harvest 1	Rep 3	25.9
AN	50	50	Harvest 1	Rep 4	17.1
AN	50	50	Harvest 2	Rep 1	15.0
AN	50	50	Harvest 2	Rep 2	10.2
AN	50				

17.1

Harvest 1

Fall 2004					
Treatment	Target rate (kg N ha ⁻¹)	Fert. applied (kg N ha ⁻¹)	Harvest	Replication	N uptake (kg N ha ⁻¹)
AN	100	100	Harvest 1	Rep 1	47.0
AN	100	100	Harvest 1	Rep 2	73.5
AN	100	100	Harvest 1	Rep 3	60.1
AN	100	100	Harvest 1	Rep 4	50.5
AN	100	100	Harvest 2	Rep 1	9.7
AN	100	100	Harvest 2	Rep 2	19.5
AN	100	100	Harvest 2	Rep 3	12.6
AN	100	100	Harvest 2	Rep 4	8.1
AN	100	100	Harvest 3	Rep 1	4.1
AN	100	100	Harvest 3	Rep 2	8.0
AN	100	100	Harvest 3	Rep 3	6.6
AN	100	100	Harvest 3	Rep 4	3.3
AN	100	100	Harvest 4	Rep 1	51.5
AN	100	100	Harvest 4	Rep 2	46.5
AN	100	100	Harvest 4	Rep 3	42.4
AN	100	100	Harvest 4	Rep 4	25.6
UAN	35	32	Harvest 1	Rep 1	43.4
UAN	35	32	Harvest 1	Rep 2	42.6
UAN	35	33	Harvest 1	Rep 3	36.4
UAN	35	32	Harvest 1	Rep 4	16.3
UAN	35	32	Harvest 2	Rep 1	17.2
UAN	35	32	Harvest 2	Rep 2	15.3
UAN	35	33	Harvest 2	Rep 3	10.2
UAN	35	32	Harvest 2	Rep 4	8.4
UAN	35	32	Harvest 3	Rep 1	6.1
UAN	35	32	Harvest 3	Rep 2	7.3
UAN	35	33	Harvest 3	Rep 3	9.1
UAN	35	32	Harvest 3	Rep 4	2.7
UAN	35	32	Harvest 4	Rep 1	64.5
UAN	35	32	Harvest 4	Rep 2	52.4
UAN	35	33	Harvest 4	Rep 3	46.8
UAN	35	32	Harvest 4	Rep 4	23.6

Fall 2004					
Treatment	Target rate (kg N ha ⁻¹)	Fert. applied (kg N ha ⁻¹)	Harvest	Replication	N uptake (kg N ha ⁻¹)
UAN	70	59	Harvest 1	Rep 1	20.5
UAN	70	60	Harvest 1	Rep 2	28.5
UAN	70	63	Harvest 1	Rep 3	42.0
UAN	70	62	Harvest 1	Rep 4	28.6
UAN	70	59	Harvest 2	Rep 1	11.1
UAN	70	60	Harvest 2	Rep 2	11.7
UAN	70	63	Harvest 2	Rep 3	12.1
UAN	70	62	Harvest 2	Rep 4	10.0
UAN	70	59	Harvest 3	Rep 1	3.1
UAN	70	60	Harvest 3	Rep 2	8.4
UAN	70	63	Harvest 3	Rep 3	3.3
UAN	70	62	Harvest 3	Rep 4	7.0
UAN	70	59	Harvest 4	Rep 1	45.1
UAN	70	60	Harvest 4	Rep 2	44.9
UAN	70	63	Harvest 4	Rep 3	28.3
UAN	70	62	Harvest 4	Rep 4	37.2
Nitamin®	35	28	Harvest 1	Rep 1	43.4
Nitamin®	35	28	Harvest 1	Rep 2	42.6
Nitamin®	35	27	Harvest 1	Rep 3	36.4
Nitamin®	35	29	Harvest 1	Rep 4	16.3
Nitamin®	35	28	Harvest 2	Rep 1	17.2
Nitamin®	35	28	Harvest 2	Rep 2	15.3
Nitamin®	35	27	Harvest 2	Rep 3	10.2
Nitamin®	35	29	Harvest 2	Rep 4	8.4
Nitamin®	35	28	Harvest 3	Rep 1	6.1
Nitamin®	35	28	Harvest 3	Rep 2	7.3
Nitamin®	35	27	Harvest 3	Rep 3	9.1
Nitamin®	35	29	Harvest 3	Rep 4	2.7
Nitamin®	35	28	Harvest 4	Rep 1	64.5
Nitamin®	35	28	Harvest 4	Rep 2	52.4
Nitamin®	35	27	Harvest 4	Rep 3	46.8
Nitamin®	35	29	Harvest 4	Rep 4	23.6

