Effect of slow release nitrogen fertilizers on corn production in Iowa

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Effect of slow release nitrogen fertilizers on corn production in Iowa

by

Marianela González

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
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Major: Soil Science (Soil Fertility)

Program of Study Committee:
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Iowa State University
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Graduate College  
Iowa State University

This is to certify that the master's thesis of  
Marianela González  
has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
To Tia Laura

Your life has always inspired me to reach my goals,
to explore the limits of my mind
and to appreciate the value of life.

Also to Mami

I have been with you since the beginning of my existence,
and we are always going to be one living spirit.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ix</td>
</tr>
<tr>
<td>CHAPTER 1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>General Literature Review</td>
<td>3</td>
</tr>
<tr>
<td>Soil nitrate and leaching</td>
<td>3</td>
</tr>
<tr>
<td>Controlled and slow-release nitrogen fertilizers</td>
<td>4</td>
</tr>
<tr>
<td>Urea-formaldehyde forms (UF)</td>
<td>6</td>
</tr>
<tr>
<td>Sulfur-coated urea (SCU)</td>
<td>9</td>
</tr>
<tr>
<td>Polymer-coated urea fertilizers (PCU)</td>
<td>10</td>
</tr>
<tr>
<td>CHAPTER 2. NITRIFICATION RATES OF UREA-BASED FERTILIZERS: AN INCUBATION STUDY</td>
<td>15</td>
</tr>
<tr>
<td>Literature Review</td>
<td>15</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>17</td>
</tr>
<tr>
<td>Results</td>
<td>19</td>
</tr>
<tr>
<td>Discussion</td>
<td>25</td>
</tr>
<tr>
<td>Conclusion</td>
<td>28</td>
</tr>
<tr>
<td>References</td>
<td>28</td>
</tr>
<tr>
<td>CHAPTER 3. EFFECT OF POLYMER-COATED UREA UPON THE EFFICIENCY OF FALL AND SPRING-APPLIED UREA FERTILIZER</td>
<td>32</td>
</tr>
<tr>
<td>Literature Review</td>
<td>32</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>35</td>
</tr>
<tr>
<td>Results</td>
<td>40</td>
</tr>
<tr>
<td>Discussion</td>
<td>60</td>
</tr>
<tr>
<td>Conclusion</td>
<td>66</td>
</tr>
<tr>
<td>References</td>
<td>67</td>
</tr>
<tr>
<td>CHAPTER 4. CONCLUSIONS</td>
<td>70</td>
</tr>
<tr>
<td>GENERAL REFERENCES</td>
<td>72</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>79</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

CHAPTER 2. NITRIFICATION RATES OF UREA-BASED FERTILIZERS:
AN INCUBATION STUDY

Figure 1. Average NH₄⁻N and NO₃⁻N accumulation in Harps and Okoboji for three different urea-based fertilizers. 20

Figure 2. Average NH₄⁻N and NO₃⁻N accumulation in Nicollet and Sac for three different urea-based fertilizers. 22

Figure 3. Percentage nitrogen recovery (NH₄⁻N + NO₃⁻N) in four Iowa soils treated with GP 4350, GP 4332 and urea. 24

CHAPTER 3. EFFECT OF POLYMER-COATED UREA UPON THE
EFFICIENCY OF FALL AND SPRING-APPLIED UREA
FERTILIZER

Figure 1. Corn grain yield response to N rate and N applications of fall-applied urea, fall-applied ESN and spring applied urea in 2003 (a) and 2004 (b) at the North Central Research Farm. 47

Figure 2. Average of corn grain yield treated with fall-applied urea, fall-applied ESN and spring-applied urea during two growing seasons at the North Central Research Farm. 48

Figure 3. Corn grain yield response to N rate and N applications of spring-applied ESN and urea in 2003 (a) and 2004 (b) at the North Central Research Farm. 58

Figure 4. Average of corn grain yield treated with spring-applied urea and ESN during two growing seasons at the North Central Research Farm. 59

Figure 5. Corn grain yield response to N rate and N applications of spring-applied ESN and urea in 2003 at the Northwest Iowa Research Farm. 60

Figure 6. Monthly total precipitation during 2003 and 2004 at the North Central Research Farm in Kanawha, Iowa. 61

Figure 7. Average mean temperature during 2003 and 2004 at the North Central Research Farm in Kanawha, Iowa. 62

Figure 8. Monthly total precipitation during 2003 at the Northwest Iowa Research Farm in Calumet, Iowa in 2003. 64
Figure 9. Average mean temperature during 2003 at the Northwest Iowa Research Farm in Calumet, Iowa.
LIST OF TABLES

CHAPTER 2. NITRIFICATION RATES OF UREA-BASED FERTILIZERS: AN INCUBATION STUDY

Table 1. Initial soil properties. ................................................................. 19
Table 2. Statistical analysis of NH$_4$-N and NO$_3$-N accumulations in four different Iowa soils treated with three urea-based fertilizers during an incubation study. ................................................. 23

CHAPTER 3. EFFECT OF POLYMER-COATED UREA UPON THE EFFICIENCY OF FALL AND SPRING-APPLIED UREA FERTILIZER

Table 1. Cultural practices for the fall-applied urea study at North Central Research Farm in Kanawha, 2003-2004. ................................................................. 35
Table 2. Cultural practices for the spring-applied urea study at the North Central Research Farm in Kanawha and the Northwest Iowa Research Farm in Calumet, 2003-2004. ................................................................. 39
Table 3. Corn response to fall and spring-applied urea fertilizers at the North Central Research Farm, 2003. ................................................................. 41
Table 4. Effect of fall and spring applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2003. ................................................................. 42
Table 5. Corn response to fall and spring-applied urea fertilizers at the North Central Research Farm, 2004. ................................................................. 44
Table 6. Effect of fall and spring-applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2004. ................................................................. 46
Table 7. Nitrogen efficiency of different nitrogen application treatments during two growing seasons at the North Central Research Farm. ................................................................. 49
Table 8. Corn response to spring-applied urea fertilizers at the North Central Research Farm, 2003. ................................................................. 50
Table 9. Effect of spring-applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2003. ................................................................. 52
Table 10. Corn response to spring-applied urea fertilizers at the North Central Research Farm, 2004. ................................................................. 53
Table 11. Effect of spring-applied urea fertilizers on soil NH₄-N and NO₃-N at the North Central Research Farm, 2004.

Table 12. Corn response to spring-applied urea fertilizers at the Northwest Iowa Research Farm, 2003.

Table 13. Effect of spring-applied urea fertilizers on soil NH₄-N and NO₃-N at the Northwest Iowa Research Farm, 2003.
ABSTRACT

Slow and controlled release fertilizers have often been used to prevent N loss through leaching. Recently, new slow release fertilizers have been developed and their potential use in corn production is an alternative to increase N efficiency. An incubation study was performed to measure and compare the release rates from two urea-formaldehyde (UF) liquid resins and conventional urea. Four different representative soils from corn production areas of Iowa were collected. The soils were classified as: Harps (Typic Calciaquoll), Nicollet (Aquic Hapludoll), Okoboji (Cumulic Hapludoll) and Sac (Oxyaquic Hapludoll). Soil samples (10 g) were amended with solutions containing rates of N equivalent to 0, 50, 100, 150 and 200 kg N ha⁻¹ of urea and the UF materials and incubated at 20 °C for 0, 7, 15, 30, 45 and 60 days. At the end of the respective incubation periods each sample was analyzed for nitrate-N (NO₃-N) and ammonium-N (NH₄-N). The results obtained showed that UF fertilizers might not meet the N requirements for corn production in Iowa due to the low percentage N recoveries (60 – 80% N) observed. The soils had different release rates mainly affected by pH and organic matter content.

A two year trial was conducted to assess the effect of a polymer-coated urea (ESN) fertilizer upon corn biomass and grain N uptake and yield when applied in the fall or spring. Nitrogen fertilizer rates used for urea and ESN treatments were 0, 34, 67, 101, 135, 168 and 200 kg N/ha. The results obtained showed that corn biomass was not affected by the use of ESN or urea in particular. Biomass weight and N uptake tended to respond to N rates in some treatments. Grain yield always increased with N rate. However the effect of ESN and urea application varied from one year to the next and among locations.
CHAPTER 1. INTRODUCTION

Although Nitrogen (N) is the predominant gas in the atmosphere, it is often a limiting growth factor in natural and agricultural ecosystems. In soils, only a very small percentage of the total N exits in readily available mineral forms for plants (Bremner, 1965). Nitrogen is the most important nutrient for plant growth. It plays a key role in the structure of the chlorophyll molecule, DNA, RNA, enzymes, proteins and regulation of carbohydrate production. A N deficiency might slow growth and even be detrimental to obtaining high yields. Crop biomass and yield are usually improved by addition of N fertilizers to the soil. However, this nutrient is subject to many physical, biological and/or chemical processes which influence the amount of plant available N.

Plants absorb N from soils in the form of ammonium-N (NH₄-N) and nitrate-N (NO₃-N). The ions interact differently with the soil particles due to their electric charges. Since ammonium is positively charged, it is adsorbed to the cation exchange sites of layer silicate clay minerals and soil organic matter. Ammonium can also be “fixed” or held within the lattice structures of silicate minerals and if so, it is considered unavailable to plants and microorganisms (Young and Aldag, 1982). Nitrate is negatively charged, thus it is repelled by the negatively charged surfaces of clay minerals. Nitrate is also very soluble in water. These two characteristics make nitrate susceptible to leaching and it moves freely through the soil profile to streams and groundwater. Brezonik et al. (1998) showed that nitrate leaches to tile systems before it can be used by the corn crop during normal and wet years.

Applied urea - CO(NH₂)₂ - can be easily transformed into ammonium by a hydrolytic enzyme called urease, present in soils and many organisms. The ammonium produced is in equilibrium with ammonia, which is susceptible to volatilization mostly in high pH soils. Ammonium can also be immobilized when readily available carbon sources are present.
However, most of the ammonium is usually oxidized to nitrate in a process referred to as nitrification (Schmidt, 1982).

Nitrification consists of two steps mediated by bacteria that obtain energy from oxidation-reduction reactions. *Nitrosomonas* spp oxidizes ammonium to nitrite which is then oxidized to nitrate by *Nitrobacter* spp. The supply of ammonium, population of nitrifying organisms, pH, aeration, moisture and temperature are factors that affect nitrification. Under certain conditions, biological reduction of nitrate and nitrite to gaseous forms of N may also occur through a process called denitrification.

Nitrification and/or denitrification are processes that reduce the efficiency of urea fertilizers. An improvement in the efficiency of these fertilizers will enhance crop production and reduce any detrimental effects on the environment. This issue has been approached by reducing excessive urea hydrolysis in soils by different means. From urea transformation with aldehydes, into compounds that slowly decompose in soils, to coating of urea granules with hydrophobic materials (waxes, oils, plastic, etc.) or with powders (sulfur).

During the last decade many have been concerned about the consequences of some agriculture practices on the environment. Goolsby et al. (1999) reported that 19% of the nitrate load in the Mississippi River was from the intensive corn-soybean cropping systems of Iowa. Recently, new controlled and slow-release urea based fertilizers have been developed to minimize the potential of N loss by leaching and/or denitrification. Environmentally Smart Nitrogen (ESN®) produced by Agrium, Inc. consists of a urea granule (44% N) coated with an organic, biodegradable, polymer membrane. The polymer coating is a physical protection mechanism that allows a slow release of urea over time. This fertilizer was introduced in limited quantities under the name Ndure® but it is now available as ESN®. Also, Nitamin™ is a N fertilizer developed by Georgia-Pacific Resins, Inc. and available in
different formulations (liquid, granular and coated sand). This is a urea-formaldehyde resin in which the chemical composition confers slow-release N properties.

The objectives of these studies were (i) to measure the N release rates from two Nitamin™ products, and (ii) to assess the efficiency of ESN® on corn production in Iowa compared to urea.

**General Literature Review**

The use of N to increase grain yields is a common practice in corn production. In 2003, Iowa produced almost 19% of the nation's corn for grain; 4.9 million ha were planted and 118 billion kg of corn were harvested (NASS, 2003). However, about 700 million kg of N fertilizer were applied with an average rate of 149 kg/ha (NASS, 2004). The emphasis on N fertilization in corn and its environmental effects have been a concern for many scientists (Bundy and Bremner, 1973; Randall and Schmitt, 1998; Drost et al., 2002). Research has been focused on reducing the potential N loss by leaching and thereby to reduce groundwater contamination (Malzer and Randall, 1985; Kpomblekou and Killorn, 1995).

**Soil nitrate and leaching**

Nitrate is the form of N that is leached into groundwater due to its high solubility, mobility and easy displacement by water (Follet, 2001). Ammonium concentrations, temperature, soil texture and percolation water (irrigation, precipitation) influence the rate of nitrate leaching (Oertli and Lunt, 1962; Legg and Meisinger, 1982). Delay of nitrification is a potential way to reduce leaching and improve N fertilizer efficiency (Herlihy and Quirke, 1975).