Fall 2004					
Treatment	Target rate (kg N ha⁻¹)	Fert. applied (kg N ha⁻¹)	Harvest	Replication	N uptake (kg N ha⁻¹)
Nitamin®	70	54	Harvest 1	Rep 1	18.4
Nitamin®	70	54	Harvest 1	Rep 2	4.2
Nitamin®	70	55	Harvest 1	Rep 3	29.2
Nitamin®	70	53	Harvest 1	Rep 4	13.2
Nitamin®	70	54	Harvest 2	Rep 1	14.5
Nitamin®	70	54	Harvest 2	Rep 2	10.6
Nitamin®	70	55	Harvest 2	Rep 3	9.2
Nitamin®	70	53	Harvest 2	Rep 4	8.5
Nitamin®	70	54	Harvest 3	Rep 1	3.9
Nitamin®	70	54	Harvest 3	Rep 2	4.1
Nitamin®	70	55	Harvest 3	Rep 3	4.0
Nitamin®	70	53	Harvest 3	Rep 4	4.8
Nitamin®	70	54	Harvest 4	Rep 1	39.4
Nitamin®	70	54	Harvest 4	Rep 2	40.4
Nitamin®	70	55	Harvest 4	Rep 3	34.3
Nitamin®	70	53	Harvest 4	Rep 4	31.4
Control	0	0	Harvest 1	Rep 1	33.6
Control	0	0	Harvest 1	Rep 2	5.4
Control	0	0	Harvest 1	Rep 3	2.8
Control	0	0	Harvest 1	Rep 4	5.1
Control	0	0	Harvest 2	Rep 1	20.8
Control	0	0	Harvest 2	Rep 2	8.9
Control	0	0	Harvest 2	Rep 3	9.4
Control	0	0	Harvest 2	Rep 4	7.6
Control	0	0	Harvest 3	Rep 1	6.6
Control	0	0	Harvest 3	Rep 2	3.6
Control	0	0	Harvest 3	Rep 3	2.8
Control	0	0	Harvest 3	Rep 4	3.3
Control	0	0	Harvest 4	Rep 1	61.5
Control	0	0	Harvest 4	Rep 2	37.9
Control	0	0	Harvest 4	Rep 3	27.5
Control	0	0	Harvest 4	Rep 4	29.0
Event	Application	Harvest 1	Harvest 2	Harvest 3	Harvest 4
Time	12/10/2004	4/11/2005	5/19/2005	6/28/2005	8/26/2005