Ammonium forms of N fertilizers are rapidly transformed to nitrate by bacteria in soils through nitrification (Kpomblekou and Killorn, 1996). This is a two step oxidation process in which the inorganic N serves as an energy source to the bacteria involved (Sylvia et al.,
Bacteria of the *Nitrosomonas* spp transform the ammonia to nitrite. The nitrite formed is rapidly oxidized to nitrate by *Nitrobacter* spp bacteria (Trenkel, 1997). Nitrification rates are affected by the nitrifying population (Hadas et al., 1986), soil temperature, moisture (Sabey et al., 1969), pH, texture and substrate availability (Goring, 1962; Sylvia et al., 2005). The nitrate produced is mobile in most soils and therefore subject to being lost through leaching and denitrification, which decreases the efficiency of urea based fertilizers (Touchton et al., 1978).

Different approaches to managing N loss and efficiency in corn production have been studied including N management practices as timing of N applications, split applications, sources of N and placement of the fertilizer in the field (Stevenson and Baldwin, 1969; Welch et al., 1971; Bundy, 1986; Vertsch and Randall, 2004). Also, inhibition of nitrification has been addressed as a major alternative to prevent N loss when urea and ammonium based fertilizers are used (Goring, 1962; Bundy and Bremner, 1973; Bundy and Bremner, 1974; Kpomblekou and Killorn, 1996). Probably the most common nitrification inhibitor used is nitrapyrin (Touchton et al., 1979). Nitrapyrin restricts the oxidation of ammonium to nitrite, acting selectively on *Nitrosomas* spp (Wolt, 2000).

**Controlled and slow-release nitrogen fertilizers**

Controlled and slow-release fertilizers are often used to reduce N loss from leaching and extend N availability to plants (Wang and Alva, 1996; Wienfeld, 1986). Although there is no official differentiation between slow-release and controlled release fertilizers, N fertilizers that are microbially decomposed (such as urea-formaldehydes), are commonly referred as slow-release fertilizers and coated or encapsulated products as controlled-release fertilizers (Trenkel, 1997). In Europe, the Comité Européen de Normalisation (CEN) declared that a fertilizer may be described as slow-release if the nutrient or nutrients meet, under defined conditions including that of a temperature of 25 °C, each of the following criteria: (i) no more
than 15% released in 24 hours, (ii) no more than 75% released in 28 hours and (iii) at least about 75% released in the stated release time (Trenkel, 1997). The Association of American Plant Food Control Officials (AAPFCO, 1995) defined controlled and slow-release fertilizers as “products that delay initial availability or extend time of continued availability by a variety of mechanisms. These include controlled water solubility of the material (by semipermeable coatings, occlusion or by inherent water insoluble polymers, protein materials, or other chemical forms), by slow hydrolysis of water-soluble low molecular weight compounds, or by other unknown means.”

There are different methods to produce controlled or slow-release N fertilizers, including chemical and physical characteristics. Several controlled or slow-release nitrogen fertilizers are low solubility compounds, products of a transformation of urea with aldehydes (methylurea, thiourea, N,N-dimethylurea, phenylurea, etc.), which require microbial decomposition (Beaton et al., 1967; Alessi and Power, 1972). Another kind is the coated materials, which consist of urea granules coated with hydrophobic and water resistant materials (asphalt, waxes, oils and plastics) or with powders (sulfur) (Lawton, 1961; Brown et al., 1966; Skogley and King, 1968). Generally, some coating materials require transformation by soil microbes to release the N over a period of time. Some materials release nutrients through a membrane which may or not be soluble or the nutrients may be also incorporated into a matrix which could be coated. Finally, the release of the nutrient is delayed in some fertilizers due to a small surface to volume ratio (super-granules, plant food stakes, briquetted, tables, etc.) (Trenkel 1997). Various organic substances such as crop residues, manure, slurry, composted sewage sludge, etc., are considered slow-release fertilizers as well.

Advantages of controlled and slow-release fertilizers include (i) reduction of possible N losses in soils between the time of application and uptake by plants, (ii) reduction in
relevant gas emissions ($N_2O$), (iii) reduction of luxury consumption of nutrients, and (iv) reduction of seed injury by the fertilizer (Wang and Alva, 1996; Trenkel, 1997; Drost et al., 2002). Nonetheless, the higher cost of some controlled release fertilizers, compared with conventional fertilizers, diminishes a wider use in agriculture. Several scientists also believe that more reliable determinations of the nutrient uptake pattern are necessary because laboratory testing results often present a poor correlation with nutrient release patterns in field conditions (Trenkel, 1997).

**Urea-formaldehyde forms (UF)**

Urea-formaldehyde products were the first group of compounds on which research concerning slow release properties was carried out. In 1924, BASF received the first patent on urea-formaldehyde condensation fertilizers in Germany. In the USA they were patented in 1947 as fertilizer products. Several types of urea-formaldehyde fertilizers are manufactured in the USA, including solids, solutions and suspensions (Trenkel, 1997).

The urea-formaldehyde resins (UF-resins) are formed by the reaction of formaldehyde with excess urea. This reaction leads to the formation of a mixture of methylene urea with different length chain polymers (Tiustos and Blackmer, 1992). The urea reacts as an amine and the formaldehyde as an alcohol depending on pH, temperature, reaction time and mole proportion of urea and formaldehyde (Meyer, 1979). The molar excess of urea over formaldehyde allows the formation of low molecular weight methyleneureas that are functional as fertilizers. When formaldehyde is added in excess, high molecular weight, insoluble, and resinous products are formed, which are used in the plastic and adhesive industry (Hays, 1987).

The length of the polymer chains and their solubility affect the rate of available nitrogen released (Hays et al., 1965; Kaempffte and Luft, 1967). Three different fractions of several lengths of polymers are present in the urea-formaldehyde resins: (i) cold water
soluble (CWS), (ii) cold water insoluble but hot water soluble (HWS), and (iii) hot water insoluble (HWI) fractions (Sasson, 1979). The CWS fraction (25 °C) contains residual urea and the shortest length polymers; the nitrification rates of this fraction are comparable to urea (Hays et al., 1965, Hays and Haden, 1966). The HWS fraction (100 °C) includes polymers of intermediate chain length which are nitrified slowly (Kravolec and Morgan, 1954; Trenkel, 1996). The HWI fraction has a low mineralization rate due to the presence of the longest polymer chains whose N is unavailable or extremely slow release (Sasson, 1979; Tlustos and Blackmer, 1992). The quantitative proportion of each of these three fractions determines the N release rate and it is characterized by the activity index (AI):

\[
AI = \frac{CWISN - HWISN}{CWISN} \times 100
\]

Where CWISN is the N percentage insoluble in cold water and HWISN is the percentage of N that is insoluble in hot buffer solution (Hays et al., 1965; Hadas and Kafkafi, 1974; Trenkel, 1996).

The decomposition of UF fertilizers, and therefore the N release, is a multi-step process that varies depending on the product. Since the UF mineralization is similar to urea nitrification, the release is affected by temperature, moisture, pH, microbial activity, etc. (Hadas and Kafkafi, 1974; Sasson, 1979; Trenkel, 1996). Hadas and Kafkafi (1974) found that the rate of mineralization of an UF product significantly increased from 14°C to 24°C and increased only slightly at 34°C. They also observed that a first release period of about 3.2% of the fertilizer, was followed by a pause in mineralization that lasted longer the lower the temperature. Mineralization started again after 50 days at the 14°C treatment, after 7 days at 24°C and no real pause was detected at 34 °C. Tlustos and Blackmer (1992) found the slow-release characteristics of UF fertilizers are largely determined by the HWS and
HWIS in very acid soils, but the release of N from these fractions is insignificant in neutral or alkaline pH soils. Tlustos and Blackmer (1992) also reported that CWS fraction behaves like urea under acid soil conditions and like a mixture of urea and inactive material in soils with pH higher than neutrality.

UF resins have been used as controlled release fertilizers primarily in horticultural crops and turfgrass (Volk and Horn, 1975; Maynard and Lorenz, 1979). Volk and Horn (1975) compared the responses of six different turfgrasses to several N sources; UF fertilizer obtained the least desirable results. Hahndel (1987) found small differences in turfgrass growth treated with UF resins and IBDH (isobutylidenediurea) during late summer, but large differences in spring treatments due to UF mineralization dependence on temperature. Although Spangenberg et al. (1986) obtained better color ratings during the early turfgrass season with spray-applied urea, UF treatments had better color ratings by the end of the summer.

Potato (Solanum tuberosum L.), cantaloupe (Cucumis melo L.) and tomato (Lycopersicon esculentum Mill.) yields with UF were less than those with urea in a study conducted by Lorenz et al. (1972). They also found that about half of the N from the UF fertilizer remained in the fertilizer band after 120 days of application. However, Huang et al. (2002) obtained greater pepper (Capsicum annuum L.) fruit weight, fruit setting, fruit length and fruit width in UF treatments than in other N treatments. UF fertilizer also tended to increase total sugar and ascorbic acid content, but had little effect on dry matter. Gouin and Link (1973) studied the effect of slow-release fertilizers on growth response of several woody ornamentals growing in containers. The use of UF had little effect on growth of these ornamentals. Alessi and Power (1974) applied different N sources to a silt loam soil for 4 years to spring barley (Hordeum vulgare L.) and wheat (Triticum aestivum L.). Their results
indicated that other ammonium and nitrate sources of N were superior to UF products for small grain production.

Many methodologies to manufacture UF resins useful as fertilizer have been developed. Recently, Wertz et al. (2001) and Gabrielson (2001) developed new slow-release urea-formaldehyde liquid fertilizer resins with 31% and 28% N respectively.

**Sulfur-coated urea (SCU)**

Sulfur-coated urea (SCU) is a well known slow-release fertilizer developed by the Tennessee Valley Authority (TVA) in 1968. It consists of urea prills, coated with a mixture of amorphous and crystalline allotropes of sulfur. The sulfur mantle over the urea is sealed with a wax or plastic material to cover cracks or holes (Jarrell and Boersma, 1979). The low cost of sulfur and its importance as a plant nutrient made it convenient as a coating material (Trenkel, 1997). Although it is known that the release rate of urea from SCU is affected by soil temperature, soil water content, thickness of the coating and soil microbial activity; the mechanism by which the coatings are broken down hasn’t been clearly explained (Jarrell and Boersma, 1979; Jarrell and Boersma, 1980).

SCU has been used in different crop systems and results vary from efficient to no difference with urea or other N sources. Beauchamp (1977) compared the effect of SCU and urea on corn grain yield. No significant difference was found between the two fertilizers when applied in the fall. Similarly, McArdle and McClurg (1986) reported that neither vine growth nor fruit yield of tomato were improved by SCU. SCU has shown advantages in minimizing volatilization and leaching, thus to improve N efficiency in flooded rice fields (Vlek and Craswell, 1979). Waddel et al. (1999) concluded that SCU is a viable N source for potato production in Minnesota. SCU has been used primarily in turfgrass, bermudagrass and for horticultural purposes, in which the application method reduces the chance of cracks
or scratches in the coating and therefore loss of urea (Skogley and King, 1968; Quiroga and Picchioni, 2003; Easton and Petrovis; 2004).

A potential disadvantage of using SCU is the decrease of pH when large amounts are applied, since urea and sulfur may contribute to increase acidity (Trenkel, 1997).

**Polymer-coated urea fertilizers (PCU)**

Since 1960's the polymer industry and controlled release technology have promised to solve problems in a vast number of areas. The widespread application of polymers as reactive molecules is used in pharmaceuticals, veterinary and medical products, flavors, aromas, pesticides and fertilizers (Somerville et al., 1976; Akelah, 1995). The molecular nature of the polymer is the key factor regulating the rate of delivery and period of effectiveness of the active components (Akelah, 1995).

Belak (1966) found that free urea incorporated in polyurethane foam is slowly released into soil over a long period of time by the leaching action of water. Soon after, Hansen (1966) patented a delayed release fertilizer containing a core of fertilizer encapsulated or acted with a mixture of epoxidized soybean oil and a polyester curing agent.

The first commercial use of coated fertilizers was originally to prevent caking during handling. Since then, modified controlled release materials have been developed to satisfy N demands for a variety of crops and to reduce the influence of some field factors, for instance water content, pH, microorganisms and soil texture (Fujita et al., 1983). The polymer-coated urea (PCU) fertilizers acquire the controlled release characteristic from the thickness and composition of their coating (Zhang et al., 1994). During an incubation study, Takahashi and Ono (1996) found that individual granules of PCU had different weights and N release rates. Increase in the individual weight led to a decrease in the rate of N release.
The relationship between individual granule weight and N release might be caused by the thickness of the coating.

Though the polymer-coating varies according to the confidential manufacturing procedures of companies, there are basic components common to all of the coatings used in PCU fertilizers. The coatings are a mixture consisting of a polymer (ethylene-carbon monoxide copolymer, polyolefin, polyethylene, polyl, etc.), water permeable and impermeable resins (natural rubber, polyisoprene rubber, styrene-butadiene block copolymer, etc.), surfactants and powers such as talc, calcium carbonate, clay, starch powder, metal oxides, silica and more (Fujita et al., 1983; Shoji, 1999 cited from Pack, 2004; Geiger et al., 2003).

The composition of the coating layers determines the effect of temperature on moisture permeability and the rate of release. Fujita et al. (1983) and Gandeza et al. (1991) described the release mechanism in the following three steps: 1) the coated fertilizer absorbs moisture from the soil through the coating layers due to difference in vapor pressure, 2) the fertilizer starts showing deliquescence and forms a solution, increasing the osmotic pressure inside the granule as water is absorbed and 3) discharge pinholes of salts are created by the osmotic pressure and the solution diffuses out of the granule as a result of a chemical concentration gradient. An increase in temperature increases the difference of water vapor pressure between the outside and inside of the granule. In addition, the moisture permeability of the coating is enhanced (Fujita et al., 1983; Hummell, 1989; Shoji, 1999 cited from Pack, 2004). Consequently, the release rate will be determined by the water gradient potential (Kochba, 1990).

The permeability of polymer coatings varies with the polymer used in the manufacturing process (Zhang et al., 1994). Fujita et al. (1983) found that the dependence of moisture permeability and rate of release on temperature can be controlled by the amount
of inorganic fine powder used during the production of the coated fertilizer. The powder disperses uniformly in the resin layer creating voids in the polymer coating. The voids increase in size when more powder is added to the mixture. Any factor which acts to reduce the ease of void formation for diffusion can be expected to decrease the overall rate of permeability within a polymer matrix. Hence, because the distance which the water must move through is increased, diffusion is slowed. In addition, as the powder content increases, the $Q_{10}$ of diffusion decreases (Shoji, 1999 cited from Pack, 2004). $Q_{10}$ is the relative increase over a 10 °C interval in a chemical reaction rates and biological processes. A $Q_{10}$ = 2 is frequently asserted for biological systems (Sylvia et al., 2005). Usually, commercial fertilizers have a $Q_{10}$ around 2 to match with chemical reactions and biological processes in plants and soil microorganisms (Shoji, 1999 cited from Pack, 2004). Fujita et al. (1983) stated that 80% by weight powder content will yield a $Q_{10}$ = 1.9 and will reduce the temperature effect to the minimum value.

Nitrogen release from PCU materials is mainly affected by temperature (Gandeza et al., 1991). Cabrera (1997) reported that certain controlled release fertilizers showed a leaching pattern that closely followed changes in average daily ambient temperatures while other materials were more stable in their leaching patterns over a wider range of temperatures. Maeda (1990, cited from Pack, 2004) assessed the effects of different soil factors that influence the rate of release. In that study, it was found that temperature affects 83% of the nutrient release, moisture 11% and other soil factors (pH, microbial activity and/or other interactions) counted up to 1%. Shoji (1999 cited from Pack, 2004) reported that diffusion is reduced under extremely dry conditions, particularly in coarse textured soils.

Recently, modifications in the production of PCU and innovative coating materials have been developed and improved. Geiger et al. (2003) developed a coating product of a mixture of a polyol, an isocyanate and an organic wax. The polyol consisted of castor oil.
The production process is based on the Hudson method (Hudson et al., 1996) in which the isocyanates and polyols react to form urethanes, which are known for their abrasion resistance and tensile strength. However, instead of creating an inner urethane coating covered by an outer organic wax coating, Geiger et al. (2003) applied independent streams of polyol combined with the organic wax and streams containing the isocyanate. The steps are repeated at least twice and a final wax layer is applied with the aim of creating a controlled release fertilizer material with several coating layers. The procedure was designed to achieve a desirable release rate using less coating components than other methods.

Although, controlled release fertilizers possess many advantages to agriculture, it has been a concern that polymer-coated fertilizers may leave plastic residues that decompose extremely slowly or not at all in the soil, leading to undesirable accumulation of plastic residues (Trenkel, 1997).

PCU materials, like other controlled and slow release fertilizers, have been extensively used in the turfgrass industry where N fertilization is one of the main cultural practices (Besemer, 1963; Peacock and DiPaola, 1992; Carrow, 1997). PCU fertilizers have been also studied in crops like rice (Oryza sativa L.), potato (Solanum tuberosum L.) and barley (Hordeum vulgare) among others. Fashola et al. (2002) compared the nitrogen use efficiency of a PCU fertilizer and conventional urea in rice production under poor water management (excessive irrigation) and high N losses. PCU treated plants had a significantly higher nitrogen use efficiency and number of grains per panicle than urea treated plants. In Minnesota, the total and marketable yields of “Russet Burbank” potatoes were higher with a PCU material than urea treated plots (Zvomuya and Rosen, 2001). Similar results were found by Drost et al. (2002) in furrow-irrigated onions (Allium cepa L.) where the use of PCU or urea had no effect in bulb maturity but the soil sampling in onion beds indicated that PCU
improved the N use efficiency. Bell pepper (*Capsicum annunnm* cv Jupiter) and tomato (*Lycopersicon esculentum* L. cv Sunny) grown on fine sand (sandy siliceous hyperthemic Alfic Haplaquod) using a full-bed polyethylene mulch with irrigation, did not show improvement of fruit size or marketable yields when treated with two controlled release fertilizers and compared with potassium nitrate and ammonium nitrate (Csizinsky, 1994).

Research on PCU fertilizers has been extended to other horticultural crops such as Boston fern (*Nephrolepsis exaltata* (L.) Schott cv. Bostoniensis), Poinsettia (*Euphorbia pulcherrima* Willd. ex Klötzh cv. Freedom Red) and begonia (*Begonia x semperflorens-culturum* Hort. cv. Brandy) (Blyhte et al., 2002).

In barley, Nyberg et al. (1999) measured the influence of two PCU materials (thick and thin coatings) on mineral N release, nitrification, yield and N uptake. They found that PCU applied in spring increased yield and N uptake, and that fall applied PCU released less mineral N and nitrified more slowly over winter than regular urea.

Shoji et al. (1991) demonstrated that a PCU fertilizer was capable of supplying the N requirements of corn throughout the whole growing period under Andisol field conditions, and that that N recovery by the crop is less likely to be influenced by climate conditions such as heavy rains when PCU fertilizers are used.

It is our understanding that several products based on the technologies previously reviewed are available now in the fertilizer market. Therefore, the objectives of this study were (i) to measure and compare the release rates from two urea-formaldehyde liquid resins produced by Georgia-Pacific Resins, Inc. and conventional urea in four Iowa soils; and (ii) to assess the effect of ESN upon corn biomass and grain N uptake and yield when applied in the fall or spring.
CHAPTER 2. NITRIFICATION RATES OF UREA-BASED FERTILIZERS: AN INCUBATION STUDY

Literature Review

Nitrate leaching reduces the efficiency of nitrogen fertilizers and represents a latent source of groundwater contamination. Delay of nitrification is a potential way to reduce leaching and improve nitrogen fertilizer efficiency (Herlihy and Quirke, 1975).

Nitrification is a two step oxidation process whereby ammonium forms of N fertilizers are rapidly transformed to nitrate by soil bacteria (Kpomblekou and Killom, 1996). Ammonia is transformed to nitrite by bacteria of the Nitrosomonas spp. The nitrite formed is oxidized to nitrate by Nitrobacter spp bacteria (Trenkel, 1997). Soil temperature, moisture, pH, texture and the nitrifying population are factors that affect nitrification rates (Sabey et al., 1969; Hadas et al., 1986).

The nitrate produced can be lost through leaching due to its mobility in most soils and its high solubility in water. Under certain conditions, nitrite and nitrate biological reduction may also occur through a process called denitrification. Leaching and denitrification decrease the efficiency of urea-based fertilizers (Touchton et al., 1978). Research has been focused on improving N use efficiency by crops and thus increasing profitability, crop quality and reducing possible groundwater contamination (Wolt, 2000). Slow and controlled-release N fertilizers have been used to reduce N loss from leaching and extend N availability to plants (Wang and Alva, 1996).

Urea-formaldehyde (UF) products have been used as slow-release fertilizers in the USA since 1947. Different types of UF resins and manufacturing methodologies have been developed. Recently, Wertz et al. (2001) and Gabrielson (2001) developed new slow-release UF liquid fertilizer resins with 31% N and 28% N respectively.
The reaction of formaldehyde with excess urea leads to a mixture of methylene urea with different length chain polymers (Tlustos and Blackmer, 1992). Temperature, pH, reaction time and mole proportion affect the reaction of urea and formaldehyde (Meyer, 1979). The low molecular weight methyleneureas that are useful as fertilizers are formed due to the molar excess of urea over formaldehyde (Hays, 1987).

The rate of N release from the UF resins depends on the length of the polymer chains and their solubility (Hays et al., 1965). The N release from UF resins varies depending on the product and the proportion of three different fractions of several lengths of polymers present in the UF resins. These three fractions are: (i) cold water soluble (25 °C) (CWS), (ii) cold water insoluble but hot water soluble (100 °C) (HWS), and (iii) hot water insoluble (HWI) fractions (Sasson, 1979). The CWS fraction contains residual urea and the shortest length polymers; the nitrification rates of this fraction are comparable to urea (Hays et al., 1965, Hays and Haden, 1966). The HWS fraction includes polymers of intermediate chain length which are nitrified slowly (Kravolec and Morgan, 1954; Trenkel, 1996). The HWI fraction has a low mineralization rate due to the presence of the longest polymer chains whose N is unavailable or extremely slow release (Sasson, 1979; Tlustos and Blackmer, 1992). The quantitative proportion of each of these three fractions determines the N release rate.

Also, since UF mineralization is similar to urea nitrification, the N release rate is affected by temperature, moisture, pH and microbial activity (Hadas and Kafkafi, 1974). Hadas and Kafkafi (1974) found an increase in the rate of mineralization of a UF product when temperature was raised from 14°C to 24°C and only a slight increase at 34°C. Tlustos and Blackmer (1992) found that the release of N from the HWS and HWIS is insignificant in neutral or alkaline soils. They also reported that CWS fraction behaves like a mixture of urea and inactive material in soils with pH higher than neutrality.
UF resins have been used as controlled release fertilizers primarily in horticultural crops such as cantaloupe (*Cucumis melo* L.), tomato (*Lycopersicon esculentum* Mill.), pepper (*Capsicum annuum* L.), potato (*Solanum tuberosum* L.) and turgrass (Lorenz et al., 1972; Maynard and Lorenz, 1979; Huang et al., 2002). Alessi and Power (1973) applied different N sources to spring barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) growing on a silt loam soil for 4 years. Their results indicated that other ammonium and nitrate sources of N were superior to UF products for small grain production.

The objective of this study was to measure and compare the release rates from two new UF liquid resins produced by Georgia-Pacific Resins, Inc. and conventional urea in four Iowa soils.

**Materials and Methods**

**Soils**

Four different representative soils from corn production areas of Iowa were collected from the surface (0-15 cm) in fall 2003. The soils were classified as: Harps (Typic Calciaquoll), Nicollet (Aquic Hapludoll), Okoboji (Cumulic Hapluquoll) and Sac (Oxyaquic Hapludolls). The first three soils came from a typical Clarion-Nicollet-Webster association in Boone County, Iowa. The Sac soil was collected in Sioux County, Iowa. In the analyses reported in Table 1, pH was determined by a combination glass electrode (soil/water or 0.01 M CaCl₂ ratio, 1:2.5). The percentage of organic matter and total N were determined by dry combustion as described by Nelson and Sommers (1996) and Bremmer (1996) respectively. Particle-size distribution was determined as described by Day (1965).

**Procedure**

Soil samples (10 g) were placed in 118-ml French square bottles and amended with 1 ml of solution containing rates of N equivalent to 0, 50, 100, 150 and 200 kg N ha⁻¹ of urea
and the new Georgia Pacific materials (32% and 29.8% N). Deionized water was added to provide 0.03 MPa of soil water content (60% water holding capacity). Each bottle was covered with parafilm perforated in the center for aeration. Two replications per treatment were incubated at 20 °C for 0, 7, 15, 30, 45 and 60 days. During these periods, water loss was measured gravimetrically and replenished if the loss exceeded 1 g.

At the end of the respective incubation periods each bottle was extracted with 50 ml of 2 M KCl solution. The extract was filtered and analyzed for nitrate-N (NO\textsubscript{3}–N) and ammonium-N (NH\textsubscript{4}–N) using a QuickChem AE Automated Ion Analyzer, by the QuickChem Method 12-107-06-2-A (Lachat Instruments, 1993) for ammonia-N and QuickChem Method 12-107-04-1-B (Lachat, 1992) for nitrate-N.