Spring 2005					
Treatment	Target rate (kg N ha ⁻¹)	Fert. applied (kg N ha ⁻¹)	Harvest	Replication	N uptake (kg N ha ⁻¹)
AN	25	25	Harvest 1	Rep 1	22.9
AN	25	25	Harvest 1	Rep 2	19.0
AN	25	25	Harvest 1	Rep 3	14.4
AN	25	25	Harvest 1	Rep 4	13.2
AN	25	25	Harvest 2	Rep 1	5.0
AN	25	25	Harvest 2	Rep 2	7.3
AN	25	25	Harvest 2	Rep 3	4.1
AN	25	25	Harvest 2	Rep 4	5.2
AN	25	25	Harvest 3	Rep 1	38.0
AN	25	25	Harvest 3	Rep 2	44.7
AN	25	25	Harvest 3	Rep 3	31.1
AN	25	25	Harvest 3	Rep 4	29.4
AN	50	50	Harvest 1	Rep 1	35.9
AN	50	50	Harvest 1	Rep 2	31.5
AN	50	50	Harvest 1	Rep 3	21.0
AN	50	50	Harvest 1	Rep 4	15.5
AN	50	50	Harvest 2	Rep 1	12.0
AN	50	50	Harvest 2	Rep 2	12.5
AN	50	50	Harvest 2	Rep 3	7.7
AN	50	50	Harvest 2	Rep 4	5.8
AN	50	50	Harvest 3	Rep 1	55.5
AN	50	50	Harvest 3	Rep 2	60.2
AN	50	50	Harvest 3	Rep 3	31.9
AN	50	50	Harvest 3	Rep 4	22.0
AN	100	100	Harvest 1	Rep 2	49.3
AN	100	100	Harvest 1	Rep 2	58.6
AN	100	100	Harvest 1	Rep 3	39.0
AN	100	100	Harvest 1	Rep 4	27.5
AN	100	100	Harvest 2	Rep 1	21.9
AN	100	100	Harvest 2	Rep 2	19.6
AN	100	100	Harvest 2	Rep 3	20.0
AN	100	100	Harvest 2	Rep 4	19.4
AN	100	100	Harvest 3	Rep 1	58.5
AN	100	100	Harvest 3	Rep 2	16.4
AN	100	100	Harvest 3	Rep 3	35.9
AN	100	100	Harvest 3	Rep 4	30.5

Spring 2005					
Treatment	Target rate (kg N ha⁻¹)	Fert. applied (kg N ha⁻¹)	Harvest	Replication	N uptake (kg N ha⁻¹)
UAN	35	37	Harvest 1	Rep 1	14.6
UAN	35	36	Harvest 1	Rep 2	21.7
UAN	35	38	Harvest 1	Rep 3	18.9
UAN	35	37	Harvest 1	Rep 4	16.4
UAN	35	37	Harvest 2	Rep 1	5.3
UAN	35	36	Harvest 2	Rep 2	9.3
UAN	35	38	Harvest 2	Rep 3	5.4
UAN	35	37	Harvest 2	Rep 4	5.0
UAN	35	37	Harvest 3	Rep 1	46.8
UAN	35	36	Harvest 3	Rep 2	39.2
UAN	35	38	Harvest 3	Rep 3	25.7
UAN	35	37	Harvest 3	Rep 4	21.7
UAN	70	71	Harvest 1	Rep 1	26.1
UAN	70	73	Harvest 1	Rep 2	56.1
UAN	70	71	Harvest 1	Rep 3	40.4
UAN	70	73	Harvest 1	Rep 4	18.5
UAN	70	71	Harvest 2	Rep 1	8.2
UAN	70	73	Harvest 2	Rep 2	18.4
UAN	70	71	Harvest 2	Rep 3	21.6
UAN	70	73	Harvest 2	Rep 4	9.6
UAN	70	71	Harvest 3	Rep 1	55.7
UAN	70	73	Harvest 3	Rep 2	54.9
UAN	70	71	Harvest 3	Rep 3	51.3
UAN	70	73	Harvest 3	Rep 4	25.5
Nitamin®	35	34	Harvest 1	Rep 1	16.8
Nitamin®	35	34	Harvest 1	Rep 2	17.3
Nitamin®	35	32	Harvest 1	Rep 3	12.2
Nitamin®	35	34	Harvest 1	Rep 4	10.6
Nitamin®	35	34	Harvest 2	Rep 1	6.9
Nitamin®	35	34	Harvest 2	Rep 2	6.7
Nitamin®	35	32	Harvest 2	Rep 3	6.2
Nitamin®	35	34	Harvest 2	Rep 4	4.0
Nitamin®	35	34	Harvest 3	Rep 1	56.8
Nitamin®	35	34	Harvest 3	Rep 2	38.6
Nitamin®	35	32	Harvest 3	Rep 3	34.4
Nitamin®	35	34	Harvest 3	Rep 4	27.0