The results were used to calculate the N release rates for urea and the UF materials. The percentage of N recovery was calculated for each incubation period using the following equation:

\[
\% \text{ N recovery} = \frac{\text{N recovered} - \text{N in the control}}{\text{N added}} \times 100
\]

\text{Equation 1}

Where:

\text{N recovered}= \text{mg of NO}_3\text{–N and NH}_4\text{–N in the extract},

\text{N in the control}= \text{mg of NO}_3\text{–N and NH}_4\text{–N where no N was added}

\text{N added}= \text{mg N added in the different treatments}

\textbf{Data analysis}

Data were analyzed using SAS (SAS Institute Inc., 1999). Analysis was done for NO\textsubscript{3}–N and NH\textsubscript{4}–N concentration in each soil separately. The factors analyzed were fertilizer, rate, incubation period, fertilizer * rate, incubation period * fertilizer, incubation period * rate and incubation period * rate * fertilizer. Significant differences were considered at p>F=0.1 level.
Table 1. Initial soil properties

<table>
<thead>
<tr>
<th>Soil series</th>
<th>pH (^{1})</th>
<th>% Organic matter</th>
<th>Total N</th>
<th>Inorganic N</th>
<th>Clay</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H(_2)O</td>
<td>CaCl(_2)</td>
<td></td>
<td></td>
<td>g kg(^{-1})</td>
<td>mg kg(^{-1})</td>
</tr>
<tr>
<td>Harps</td>
<td>7.9</td>
<td>7.6</td>
<td>2.1</td>
<td>13.0</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>Nicollet</td>
<td>6.1</td>
<td>5.4</td>
<td>2.2</td>
<td>9.8</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Okoboji</td>
<td>7.6</td>
<td>7.3</td>
<td>3.0</td>
<td>16.0</td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td>Sac</td>
<td>6.5</td>
<td>6.0</td>
<td>6.21</td>
<td>13.0</td>
<td>37</td>
<td>23</td>
</tr>
</tbody>
</table>

\(^{1}\)Subgroups: Harps, Typic Calciaquoll; Nicollet, Aquic Hapludoll; Okoboji, Cumulic Haplquoll; Sac, Oxyaquic Hapludoll.

Nitrification Rates

The Harps soil had the highest pH and organic matter percentage, followed by Okoboji (Table 1). Both soils had a similar behavior in the nitrification process of the three urea-based fertilizers (Figure 1). The NO\(_3\)-N concentration at 0 days was close to 0 mg/kg in Okoboji and Harps, while the NH\(_4\)-N concentration was relatively higher in Harps (from 15.23 to 21.38 mg/kg) and lower in Okoboji (from 4.2 to 6.3 mg/kg). The NH\(_4\)-N concentration decreased as the NO\(_3\)-N production increased, reaching the highest NO\(_3\)-N concentration between 30 and 45 days. Greatest NO\(_3\)-N production was observed in the urea treatment, followed by GP 4332 (32% N) and GP 4350 (29.8% N) in Harps and Okoboji. Ammonium and NO\(_3\)-N concentrations were significantly affected by the different urea-based fertilizers, rate, incubation period and all the interactions listed in Table 2 in Harps and Okoboji.
Figure 1. Average NH$_4$-N and NO$_3$-N accumulation in Harps and Okoboji for three different urea-based fertilizers.

Nicollet and Sac soils had lower pH and organic matter percentage than Harps and Okoboji (Table 1). The nitrification process in Nicollet and Sac differed from the one observed in the other two soils (Figure 2). The initial NH$_4$-N concentration (0 days) was
higher in Sac (from 18.44 to 24.84 mg/kg) than in Nicollet (from 6.52 to 14.32 mg/kg). The NO₃-N concentration at 0 days was close to 0 mg/kg. An accumulation of NH₄-N was observed in both soils from 0 days to 15 days. The NH₄-N concentration tended to increase from GP 4350, GP 4332 to urea, and it was higher in Sac than in Nicollet. After 15 days of incubation, the NH₄-N concentration started to diminish. The NO₃-N production in Nicollet increased progressively from the beginning of the incubation and reached a maximum between 45 and 60 days. The NO₃-N concentration started to increase after 15 days of incubation in the Sac soil and reached a maximum between 45 and 60 days. At the end of the incubation period, there was still NH₄-N present in the GP 4350 and urea treatments in the Sac soil. The NO₃-N concentrations were lower in Sac than in Nicollet.

In Nicollet, the greatest NO₃-N concentration was observed in the urea treatment, followed by GP 4332 and GP 4350, respectively. The highest NO₃-N concentration occurred in the GP 4332 treatment in Sac.

Ammonium and NO₃-N concentration in Nicollet was significantly affected by the fertilizer, rate, incubation period and all the interactions analyzed except fertilizer * rate (p>F=0.3328) for the NH₄-N concentration (Table 2). The NH₄-N concentration was not significantly affected by the incubation period*rate*fertilizer interaction (p>F=0.1536) in Sac. The rest of the factors analyzed were significant. The NO₃-N concentration was significantly affected by all the factors listed in Table 2 except fertilizer*rate (p>F=0.4781) in Sac.
Figure 2. Average NH$_4$-N and NO$_3$-N accumulation in Nicollet and Sac for three different urea-based fertilizers.
Table 2. Statistical analysis of NH$_4^+$-N and NO$_3^-$-N accumulations in four different Iowa soils treated with three urea-based fertilizers during an incubation study.

<table>
<thead>
<tr>
<th>Soil</th>
<th>p &gt; F NH$_4^+$ - N</th>
<th>p &gt; F NO$_3^-$ - N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fertilizer * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate * Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Nicollet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>0.01</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fertilizer * Rate</td>
<td>0.3328</td>
<td>0.0172</td>
</tr>
<tr>
<td>Incubation period * Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate * Fertilizer</td>
<td>0.008</td>
<td>0.0012</td>
</tr>
<tr>
<td>Okoboji</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fertilizer * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate * Fertilizer</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sac</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>0.08</td>
<td>0.0134</td>
</tr>
<tr>
<td>Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fertilizer * Rate</td>
<td>0.0455</td>
<td>0.4751</td>
</tr>
<tr>
<td>Incubation period * Fertilizer</td>
<td>0.016</td>
<td>0.088</td>
</tr>
<tr>
<td>Incubation period * Rate</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Incubation period * Rate * Fertilizer</td>
<td>0.1536</td>
<td>0.517</td>
</tr>
</tbody>
</table>
Figure 3. Percentage nitrogen recovery (NH₄-N + NO₃-N) in four Iowa soils treated with GP 4350, GP 4332 and urea.
Percentage recovery of inorganic N ($\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$)

In Okoboji, most of the N ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) was recovered between 7 and 15 days from the three fertilizers used (Figure 3). In the urea treatment, 100% N was recovered at 15 days of incubation. GP 4332 also reached a maximum at 15 days but only 72% N was recovered. The maximum recovery from GP 4350 occurred at 45 days but only 72% N was recovered.

About 40% was recovered at 0 days of incubation for the three fertilizers in the Harps soil. At 7 days, 100% N from the urea treatment was recovered and 64% N from GP 4332, while GP 4350 reached its maximum recovery percentage at 45 days with 65% N recovered (Figure 3).

All through the incubation period, Nicollet showed fluctuations on the percentage recovery of the three fertilizers used (Figure 3). However, the maximum N percentage was also recovered between 7 and 15 days. At 7 days, 100% N was recovered from the urea treatment and 82% from GP 4350 and 82% N from GP 4332 at 15 days of incubation.

In Sac soil, from 40% and 55% N was recovered at 0 days from the three fertilizer treatments. Percentages increased from 7 to 30 days, reaching a maximum at 30 days. About 80% N was recovered from GP 4332 and GP 4350 and 95% from Urea at 30 days of incubation (Figure 3).

DISCUSSION

The nitrate accumulation results suggest that nitrification rates vary from one soil to another and are affected by the soil chemical properties. Rapid oxidation of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ accumulation were observed in Harps and Okoboji. Both of these soils had a high initial pH and high organic matter content (Table 1). Accumulation of $\text{NH}_4\text{-N}$ was observed at the beginning of the incubation period and delay in $\text{NO}_3\text{-N}$ accumulation in Nicollet and Sac.
Justice and Smith (1962) observed that higher ammonium concentrations showed an inhibiting effect on nitrification. Many other factors can influence differences in nitrification among the soils studied. Organic matter content and pH might have affected the initial nitrifying populations and complete nitrification process in Nicollet and Sac. Dancer et al. (1973) found that NO$_3$-N accumulation decreased with a decrease in soil pH. Growth and metabolism of nitrifying bacteria is optimal in the neutral to slightly alkaline range (pH 7-8). Complete nitrification is also a pH dependant process. At alkaline pH, free ammonia is toxic, and at low pH nitrous acid is toxic to Nitrobacter (Focht and Verstraete, 1977).

The activity and proliferation of Nitrosomonas spp and Nitrobacter spp may also explain the differences seen among the four soils studied. Morrill and Dawson (1967) found a delay in NO$_3$-N production due to high initial activity of Nitrosomonas spp accompanied by a long lag in proliferation of Nitrobacter spp. Although, nitrite was not measured during the incubation period, in some soils it is expected to find an accumulation of nitrite before the nitrate production starts to increase (Frakenberger and Tabatabai, 1982). Dancer et al. (1973) suggested that nitrite accumulates in neutral or alkaline soils because of Nitrobacter spp limiting nitrification.

Though it has been reported that nitrification rates appear to be greater with increasing clay content (Focht and Verstrate, 1977), these results obtained do not support that tendency. Ammonium fixation might have caused this inconsistency, primarily in clay present in Sac, which had the highest clay content but the lowest NO$_3$-N accumulations. The NO$_3$-N accumulation in the soils studied seemed to be the result of a complex relationship among the soil factors, more than the effect of one factor in particular.

Among the three urea-based fertilizers used, urea had the highest NO$_3$-N accumulations except in Sac, followed by GP 4332 and GP 4350 respectively. Ammonium fixation might have occurred in Sac but no measurements were made. It is also possible that
high NH$_4$-N concentrations might have had an inhibiting effect on the nitrite oxidizer population. Similar results were observed in the 200 kg/ha rates in the urea treatments in three of the soils. Justice and Smith (1962) found that highest N treatments delayed nitrification, which was associated with high concentrations of NH$_4$-N.

The N percentage recovery showed that most of the N applied in the urea treatment can be easily recovered within 7 to 15 days after application. GP 4332 and GP 4350 had lower percentage recoveries. Only 60 to 80% N was recovered from these products in all the soils examined. The lowest N percentage recoveries in the urea treatment were found in Sac. Ammonium fixation, ammonia loss, N immobilization by microorganisms and/or nitrite accumulation might have taken place (Kpombleukou and Killorn, 1996). However, none of these mechanisms were measured in the present study.

Differences in the N percentage recovery among urea and the UF fertilizers may be due to the mineralization properties of these slow-release fertilizers and properties of soils to which they were applied. Mineralization of UF compounds depends on the molecular ratio of urea and formaldehyde and the preparation method (Banerjee and Srivastava, 1979). This could explain also the differences found between GP 4332 and GP 4350.

The short and intermediate polymer lengths are responsible for the short and medium term N availability. Tlustos and Blackmer (1992) found that the release of N from the hot water soluble fraction (HWS) in an UF fertilizer is insignificant in neutral and alkaline soils, and that the cold water soluble fraction (CWS) behaves like a mixture of urea and inert materials in alkaline soils. According to the results obtained, the CWS might have been the most important fraction in providing N in the soils studied, since the HWS might have been affected by pH and reflected in the reduction of the N percentage. Basabara (1963) reported 2 to 5% higher nitrate production from UF compounds in soils with an initial pH 5.7 than in soils having an initial pH 7.0. The nitrate accumulations were slightly higher in Nicollet (pH
6.1) than in Sac, Okoboji and Harps for both UF fertilizers. All of these factors might lead to insufficient N in the soil for corn growth in Iowa, or will require higher UF N rates in order to fulfill corn N requirements. Another possibility is the modification of the molecular structure of the polymers to make able to release higher N contents through the whole growing season.

CONCLUSION

The use of UF fertilizers tested might not fulfill the N requirements for corn production in Iowa due to the low percentage N recoveries (60 – 80% N) observed.

It is also complicated to predict the behavior of these slow-release fertilizers in different soils. Factors related to the soil and the solubility of the fertilizers influence the N release pattern of the fertilizer. Organic matter content and soil pH might have influenced the mineralization of the fertilizers as well as the nitrifying bacteria populations, which might have affected the nitrate accumulation in the soils studied.

Although the fertilizer, rate, incubation period and their interactions were significant for most of the soils studied, other factors such as nitrite accumulation, NH$_4$-N fixation and/or ammonia loss might have affected the results obtained. Future experiments should take into account these potential mechanisms to occur. It would be also helpful to have more knowledge about the specific composition of the CWS and HWS fractions of the UF fertilizers produced by Georgia-Pacific Resins, Inc.

REFERENCES


CHAPTER 3. EFFECT OF POLYMER-COATED UREA UPON THE EFFICIENCY
OF FALL AND SPRING-APPLIED UREA FERTILIZER.

**Literature Review**

Corn crop biomass and yield are usually improved by addition of N fertilizers to the soil. However, this nutrient is subject to many physical, biological and/or chemical processes which influence the amount of plant available N.

Applied urea can be easily transformed into ammonium by a hydrolytic enzyme called urease, present in soils and many organisms. The ammonium produced is in equilibrium with ammonia, which is susceptible to volatilization mostly in high pH soils. Because ammonium is positively charged, it is adsorbed to the cation exchange sites of layer silicate clay minerals and soil organic matter. Ammonium can be "fixed" or held within the lattice structures of silicate minerals and if so, it is considered unavailable to plants and microorganisms (Young and Aldag, 1982). Ammonium can also be immobilized when readily available carbon sources are present. However, most of the ammonium is usually oxidized to nitrate in a process referred to as nitrification (Schmidt, 1982).

Nitrification is a two step oxidation process in which the inorganic N serves as an energy source to the bacteria involved (Sylvia et al., 2005). Bacteria of the *Nitrosomonas* spp transform the ammonia to nitrite. The nitrite formed is rapidly oxidized to nitrate by *Nitrobacter* spp bacteria (Trenkel, 1997).

The nitrate produced is mobile in most soils and therefore subject to being lost through leaching and denitrification, which decreases the efficiency of urea based fertilizers (Touchton et al., 1978). Nitrate is leached into groundwater due to its high solubility, mobility and easy displacement by water (Follet, 2001). Ammonium concentrations, temperature, soil
texture and percolation water (irrigation, precipitation) influence the rate of nitrate leaching (Oertli and Lunt, 1962; Legg and Meisinger, 1982).

Controlled and slow release fertilizers have often been used to reduce N leaching and extend N availability to plants in several horticultural crops and turfgrasses. Urea coated materials are controlled release fertilizers, which consist of urea granules coated with hydrophobic and water resistant substances (asphalt, waxes, oils and plastics) or with powders (sulfur) (Lawton, 1961; Brown et al., 1966; Skogley and King, 1968).

Polymers have been used as reactive molecules to regulate the rate of delivery and period of effectiveness of active components in pharmaceutical products, aromas, pesticides and fertilizers (Akelah, 1995). The polymer-coated urea (PCU) fertilizers acquire the controlled release characteristic from the thickness and composition of their coating (Zhang et al., 1994). The coatings are a mixture consisting of a polymer (ethylene-carbon monoxide copolymer, polyolefin, polyethylene, polyol, etc.), water permeable and impermeable resins (natural rubber, polyisoprene rubber, styrene-butadiene block copolymer, etc.), surfactants and powders such as talc, calcium carbonate, clay, starch powder, metal oxides, silica and more (Fujita et al., 1983; Shoji, 1999 cited from Pack, 2004; Geiger et al., 2003).

The composition of the coating layers determines the effect of temperature on moisture permeability and the rate of release. An increase in temperature will enhance the moisture permeability of the coating (Fujita et al., 1983; Hummell, 1989; Shoji, 1999 cited from Pack, 2004), and will affect the N release rates from the PCU material (Gandeza et al., 1991).

Maeda (1990, cited from Pack, 2004) assessed the effects of different soil factors that influence the rate of release. It was found that temperature affects 83% of the nutrient release, moisture 11% and other soil factors (pH, microbial activity and/or other interactions) counted up to 1%.
In corn production, different approaches to managing N loss and efficiency have been studied including N management practices as timing of N applications, split applications, sources of nitrogen and placement of the fertilizer in the field (Stevenson and Baldwin, 1969; Welch et al., 1971; Bundy, 1986; Vertsch and Randall, 2004).

Timing of N fertilizer applications is an important factor that affects the efficiency of N fertilizer primarily because of the period of time between application and uptake by the crop. Long exposure times of the N fertilizer in the field will increase the chances of N loss through processes such as leaching and denitrification (Bundy, 1986). Leaching losses occur more frequently on well-drained soils while denitrification occurs primarily on poorly drained soils under warmer temperatures. Excess precipitation will enhance the losses through these processes (Randall and Schmitt, 1998).

Fall N recommendations usually specify use of ammonium forms of N and delay of application until soil temperatures reach 10 °C, which retards nitrification of ammonium (Bundy, 1986).

Application of N in the fall has several logistical and economic advantages; better distribution of labor and equipment demands, time savings during spring planting season, lower N costs in some years, and frequently more favorable soil conditions for field work (Bundy, 1986; Randall and Schmitt, 1998).

Recently, new controlled and slow-released urea based fertilizers have been developed to minimize the potential of N loss by leaching and/or denitrification. The objective of this study was to assess the effect of ESN, a slow release fertilizer, upon corn biomass and grain N uptake and yield when applied in the fall or spring.
**Materials and Methods**

**FALL-APPLIED UREA STUDY**

**Description**

The study was conducted over two growing seasons (2003 and 2004) on the North Central Research Farm near Kanawha, Iowa.

Treatments were arranged as a factorial in a randomized complete block design with four replications. Each experimental unit measured 4.6 m by 12.2 m. Polymer-coated urea (ESN) and urea were hand-applied in the fall. Another set of urea treatments was applied in the spring before planting. Nitrogen fertilizer rates used for all the treatments were 0, 34, 67, 101, 135, 168 and 200 kg N/ha. Six rows of corn were planted in each plot and spaced 76 cm apart. Information about the cultural practices is listed in Table 1. Corn crops followed soybean in both years.

Table 1. Cultural practices for the fall-applied urea study at North Central Research Farm in Kanawha, 2003-2004.

<table>
<thead>
<tr>
<th>N application / Year</th>
<th>Treatment Application</th>
<th>Planting Date</th>
<th>Hydrid</th>
<th>Seed Density seeds/ha</th>
<th>Harvest Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Urea</td>
<td>December 12, 2002</td>
<td>April 26, 2003</td>
<td>DeKalb 53-32</td>
<td>74627</td>
<td>October 18, 2003</td>
</tr>
<tr>
<td>Fall ESN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring Urea</td>
<td>April 26, 2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Urea</td>
<td>November 21, 2003</td>
<td>April 28, 2004</td>
<td>DeKalb 53-32</td>
<td>79075</td>
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<tr>
<td>Fall ESN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring Urea</td>
<td>April 10, 2004</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Stalk biomass production

Whole plant samples were collected after the crop reached physiological maturity. Six plants from the middle two rows at approximately 1 m into the plot were cut at ground level and their ears were removed. The plant samples (excluding the ears) were chopped and weighed. A sub-sample was taken, dried at 38 °C and ground. Nitrogen content was determined using the Hach Plant Tissue and Tissue Analysis System (Hach Company, 1988). A 0.25 g sub-sample was weighed for each plot and digested with concentrated sulfuric acid and hydrogen peroxide (50% H₂O₂). Total N was determined by using Nessler’s procedure and a Hach DR/3000 Spectrophotometer, as described in the method for Nitrogen Analysis in Total Plant Tissue (Hach Company, 1988). Dry weight and % total N were used to calculated N uptake.

Grain yield

The three center rows of each plot were harvested with a combine in each plot. Grain weight and moisture were recorded. A sub-sampled of grain was taken and oven dried at 60 °C. The sample was weighed before and after drying to calculate moisture content. Yields were recalculated based on dry weight and are reported at 15.5% moisture. Nitrogen content was determined and N uptake was calculated as mentioned in the previous section for whole plant samples. N efficiency was calculated for each year and each nitrogen treatment by using regression equations of yield vs. N rate (Figure 1). The derivative of each equation was used for calculating the maximum yield and the nitrogen required to obtain that specific grain yield.

\[
\text{N efficiency} = \frac{\text{Max. yield}}{\text{N rate}} \quad \text{Equation 1}
\]

Where:

N efficiency= kg grain produced per kg N applied at maximum yield
Max. yield = calculated maximum yield (kg grain/ha)

N rate = Nitrogen rate required to obtain the calculated maximum yield (kg N/ha)

Soil sampling and N analysis

After harvest, soil samples were randomly collected to a depth of 30 cm and 61 cm from plots corresponding to N rates of 0, 101 and 200 kg N/ha. Each sample consisted of three cores taken at the same depth. The samples were dried at 38 °C and ground through a 2 mm sieve. A 10 g sub-sample was weighed and extracted with 50 ml 2 M KCl solution. The extract was filtered and analyzed for nitrate-N (\(\text{NO}_3^-\)-N) and ammonium-N (\(\text{NH}_4^+\)-N) using a QuickChem AE Automated Ion Analyzer, by the QuickChem Method 12-107-06-2-A (Lachat Instruments, 1993) for ammonia-N and QuickChem Method 12-107-04-1-B (Lachat, 1992) for nitrate-N.

The soil type in the 2003 trial was Canisteo (Typic Endoaquolls) and Clarion (Typic Hapludoll) in the 2004 trial.

Data analysis

SAS (SAS Institute Inc., 1999) was used to analyze the data. Analysis was done for each year separately. The factors analyzed were N application, N rate and N application * N rate. Nitrate and \(\text{NH}_4^+\)-N content in soils were also analyzed for each year separately. The factors analyzed were N rate, N application, depth, N rate * N application, depth * rate, N application * depth and depth * rate * treatment. Differences were considered to be significant at the p>F=0.10 level.

SPRING-APPLIED UREA STUDY

Description

This study was conducted at two different sites over two years (2003-2004). One site was located at the North Iowa Research Farm near Kanawha, Iowa. The other site was located on the Northwest Iowa Research Farm near Calumet, Iowa.
Treatments were arranged as a factorial in a randomized complete block design with four replications. ESN and urea were hand-applied in the spring at the following N rates: 0, 34, 67, 101, 135, 168 and 200 kg N/ha. At the North Central Research Farm, each experimental unit measured 4.6 m by 12.2 m and contained six rows of corn spaced at 76 cm. The experimental units at the Northwest Iowa Research Farm were 3 m by 12 m. Each plot contained 4 rows of corn spaced at 76 cm. Information about cultural practices in both sites and years is presented in Table 2. Corn crops followed soybean in both years.

Stalk biomass production, soil sampling and N analysis were performed as described above in the Fall-applied urea study.

Grain yield

In 2003, at the North Central Research Farm the three center rows in each plot were harvested with a combine. Grain weight and moisture were recorded. In 2004 at the same location, two or three of center rows were machine harvested. Grain yield was measured by harvesting only two rows of each plot at Calumet in 2003. Weight was recorded in all the plots. A sub-sample of grain was taken and oven dried at 60 °C. The sample was weighed before and after drying to calculate moisture content. Yields were recalculated based on dry weight and are reported at 15.5% moisture. N content was determined and used to calculate N uptake.
Table 2. Cultural practices for the spring-applied urea study at the North Central Research Farm near Kanawha and the Northwest Iowa Research Farm near Calumet, 2003-2004.

<table>
<thead>
<tr>
<th>Site / Year</th>
<th>Treatment Application</th>
<th>Planting Date</th>
<th>Hydrid</th>
<th>Seed Density seeds/ha</th>
<th>Harvest Date</th>
</tr>
</thead>
<tbody>
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<td>2003</td>
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<td>North Central Research Farm</td>
<td>May 3, 2003</td>
<td>April 26, 2003</td>
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<td>74133</td>
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</tr>
<tr>
<td>2004</td>
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<td>North Central Research Farm</td>
<td>April 17, 2004</td>
<td>April 28, 2004</td>
<td>DeKalb 53-32</td>
<td>79075</td>
<td>October 16, 2004</td>
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<td>Northwest Iowa Research Farm</td>
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<td>April 30, 2004</td>
<td>H-8294</td>
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</tbody>
</table>

Data analysis

The data analysis was done as described previously. However, in this study the data for each location and each year were analyzed separately.

Results

FALL-APPLIED UREA STUDY

Growing season 2003

Stalk biomass production

Yield was significantly affected only by N rate (Table 3). The average yield for the fall urea application was 7853 kg ha⁻¹, 7831 kg ha⁻¹ for fall-applied ESN and 7682 kg ha⁻¹ for the spring-applied urea. Nitrogen application did not significantly affect yield (p>F=0.7960). The greatest yield of 9222 kg ha⁻¹ was obtained by addition of 168 kg ha⁻¹ of N for the fall-applied
For the fall-applied urea, the plots treated with 135 kg ha\(^{-1}\) of N produced 9126 kg ha\(^{-1}\), and plots with 202 kg ha\(^{-1}\) of N yielded 8495 kg ha\(^{-1}\) for the spring-applied urea.