Spring 2005					
Treatment	Target rate (kg N ha⁻¹)	Fert. applied (kg N ha⁻¹)	Harvest	Replication	N uptake (kg N ha⁻¹)
Nitamin®	70	66	Harvest 1	Rep 1	30.7
Nitamin®	70	68	Harvest 1	Rep 2	22.8
Nitamin®	70	67	Harvest 1	Rep 3	28.3
Nitamin®	70	62	Harvest 1	Rep 4	13.0
Nitamin®	70	66	Harvest 2	Rep 1	11.8
Nitamin®	70	68	Harvest 2		

Fall 2005					
Treatment	Target rate (kg N ha ⁻¹)	Fert. applied (kg N ha ⁻¹)	Harvest	Replication	N uptake (kg N ha ⁻¹)
AN	50	50	Harvest 1	Rep 1	19.9
AN	50	50	Harvest 1	Rep 2	22.0
AN	50	50	Harvest 1	Rep 3	13.4
AN	50	50	Harvest 1	Rep 4	41.8
AN	50	50	Harvest 2	Rep 1	15.5
AN	50	50	Harvest 2	Rep 2	NS
AN	50	50	Harvest 2	Rep 3	12.7
AN	50	50	Harvest 2	Rep 4	26.6
AN	100	100	Harvest 1	Rep 1	29.0
AN	100	100	Harvest 1	Rep 2	49.2
AN	100	100	Harvest 1	Rep 3	53.7
AN	100	100	Harvest 1	Rep 4	41.3
AN	100	100	Harvest 2	Rep 1	24.7
AN	100	100	Harvest 2	Rep 2	20.9
AN	100	100	Harvest 2	Rep 3	27.6
AN	100	100	Harvest 2	Rep 4	21.9
AN	200	200	Harvest 1	Rep 1	86.8
AN	200	200	Harvest 1	Rep 2	90.5
AN	200	200	Harvest 1	Rep 3	90.6
AN	200	200	Harvest 1	Rep 4	82.6
AN	200	200	Harvest 2	Rep 1	27.9
AN	200	200	Harvest 2	Rep 2	35.0
AN	200	200	Harvest 2	Rep 3	40.2
AN	200	200	Harvest 2	Rep 4	35.4
UAN	70	73	Harvest 1	Rep 1	30.2
UAN	70	74	Harvest 1	Rep 2	38.4
UAN	70	74	Harvest 1	Rep 3	13.9
UAN	70	76	Harvest 1	Rep 4	15.6
UAN	70	73	Harvest 2	Rep 1	19.7
UAN	70	74	Harvest 2	Rep 2	28.9
UAN	70	74	Harvest 2	Rep 3	9.3
UAN	70	76	Harvest 2	Rep 4	10.8