Nitrogen uptake in plant tissue was significantly affected by N rate (\(p>F=<0.0001\)). Nitrogen uptake tended to increase with addition of N (Table 3). The mean N uptake for fall-applied urea was 46 kg ha\(^{-1}\), 48 kg ha\(^{-1}\) for the fall-applied ESN and 52 kg ha\(^{-1}\) for the spring-applied urea. In all the N application treatments, the maximum N uptake was reached by addition of 202 kg N ha\(^{-1}\). The N application and N rate *N application interaction were not significant.

**Grain production**

Nitrogen rate and N application were significantly affected by treatments (Table 3). The mean yield was 11028 kg ha\(^{-1}\) for the fall-applied ESN. Fall-applied urea plots yielded 10400 kg ha\(^{-1}\). Spring-applied treatments yielded 10795 kg ha\(^{-1}\). The highest yield of 12330 kg ha\(^{-1}\) was obtained by addition of 202 kg ha\(^{-1}\) of N for the fall-applied urea treatment, 168 kg N ha\(^{-1}\) produced 12093 kg grain ha\(^{-1}\) for the fall-applied ESN and 202 kg N ha\(^{-1}\) were necessary to produce a yield of 11840 kg grain ha\(^{-1}\) for the spring-applied treatments.

The grain N uptake had a significant response to N rate (\(p>F=<0.0001\)). Addition of N tended to increase the grain N uptake (Table 3). Nitrogen application was significant for N uptake (\(p>F=0.0041\)). The mean N uptake of fall-applied urea was 94 kg ha\(^{-1}\), 103 kg ha\(^{-1}\) for fall-applied ESN and 102 kg ha\(^{-1}\) for spring-applied urea. The N rates that produced the highest yields also had the highest N uptakes in the grain. Grain yield response to N rate and N application is shown in Figure 1. The N rate *N application interaction was not significant.
Table 3. Corn response to fall and spring-applied urea fertilizers at the North Central Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate</th>
<th>N uptake</th>
<th>Yield&lt;sup&gt;a&lt;/sup&gt;</th>
<th>N uptake</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt;</th>
<th>N uptake</th>
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<td></td>
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<tr>
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</tr>
<tr>
<td></td>
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<td>9126</td>
<td>10841</td>
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</tr>
<tr>
<td></td>
<td>168</td>
<td>7822</td>
<td>11422</td>
<td>117</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>202</td>
<td>7727</td>
<td>12330</td>
<td>118</td>
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<td>10955</td>
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<td>8210</td>
<td>11259</td>
<td>114</td>
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<td>8158</td>
<td>11357</td>
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<td>11679</td>
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<td></td>
<td>202</td>
<td>8495</td>
<td>11840</td>
<td>121</td>
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<td></td>
</tr>
<tr>
<td>Spring urea 2003</td>
<td></td>
<td>7682</td>
<td>52</td>
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<tr>
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<td>8495</td>
<td>11840</td>
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<tr>
<td>Spring urea 2003</td>
<td></td>
<td>7682</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Statistics**

- N rate: 0.0004 < 0.0001 < 0.0001
- N application: 0.7960 0.2939 0.0584 0.0041
- N rate* N application: 0.2361 0.4479 0.7414 0.2112

<sup>a</sup> dry weight

<sup>b</sup> 15.5% moisture
Soil analysis

Concentration of NH$_4$-N was higher in the depth of 0 - 30 cm than the 30 - 61 cm for all the N treatments (Table 4). Depth was the only significant factor in the concentration of NH$_4$-N in the soil at North Central Farm in 2003 (p>F=<0.0001). Addition of higher N rates did not significantly change the NH$_4$-N concentration in soil. Although NH$_4$-N concentration was higher for the fall-applied ESN at a depth of 0 - 30 cm, the difference was not significant (p>F=0.6872). None of the interactions among the factors analyzed and listed in Table 4 were significant.

Table 4. Effect of fall and spring applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate kg ha$^{-1}$</th>
<th>NH$_4$-N mg kg$^{-1}$ depth (cm)</th>
<th>NO$_3$-N mg kg$^{-1}$ depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall urea 2002</td>
<td>0</td>
<td>4.3 0.9</td>
<td>1.7 0.3</td>
</tr>
<tr>
<td></td>
<td>101</td>
<td>5.1 0.8</td>
<td>1.7 0.2</td>
</tr>
<tr>
<td></td>
<td>202</td>
<td>4.7 0.9</td>
<td>2.1 0.4</td>
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<tr>
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<td></td>
<td>4.7 0.9</td>
<td>1.8 0.3</td>
</tr>
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<td>Fall ESN 2002</td>
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<td>1.3 0.3</td>
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<td>101</td>
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<tr>
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<td>202</td>
<td>5.4 1.0</td>
<td>3.4 1.9</td>
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<td>5.2 1.0</td>
<td>2.2 0.8</td>
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<td>1.3 0.2</td>
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<td></td>
<td>202</td>
<td>6.4 0.9</td>
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<tr>
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<td>4.8 1.2</td>
<td>1.8 0.3</td>
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Statistics

<table>
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<td>Depth</td>
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<tr>
<td>N rate</td>
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<td>Depth * N rate</td>
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<td>0.6872</td>
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<tr>
<td>Depth * N application</td>
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<td>N rate * N application</td>
<td>0.7617</td>
</tr>
<tr>
<td>Depth * N rate * N application</td>
<td>0.4139</td>
</tr>
</tbody>
</table>
Nitrate concentrations were also higher in the depth of 0 - 30 cm than at 30 - 61 cm (p>F=<0.0001) (Table 4). Addition of 202 kg ha\(^{-1}\) of N tended to increase NO\(_3\)-N concentrations for all the N application treatments. Fall-applied ESN had higher NO\(_3\)-N concentrations at both depths, though N application was not significant (p>F=0.2146).

**Growing season 2004**

**Stalk biomass production**

Yield was significantly affected by N rate (p>F=0.0038). Yield increased with addition of N (Table 5). N application and the N rate * N application interaction were not significant. The mean yield was 4732 kg ha\(^{-1}\), 4891 kg ha\(^{-1}\) and 4316 kg ha\(^{-1}\) for fall-applied urea, fall-applied ESN and spring-applied urea, respectively. The greatest yield of 5900 kg ha\(^{-1}\) was obtained by addition of 202 kg N ha\(^{-1}\) for the fall-applied urea, followed by 5796 kg ha\(^{-1}\) produced by plots treated with 202 kg ha\(^{-1}\) of N for the fall-applied ESN, and 5480 kg ha\(^{-1}\) from 168 kg N ha\(^{-1}\) plots for fall-applied urea treatment.

N uptake response to N rate was significant (p>F=<0.0001). It tended to increase with addition of N (Table 5). The mean N uptake for fall-applied urea, fall-applied ESN and spring-urea was 39 kg ha\(^{-1}\), 38 kg ha\(^{-1}\) and 43 kg ha\(^{-1}\), respectively. Nitrogen application and the N rate * N application interaction were not significant.
Table 5. Corn response to fall and spring-applied urea fertilizers at the North Central Research Farm, 2004.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate</th>
<th>Yield&lt;sup&gt;a&lt;/sup&gt;</th>
<th>N uptake</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt;</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>kg ha&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fall urea 2003</td>
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<td>18</td>
<td>8718</td>
<td>88</td>
</tr>
<tr>
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<td>19</td>
<td>10225</td>
<td>100</td>
</tr>
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</tr>
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<td>10956</td>
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<td>135</td>
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<td>22</td>
<td>12042</td>
<td>123</td>
</tr>
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<td></td>
<td>168</td>
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<td>39</td>
<td>12196</td>
<td>131</td>
</tr>
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<td>202</td>
<td>5353</td>
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</tr>
<tr>
<td>Average</td>
<td></td>
<td>4732</td>
<td>26</td>
<td>11174</td>
<td>116</td>
</tr>
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<td>Fall ESN 2003</td>
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<td>8937</td>
<td>88</td>
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<tr>
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<td>10202</td>
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<td>4891</td>
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<td>9079</td>
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Statistics

<table>
<thead>
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</tr>
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<td>0.0038                  &lt;0.0001 &lt;0.0001 &lt;0.0001</td>
</tr>
<tr>
<td>N application</td>
<td>0.1375                  0.8286 0.0251 0.0251</td>
</tr>
<tr>
<td>N rate* N application</td>
<td>0.6299 0.8303 0.8823 0.4921</td>
</tr>
</tbody>
</table>

<sup>a</sup> dry weight
<sup>b</sup> 15.5% moisture
Grain production

N rate and N application significantly affected grain yield (Table 5). Addition of N increased grain yield. The mean yield for the fall-applied urea treatment was 11,174 kg ha\(^{-1}\). The fall-applied ESN yielded 11,177 kg ha\(^{-1}\). The spring-applied urea yielded 11,456 kg ha\(^{-1}\). The highest yields in the different N applications were obtained by addition of 202 kg ha\(^{-1}\). These yields were 12,637 kg ha\(^{-1}\), 12,459 kg ha\(^{-1}\) and 12,796 kg ha\(^{-1}\) for the fall-applied urea, fall-applied ESN and spring-applied urea, respectively.

Grain N uptakes were significantly affected by N rate (p>F=<0.0001) and N application (p>F=0.0251) (Table 5). The mean N uptake for fall applied urea and fall-applied ESN treatments was 116 kg ha\(^{-1}\) and 122 kg ha\(^{-1}\) for spring-applied urea. The greatest N uptake of 148 kg ha\(^{-1}\) was observed at the spring-applied urea with addition of 168 kg ha\(^{-1}\). The highest N uptake of 134 kg ha\(^{-1}\) was reached in the fall-applied ESN treatment by addition of 202 kg ha\(^{-1}\). A maximum N uptake of 131 kg ha\(^{-1}\) was reached by adding 168 kg ha\(^{-1}\) for the fall-applied urea. Grain yield response to N rate and N application in 2004 is shown in Figure 1.

Soil analysis

Depth was the only factor that significantly affected NH\(_4\)-N concentration in soil at North Central Farm in 2004 (p>F=<0.0001). Ammonium concentrations were higher in the 0 - 30 cm depth. Nitrogen rate, N application and all the interactions listed in Table 6 were not significant.

Nitrate concentrations were significantly affected by depth (p>F=0.0017). Higher nitrate concentrations were found in the 0 - 30 cm depth (Table 6). Addition of N tended to increase NO\(_3\)-N concentrations at both depths (p>F=<0.0001). N application did not significantly affected NO\(_3\)-N concentration (p>F=0.1399).
Table 6. Effect of fall and spring-applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2004.

<table>
<thead>
<tr>
<th>N application</th>
<th>NH$_4$-N (mg kg$^{-1}$)</th>
<th>NO$_3$-N (mg kg$^{-1}$)</th>
<th>N rate</th>
<th>depth (cm)</th>
<th>N rate</th>
<th>depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg ha$^{-1}$</td>
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<td>61</td>
<td>30</td>
</tr>
<tr>
<td>Fall urea 2002</td>
<td></td>
<td></td>
<td>0</td>
<td>1.9</td>
<td>1.3</td>
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<td></td>
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<td>1.5</td>
<td>2.6</td>
</tr>
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<td></td>
<td></td>
<td>2.1</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Fall ESN 2002</td>
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<td></td>
<td>0</td>
<td>2.1</td>
<td>1.4</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>101</td>
<td>2.1</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
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<td></td>
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<td>1.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td></td>
<td>2.1</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Spring urea 2003</td>
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<td>0</td>
<td>2.8</td>
<td>1.6</td>
<td>2.3</td>
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<td>101</td>
<td>2.1</td>
<td>1.3</td>
<td>3.1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>202</td>
<td>2.4</td>
<td>1.6</td>
<td>5.4</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>2.4</td>
<td>1.5</td>
<td>3.6</td>
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</tbody>
</table>

**Statistics**

<table>
<thead>
<tr>
<th></th>
<th>p&gt;F</th>
<th>p&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>&lt;0.0001</td>
<td>0.0017</td>
</tr>
<tr>
<td>N rate</td>
<td>0.9960</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Depth * N rate</td>
<td>0.5878</td>
<td>0.2703</td>
</tr>
<tr>
<td>N application</td>
<td>0.5340</td>
<td>0.1399</td>
</tr>
<tr>
<td>Depth * N application</td>
<td>0.2066</td>
<td>0.2307</td>
</tr>
<tr>
<td>N rate * N application</td>
<td>0.4210</td>
<td>0.3908</td>
</tr>
<tr>
<td>Depth * N rate * N application</td>
<td>0.2709</td>
<td>0.4803</td>
</tr>
</tbody>
</table>

**Grain yield and N efficiency comparison in 2003 and 2004**

Grain yield tended to increase with addition of N in both growing seasons (Figure 1). However, the response to N rate and N application treatments varied in 2003 and 2004. Fall-applied ESN had higher yields than fall-applied urea in 2003, except at 202 kg ha$^{-1}$ of N. Spring-applied urea yields were higher than fall-applied urea but less than fall-applied urea yields.
Figure 1. Corn grain yield response to N rate and N applications of fall-applied urea, fall-applied ESN and spring applied urea in 2003 (a) and 2004 (b) at the North Central Research Farm.
Fall-applied urea and ESN yields were very similar in 2004 (Figure 2). The spring-applied urea plots had higher yields than the other two N application treatments in 2004. N application was significant (p>F=0.0251).

![Figure 2](image)

Figure 2. Average of corn grain yield treated with fall-applied urea, fall-applied ESN and spring-applied urea during two growing seasons at the North Central Research Farm.

The amount of N fertilizer required to produce maximum grain yield of 12130 kg ha\(^{-1}\) was 139 kg ha\(^{-1}\) of N for the fall-applied ESN treatments in 2003 (Table 7). It required 247 kg ha\(^{-1}\) of N to produce a maximum yield of 12172 kg ha\(^{-1}\) for fall-applied urea treatments in the same year. The spring-applied urea treatments required 173 kg ha\(^{-1}\) of N to produce a maximum yield of 11773 kg ha\(^{-1}\) in 2003. The fertilizer efficiency was 87 kg grain/ kg N, 49 kg grain/ kg N, and 68 kg grain/ kg N for the fall-applied ESN, fall-applied urea and spring-applied urea, respectively.

In 2004, it required 200 kg ha\(^{-1}\) of N to produce a maximum yield of 12393 kg ha\(^{-1}\) for the fall-applied ESN (Table 7). 210 kg ha\(^{-1}\) of N were required to produce a maximum yield
of 12478 kg ha\(^{-1}\) for the fall-applied urea treatment, and 216 kg ha\(^{-1}\) of N to produce a maximum yield of 12828 kg ha\(^{-1}\) for the spring-applied urea plots. The fertilizer efficiencies decreased compared to the ones obtained in 2003. The fertilizer efficiency was 59 kg grain/kg N for the fall-applied urea and spring-applied urea, and 62 kg grain/kg N for fall applied-ESN.

Table 7. Nitrogen efficiency of different urea nitrogen application treatments during two growing seasons at the North Central Research Farm.

<table>
<thead>
<tr>
<th>N application</th>
<th>Maximum yield (kg/ha)</th>
<th>N rate (kg/ha)</th>
<th>N efficiency (kg grain/kg N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Urea</td>
<td>12172</td>
<td>247</td>
<td>49</td>
</tr>
<tr>
<td>Fall ESN</td>
<td>12130</td>
<td>139</td>
<td>87</td>
</tr>
<tr>
<td>Spring Urea</td>
<td>11773</td>
<td>173</td>
<td>68</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Urea</td>
<td>12478</td>
<td>210</td>
<td>59</td>
</tr>
<tr>
<td>Fall ESN</td>
<td>12393</td>
<td>200</td>
<td>62</td>
</tr>
<tr>
<td>Spring Urea</td>
<td>12828</td>
<td>216</td>
<td>59</td>
</tr>
</tbody>
</table>

N rate required to obtain maximum yield
N efficiency = kg grain produced per kg N at maximum yield

**SPRING-APPLIED UREA STUDY**

**North Central Research Farm Site, 2003**

**Stalk biomass production**

Yield was not significantly affected by N rate, N application nor the interaction between these factors. Yield did not increase constantly with addition of N fertilizer. The mean yield was 7971 kg ha\(^{-1}\) for the urea treatments and 7715 kg ha\(^{-1}\) for the ESN treatments (Table 8).
Nitrogen uptake was significantly affected by N rate \( (p>F=0.0001) \) (Table 8).

Addition of N tended to increase N concentration in plant tissue and thus N uptake. The mean N uptake for the urea treatments was 55 kg ha\(^{-1}\), and 56 kg ha\(^{-1}\) for the ESN treatments. N application and N rate* N application interaction were not significant.

Table 8. Corn response to spring-applied urea fertilizers at the North Central Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate</th>
<th>Yield ( ^a )</th>
<th>N uptake</th>
<th>Yield ( ^b )</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>0</td>
<td>7097</td>
<td>38</td>
<td>7145</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>7043</td>
<td>38</td>
<td>8847</td>
<td>72</td>
</tr>
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<td></td>
<td>135</td>
<td>7843</td>
<td>60</td>
<td>11600</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>9022</td>
<td>79</td>
<td>10981</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>202</td>
<td>8917</td>
<td>71</td>
<td>11289</td>
<td>112</td>
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<tr>
<td>Average</td>
<td></td>
<td>7971</td>
<td>55</td>
<td>10212</td>
<td>92</td>
</tr>
</tbody>
</table>

| ESN           | 0      | 6975          | 40       | 6992          | 52       |
|               | 34     | 7888          | 52       | 9334          | 74       |
|               | 67     | 8487          | 62       | 10573         | 90       |
|               | 101    | 8098          | 49       | 11462         | 101      |
|               | 135    | 7009          | 49       | 10955         | 102      |
|               | 168    | 7457          | 61       | 10977         | 108      |
|               | 202    | 8095          | 79       | 10589         | 108      |
| Average       |        | 7715          | 56       | 10126         | 91       |

**Statistics**

| N rate | 0.1296 | <0.0001 | <0.0001 | <0.0001 |
| N application | 0.4976 | 0.8087 | 0.7065 | 0.5202 |
| N rate* N application | 0.4109 | 0.2961 | 0.6008 | 0.9501 |

\(^a\) dry weight
\(^b\) 15.5% moisture
Grain production

Grain yield tended to increase with addition of N (p>F=<0.0001) (Table 8). Urea treatments yielded 10212 kg ha\(^{-1}\). ESN treatments yielded 10216 kg ha\(^{-1}\). The N application and N rate * N application were not significant. The highest yield of 11289 kg ha\(^{-1}\) was obtained by addition of 202 kg ha\(^{-1}\) for the urea treatments. For the ESN treatments, the highest yield of 10977 kg ha\(^{-1}\) required the addition of 168 kg ha\(^{-1}\) of N.

Grain N uptake was significantly affected by N rate (p>F=<0.0001) (Table 8). The mean N uptake was 92 kg ha\(^{-1}\) and 91 kg ha\(^{-1}\) for the urea and ESN treatments, respectively. The highest grain yield treatments also had the highest N concentrations. N application and N rate * N application were not significant.

Soil analysis

Ammonium concentrations in soil were higher in the 0 - 30 cm depth at the North Central Research Farm in 2003. Nitrogen rate, N application and any of the interactions listed in Table 9 were not significant.

Nitrate concentrations were significantly affected by depth (p>F=<0.0001) and N rate (p>F=<0.0001). Higher NO\(_3\)-N concentrations were found in the 0 - 30 cm depth and tended to increase with addition of N fertilizer (Table 9). ESN application had higher NO\(_3\)-N concentrations than the urea treatment. The difference in NO\(_3\)-N concentration between N application treatments was close to be significant (p>F=0.1051). None of the interactions were significant (Table 9).
Table 9. Effect of spring-applied urea fertilizers on soil NH$_4$-N and NO$_3$-N at the North Central Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate kg ha$^{-1}$</th>
<th>NH$_4$-N mg kg$^{-1}$ depth (cm)</th>
<th>NO$_3$-N mg kg$^{-1}$ depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>61</td>
</tr>
<tr>
<td>Urea</td>
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</tr>
<tr>
<td></td>
<td>101</td>
<td>2.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>202</td>
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<tr>
<td>Average</td>
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<th>&lt;0.0001</th>
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<td>0.1051</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Depth * N rate * N application</td>
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<td>0.2324</td>
<td>0.3024</td>
</tr>
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</table>

North Central Research Farm Site, 2004

Stalk biomass production

Nitrogen rate, N application and the N rate * N application interaction did not significantly affect yield (Table 10). The urea and ESN treatments yielded 3990 kg ha$^{-1}$ and 4428 kg ha$^{-1}$ respectively for stalk biomass production (dry weight).

Nitrogen uptake was not affected by any of the main factors (Table 10). Addition of N did not constantly increase N concentration in plant tissue. The average N concentration was 22 kg ha$^{-1}$ for the urea plots and 24 kg ha$^{-1}$ for the ESN treatments.
Table 10. Corn response to spring-applied urea fertilizers at the North Central Research Farm, 2004.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate</th>
<th>Yield&lt;sup&gt;a&lt;/sup&gt;</th>
<th>N uptake&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt;</th>
<th>N uptake&lt;sup&gt;b&lt;/sup&gt;</th>
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<td>kg ha&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td></td>
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Statistics:

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<td>N rate * N application</td>
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</tbody>
</table>

<sup>a</sup> dry weight  
<sup>b</sup> 15.5% moisture

Grain production

Grain yield and N uptake were significantly affected by N rate. An increase in grain yield and nitrogen concentration was observed with addition of N fertilizer. Nitrogen application had a significant effect on grain yield (p>F=0.0646). Nitrogen rate * N application interaction were not significant (Table 10).
The mean yield was 11175 kg ha\(^{-1}\) for the urea treatment. ESN treatments yielded 11634 (Figure 4). The highest yield of 13368 kg ha\(^{-1}\) was obtained by addition of 202 kg ha\(^{-1}\) for the urea treatments. 168 kg ha\(^{-1}\) of N were required to yield 13793 kg ha\(^{-1}\) for the ESN treatments (Table 10).

The mean grain N uptake was 115 kg ha\(^{-1}\) and 121 kg ha\(^{-1}\) for the urea and ESN plots, respectively. The highest N uptake was 146 kg ha\(^{-1}\) for urea plots treated with 202 kg ha\(^{-1}\) of N, and 157 kg ha\(^{-1}\) for ESN plots treated with 168 kg ha\(^{-1}\) of N (Table 10).

**Soil analysis**

Ammonium and NO\(_3\)-N concentrations were affected by depth and N rate at the North Central Research Farm in 2004 (Table 11). Increase in depth tended to decrease the concentration of NO\(_3\)-N and NH\(_4\)-N.

Table 11. Effect of spring-applied urea fertilizers on soil NH\(_4\)-N and NO\(_3\)-N at the North Central Research Farm, 2004.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate kg ha(^{-1})</th>
<th>NH(_4)-N mg kg(^{-1}) depth (cm)</th>
<th>NO(_3)-N mg kg(^{-1}) depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>61</td>
</tr>
<tr>
<td>Urea</td>
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<td></td>
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<td>2.2</td>
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</tr>
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<td>2.1</td>
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**Statistics**

<table>
<thead>
<tr>
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<th>p&gt;F</th>
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</thead>
<tbody>
<tr>
<td>Depth</td>
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<tr>
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<td>0.0188</td>
</tr>
<tr>
<td>N rate * N rate</td>
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</tr>
<tr>
<td>N application</td>
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</tr>
<tr>
<td>Depth * N application</td>
<td>0.6834</td>
</tr>
<tr>
<td>N rate * N application</td>
<td>0.3886</td>
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<tr>
<td>Depth * N rate * N application</td>
<td>0.3500</td>
</tr>
</tbody>
</table>
Addition of N fertilizer did not constantly increase soil NO$_3$-N and NH$_4$-N concentrations. Nitrogen application and all the interaction analyzed in Table 11 were not significant for NO$_3$-N and NH$_4$-N. Nitrate concentration was highest in the 0 - 30 cm depth for the ESN treatment, but N application did not significantly affect it (p>F=0.2466).

Northwest Iowa Research Farm Site, 2003

Stalk biomass production

Yield was not affected by any of the factors analyzed or by their interaction (Table 12). Application of N fertilizer did not increase yield constantly. The mean yield was 4901 kg ha$^{-1}$ for the urea treatments and 4914 kg ha$^{-1}$ for the ESN plots.

Nitrogen rate significantly affected N uptake (p>F=0.053). N application and N rate * N application were not significant (Table 12). Nitrogen concentration tended to increase with addition of N for both fertilizer treatments. The mean N uptake was 32 kg ha$^{-1}$ for urea plots and 30 kg ha$^{-1}$ for ESN treatments.

Grain production

Grain yield response to N rate and N application was significant (Table 12). The mean yield was 6109 kg ha$^{-1}$ for urea treatments and 6281 kg ha$^{-1}$ for ESN plots. Addition of N did not increase grain yield constantly among the different N rates used. Both fertilizer treatments reached the highest grain yields by addition of 135 kg ha$^{-1}$. Urea and ESN treatments yielded 6870 kg ha$^{-1}$ and 6979 kg ha$^{-1}$ respectively.