Fall 2005					
Treatment	Target rate (kg N ha⁻¹)	Fert. applied (kg N ha⁻¹)	Harvest	Replication	N uptake (kg N ha⁻¹)
UAN	140	149	Harvest 1	Rep 1	42.3
UAN	140	149	Harvest 1	Rep 2	51.2
UAN	140	152	Harvest 1	Rep 3	52.6
UAN	140	151	Harvest 1	Rep 4	55.9
UAN	140	149	Harvest 2	Rep 1	30.2
UAN	140	149	Harvest 2	Rep 2	15.7
UAN	140	152	Harvest 2	Rep 3	29.0
UAN	140	151	Harvest 2	Rep 4	22.6
Nitamin®	70	73	Harvest 1	Rep 1	32.6
Nitamin®	70	74	Harvest 1	Rep 2	28.3
Nitamin®	70	74	Harvest 1	Rep 3	30.8
Nitamin®	70	76	Harvest 1	Rep 4	29.9
Nitamin®	70	73	Harvest 2	Rep 1	26.1
Nitamin®	70	74	Harvest 2	Rep 2	22.8
Nitamin®	70	74	Harvest 2	Rep 3	13.8
Nitamin®	70	76	Harvest 2	Rep 4	27.9
Nitamin®	140	149	Harvest 1	Rep 1	33.8
Nitamin®	140	149	Harvest 1	Rep 2	46.5
Nitamin®	140	152	Harvest 1	Rep 3	46.7
Nitamin®	140	151	Harvest 1	Rep 4	50.0
Nitamin®	140	149	Harvest 2	Rep 1	34.4
Nitamin®	140	149	Harvest 2	Rep 2	32.4
Nitamin®	140	152	Harvest 2	Rep 3	17.6
Nitamin®	140	151	Harvest 2	Rep 4	25.1
Control	0	0	Harvest 1	Rep 1	19.5
Control	0	0	Harvest 1	Rep 2	17.4
Control	0	0	Harvest 1	Rep 3	14.4
Control	0	0	Harvest 2	Rep 1	13.9
Control	0	0	Harvest 2	Rep 2	7.8
Control	0	0	Harvest 2	Rep 3	21.3
Control	0	0	Harvest 2	Rep 4	10.7
Event	Application	Harvest 1	Harvest 2		
Time	10/21/2005	4/25/2006	7/26/2006		

Spring 2006					
Treatment	Target rate (kg N ha⁻¹)	Fert. applied (kg N ha⁻¹)	Harvest	Replication	N uptake (kg N ha⁻¹)
AN	50	50	Harvest 1	Rep 1	34.3
AN	50	50	Harvest 1	Rep 2	36.3
AN	50	50	Harvest 1	Rep 3	36.9
AN	50	50	Harvest 1	Rep 4	35.5
AN	100	100	Harvest 1	Rep 1	49.0
AN	100	100	Harvest 1	Rep 2	52.1
AN	100	100	Harvest 1	Rep 3	46.5
AN	100	100	Harvest 1	Rep 4	43.7
AN	200	200	Harvest 1	Rep 1	66.4
AN	200	200	Harvest 1	Rep 2	97.9
AN	200	200	Harvest 1	Rep 3	83.6
AN	200	200	Harvest 1	Rep 4	67.4
UAN	70	65	Harvest 1	Rep 1	3.03
UAN	70	68	Harvest 1	Rep 2	39.5
UAN	70	67	Harvest 1	Rep 3	48.7
UAN	70	67	Harvest 1	Rep 4	42.2
UAN	140	140	Harvest 1	Rep 1	47.1
UAN	140	138	Harvest 1	Rep 2	46.6
UAN	140	134	Harvest 1	Rep 3	65.8
UAN	140	134	Harvest 1	Rep 4	71.2
Nitamin®	70	73	Harvest 1	Rep 1	24.6
Nitamin®	70	71	Harvest 1	Rep 2	38.6
Nitamin®	70	71	Harvest 1	Rep 3	40.0
Nitamin®	70	73	Harvest 1	Rep 4	40.2
Nitamin®	140	145	Harvest 1	Rep 1	54.6
Nitamin®	140	146	Harvest 1	Rep 2	78.1
Nitamin®	140	146	Harvest 1	Rep 3	52.0
Nitamin®	140	151	Harvest 1	Rep 4	51.3
Control	0	0	Harvest 1	Rep 1	13.9
Control	0	0	Harvest 1	Rep 2	7.8
Control	0	0	Harvest 1	Rep 3	21.3
Control	0	0	Harvest 1	Rep 4	10.7
Event	Application	Harvest 1			
Time	5/04/2006	7/26/2006			