Grain N concentration and N uptake tended to increase with addition of N fertilizer. Nitrogen rate significantly affected N uptake. The mean N uptake was 54 kg ha$^{-1}$ for urea and 55 kg ha$^{-1}$ for ESN treatments. Nitrogen application and N rate * N application interaction were not significant for N uptake.
Table 12. Corn response to spring-applied urea fertilizers at the Northwest Iowa Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate</th>
<th>Yield a</th>
<th>N uptake</th>
<th>Yield b</th>
<th>N uptake</th>
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<tr>
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<td>kg ha⁻¹</td>
<td></td>
<td></td>
<td>kg ha⁻¹</td>
<td></td>
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<td>Urea</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>N rate* N application</td>
<td>0.9338</td>
</tr>
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</table>

a dry weight  
b 15.5% moisture

Soil analysis

The effect of depth on NO₃-N and NH₄-N concentrations was significant. Increase in depth tended to decrease NO₃-N and NH₄-N concentrations (Table 13). Nitrogen rate, N application and the interactions listed in Table 13 were not significant for NH₄-N concentration in soil at the Northwest Iowa Research Farm in 2003.
Nitrate concentrations were significantly affected by N rate. Higher concentrations were observed with addition of N fertilizers at both sampling depths (Table 13). Depth * N application and N rate * N application interactions were significant.

Ammonium concentrations were higher than NO₃-N concentrations at both sampling depths, N applications and N rates.

Table 13. Effect of spring-applied urea fertilizers on soil NH₄-N and NO₃-N at the Northwest Iowa Research Farm, 2003.

<table>
<thead>
<tr>
<th>N application</th>
<th>N rate kg ha⁻¹</th>
<th>NH₄-N mg kg⁻¹ depth (cm)</th>
<th>NO₃-N mg kg⁻¹ depth (cm)</th>
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<td></td>
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<tr>
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<td>Depth * N rate * N application</td>
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<td>0.5040</td>
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</table>

Northwest Iowa Research Farm Site, 2004

The corn crop was early lost in the 2004 season at the Northwest Iowa Research Farm due to hail damage. Therefore, no data was collected at this location in 2004.
Grain yield and N efficiency comparison in 2003 and 2004 at both sites

Grain yields tended to increase in both sites with increasing N rates in 2003 and 2004 (Figure 3 and Figure 5). The effect of the fertilizer or N application on yield varied between years and locations.

Figure 3. Corn grain yield response to N rate and N applications of spring-applied ESN and urea in 2003 (a) and 2004 (b) at the North Central Research Farm.
There was not a significant effect from fertilizer treatments at the North Central Farm in 2003. Urea plots had slightly higher yields than ESN plots (Figure 4). At the Northwest Iowa Research Farm, ESN plots yielded higher than urea plots though the effect from N application was not significant in 2003 (Figure 5).

![Figure 4. Average of corn grain yield treated with spring-applied urea and ESN during two growing seasons at the North Central Research Farm.](image)

In 2004, ESN plots had higher yields than urea plots (Figure 3 and Figure 4). Grain yield had a significant response to ESN application (p>F=0.0646).
Discussion

FALL-APPLIED UREA STUDY

Stalk biomass production (yield and N uptake) were not significant affected by N applications in either year. Grain production responded to N applications and N rate in 2003 and 2004. Grain yields varied from one year to the next. Higher yields were obtained in 2004 for all the N application treatments (Table 3 and Table 5).

Precipitation was higher than the 54 year average for May and June in both years, which may have produced favorable conditions for leaching and/or denitrification (Figure 6). However, drier conditions in the second half of the growing season might have affected grain yields in 2003.

Fall ESN treatments yielded higher than fall urea in 2003 but no significant difference between these two N applications was observed in 2004. Fall-applied ESN behaved as regular urea fertilizer in 2004, producing similar grain yields (Figure 2). Changes in the
coating components during the manufacturing process might have influenced the behavior of ESN in 2004. The coating composition will determine the effects of temperature on moisture permeability and thus N release rates will be affected (Fujita et al., 1983). Handling from the manufacturer to the retail dealer might have affected the physical conditions of the coating in 2004. Thus, the N release from the material might have been greater than expected.

Figure 6. Monthly total precipitation during 2003 and 2004 at the North Central Research Farm in Kanawha, Iowa.

The average mean temperatures at the beginning of the growing season in 2004 were higher than the average mean temperatures in 2003 (Figure 7). Higher temperatures might have increased the permeability of the coating to moisture, enhancing N release from ESN in 2004. Cabrera (1997) reported that leaching patterns from certain controlled release fertilizers are closely related to average daily temperatures while other materials could be more stable over a wider range of temperatures. Other soil factors such as pH and microbial
activity might have affected release from the ESN material (Maeda, 1990 cited from Pack, 2004).

Figure 7. Average mean temperature during 2003 and 2004 at the North Central Research Farm in Kanawha, Iowa.

The effect of N applications on grain yield in 2004 was significant due to the difference between spring-applied urea and the N fall application treatments. Spring-applied urea treatments might have yielded higher if the fertilizer would have had been incorporated before the study was planted in 2003. Volatilization may have occurred, reducing the efficiency of the urea fertilizer (Stehouwer and Johnson, 1990). Ammonia volatilization loss from the surface of PCU materials is reduced by the polymer coating layers (Blaise and Prasad, 1995).

Efficiency of fall and spring N applications are largely influenced by the soil characteristics and climatic conditions (Bundy, 1986). Therefore, variations in grain production among years and locations are anticipated in this kind of study.
Year variability in N efficiency was observed in all N application treatments. Fall-applied ESN had the highest N efficiencies in both years, which represents more kg of grain produced per kg of N fertilizer applied.

Ammonium concentrations in soils were only affected by depth in both years. Nitrate concentrations were significantly affected by depth and N rate. Application of ESN did not significantly change ammonium and nitrate concentrations in soils after harvest (Table 4 and Table 6). Concentrations of ammonium and nitrate tended to decrease with depth in 2003 and 2004 for all the N application treatments. Use of ESN might not have any effects on preventing nitrate loss through leaching and/or denitrification. However, general conclusions can not be made because the amount of time between the N applications and the soil sampling was too great. Possible leaching might have been detected by more frequent soil sampling during the growing season.

**SPRING-APPLIED UREA STUDY**

N application treatments did not have significant effects on stalk biomass production (yield and N uptake) in 2003 and 2004 at any location. Grain production at the North Central Research Farm sites was affected by N rate in both years (Table 8 and Table 10). Year to year variability in grain yields was observed, higher yields were obtained in 2004.

Differences in grain yield between ESN and urea applications were not significant in 2003 at the North Central Research Farm. Although ESN behaved as regular urea in 2003, ESN had a significant effect on grain yield in 2004 (Figure 4).

Variability in grain yield was observed due to location in 2003. ESN treatments had a significant effect on grain yield at the Northwest Iowa Research Farm in 2003. Average yield was greater for ESN treatments at this location in 2003.
Many factors could have influenced the ESN effect on grain yield from one site to the other. Hybrids, soils and weather conditions were different at the North Central Research Farm and Northwest Iowa Research Farm in 2003.

Figure 8. Monthly total precipitation during 2003 at the Northwest Iowa Research Farm in Calumet, Iowa in 2003.
Figure 9. Average mean temperature during 2003 at the Northwest Iowa Research Farm in Calumet, Iowa.

Rainfall was less at the Northwest Iowa Research Farm than at the North Central Research Farm, and average mean temperature at the beginning of the growing season was higher at Northwest Iowa Research Farm in 2003 (Figure 8 and Figure 9). Therefore, permeability to moisture and release from ESN might have been affected differently due to weather conditions at the North Central Research Farm and the Northwest Iowa Research Farm in 2003.

Unfortunately, it is impossible to make any kind of conclusions about the effect of ESN on corn grain yield when applied in the spring, due to lack of data in 2004 at the Northwest Iowa Research Farm.

Ammonium concentrations in soil were significantly affected by depth in 2003 at North Central Farm. In 2004, NH₄-N concentrations responded to depth and N rate. Nitrate concentrations were affected by depth and N rate in both years at the same site. Concentrations of NO₃-N and NH₄-N tended to decrease with depth in 2003 and 2004 for all
the N application treatments. Application of ESN did not tend to change concentrations of NH$_4$-N and NO$_3$-N. Weather conditions could have caused leaching and denitrification at the beginning of the growing season in both years. Similar results were found in the fall-applied urea study at the North Central Research Farm near Kanawha.

However, the soil results for NH$_4$-N and NO$_3$-N concentrations at the Northwest Iowa Research in 2003 were completely different from the results obtained at the North Central Research Farm. Ammonium concentrations were higher than NO$_3$-N concentrations for urea and ESN treatments. Nitrification might have been retarded at the end of the growing season due to lower temperatures (Figure 9) and/or a small number of nitrifying bacteria populations in soils. Leaching of nitrate was unlikely to happen after August because rainfall was less than the average in 2003 (Figure 8). Concentrations of NH$_4$-N and NO$_3$-N tended to decrease with increase of depth. Ammonium was significantly affected by depth, while NO$_3$-N concentrations were affected by depth, N rate, depth * N rate and N rate * N application. ESN might have helped to prevent movement of nitrate to depths higher than 30 cm when 202 kg ha$^{-1}$ of N where applied (Table 13).

**CONCLUSION**

The results obtained from field trials conducted for fall and spring-applied urea studies showed that corn biomass was not affected by the use of ESN or urea in particular. Dry weight and N uptake tended to respond to N rates in some treatments.

The effect of the different factors analyzed was more evident in grain production than stalk biomass production. Grain yield was always affected by N rate. However the effect of ESN and urea application varied from one year to the next and among locations. ESN behaved like regular urea in some trials but, and a positive response was observed in spring
applications at two locations. Ammonium and NO$_3$-N concentrations in soils were not significantly affected by N application.

The inconsistency in the results among years and locations might be due to multiple reasons related to weather, soil conditions and, chemical and/or physical modification in the coating of the ESN fertilizer. It is impossible to obtain accurate data if the product that is the subject of the study does not keep the same properties; especially about the coating composition which determines the nitrogen release rates of coated materials.

Because temperature and precipitation affect the release from coated fertilizers, it will be an advantage to monitor soil temperature and moisture during the growing season to understand the magnitude of the effect of these factors on the nitrogen release in field conditions. Different soils have different pH, texture and nitrifying populations among other characteristics, that might affect the nitrogen release from the polymer-coated fertilizer but also that affect nitrification, thus the concentrations of NH$_4$-N and NO$_3$-N present in soils. Efficiency of fall and spring applied urea are also influenced by weather and soil characteristics.

Appropriate conditions for leaching and/or denitrification might have been present in some years or locations. It would be helpful to take soil samples more often during the season to measure the changes in NH$_4$-N and NO$_3$-N concentrations and possible release behavior of the different materials.

The use of coating material like ESN has a potential to improve N efficiency. Nevertheless, more research is necessary to understand the effect on corn yield depending on weather and soil conditions. Manufacturing companies of coated fertilizer materials have to assure constant composition of the coating to provide regular effects of temperature and moisture on the nitrogen release patterns from the materials. Also, consumers of this kind of fertilizers deserve to get a product that guarantees the benefits for what they have paid.
REFERENCES


CHAPTER 4. CONCLUSIONS.

General Conclusions

Slow and controlled release fertilizers have been used in several crops where nitrogen fertilization is an important cultural practice. The use of this kind of fertilizer for corn production requires more research that provides conclusive results. Many factors, from the different chemical nature of the material to soil properties and weather conditions, can affect the release of nitrogen from the material and the response of corn crops. Therefore, future research should include more and different parameters that can better assess the behavior of the slow release and controlled release fertilizers in soils.

The N percentage recoveries from UF fertilizers suggest that corn N requirements might not be met by these materials. Modifications on the length of the polymer chains can be made to increase the solubility of UF fertilizers and the rate of available nitrogen released. Because soil properties, such as organic matter and pH, influence the mineralization of these fertilizers, future research should study the effects of these factors in different corn production soils. Ammonium fixation and ammonia loss should be included in the research too.

In general, field trials showed that corn biomass, and NH₄-N and NO₃-N concentrations in soils were affected N rates but not by the fertilizer materials. ESN had a positive effect on grain yield in one location only. However, variations from one year to the next and among locations made it impossible to reach definitive conclusions about the efficiency of fall and spring-applied ESN on corn production.

It is imperative to assure constant composition of the polymer coating to understand the behavior of PCU materials and the effects of temperature and moisture on the nitrogen release patterns. It would be helpful to monitor soil temperature and moisture to understand
the significance of weather conditions on the release of nitrogen from PCU fertilizers. Of course, more accurate data can be obtained by several years of research.
GENERAL REFERENCES


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