MANAGEMENT ALTERNATIVES FOR UREA USE IN CORN AND WHEAT PRODUCTION

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To my sister, Viviane

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LITERATURE REVIEW

The growth in adoption of no-tillage and other conservation tillage cropping systems is one of the main developments in crop agriculture during the past 50 years in the United States and many other countries. Adoption of no-till, the most soil-conserving form of conservation tillage, increased from 16.6 million hectares (14.7 percent of all cropland in the United States) in 1995 to 22.4 million hectares (19.6 percent of all cropland in the United States) in 2002. This represents a growth of 35 percent in no-till system use over this seven year period (CTIC, 2002). This increase in no-till adoption is likely due to the increasing number of farmers adopting a biological philosophy of management that recognizes and utilizes the many complex interrelationships that exist among climate, soils, and plants, for cropping success.

The great majority of cultivated crops require the addition of plant nutrients for optimal growth: principally nitrogen, phosphorus, and potassium, which are basic chemical elements in plant nutrition. The nitrogen reserves in the soil can rarely provide enough of this element to obtain high sustained yields. The rest must be supplied as commercial or organic fertilizers (Lamarca, 1996). Nearly all the nitrogen utilized by plants is in the form of ammonium (NH_4^+) or nitrate (NO_3^-). However, the amount of these ions in the soil at a given time is a poor indicator of the nitrogen availability to crops during a growing season. Nitrogen nutrition of crops depends more on the capacity of the soil to supply available nitrogen for an extended period than on the concentration of NH_4^+ and NO_3^- in the soil at a specific time (Scarsbrook, 1965).

Urea is the most widely produced and used solid N fertilizer in the world, and it is growing in importance. When urea is surface applied, there is a risk of loss due to ammonia volatilization. This loss can be greater when the application is made on no-till soils than on bare soils. No-till cropping systems have been shown to cause changes in the activities of several soil enzymes when compared with other systems. The presence of crop residues on the soil surface containing urease can increase the rate of urea hydrolysis, thus increasing the potential for ammonia volatilization in no-till systems (Barreto and Westerman, 1989). The growth in no-till use, the wide use of urea, the need to protect profitability, and the constant concern with environmental protection are all good reasons for the development of techniques that make urea use in no-till systems more efficient and secure.

The addition of urease inhibitors, use of polymer- or gel-coated urea, and knife injection of urea are some of the promising management practices that could turn urea into a more reliable and profitable option for agricultural systems. The objective of this research is to evaluate these practices for no-till corn, and conventional and no-till wheat in Missouri.

NO-TILL SYSTEMS

By definition, no-tillage is a soil management system where the soil is left undisturbed from harvest to planting, and planting or drilling is accomplished in a narrow seedbed or slot created by a coulter, row cleaner, disk opener, or tine opener. As a result, crop residues are left on top of the soil after the harvest and during the growth of the following crop. Historically, crop residues have played an important role as mulch, which promotes soil and water conservation, and in maintaining or increasing soil organic matter levels.

The most important advantages of no-till systems are: the increase in soil organic matter concentrations, the preservation of soil structure and moisture, cost-savings in labor and fuel to operate equipment, reduced air pollution, and reduced soil erosion, leading to reduced loss of phosphorus into surface water. The benefits of adopting no-till systems also include an increase in earthworms and beneficial soil microbes (Tisdale et al., 1999).

Reluctance to adopt no-till systems by some farmers might be due to increased herbicide costs and the risk of lower yields when compared with conventional tillage systems, particularly in wet years or during the first years of no-till adoption. However, Smart and Bradford (1999), working with corn in a semiarid, subtropical environment, showed that no-till systems resulted in greater economic returns compared with conventional tillage, due both to greater yields (especially in dry years) and lower production costs in almost all years. Furthermore, a number of economic and environmental benefits, such as cost-share payments for soil conservation and possibly carbon sequestration, are associated with the use of no-till systems in agriculture. The development of herbicide-tolerant crops has reduced differences in herbicide use between no-till and tillage systems.

Increase in Soil Organic Matter

Carbon is the key element of all life on Earth, and it is essential for the maintenance of microbial life in soils. In the past two centuries, large amounts of carbon have been released into the atmosphere through the conversion of grasslands and forests to cropland, as well as through tillage. Carbon dioxide emissions from agricultural soils have now been declining for some years due to reductions in tillage, and soils are expected to move from being net sources to net sinks for atmospheric carbon.

Essentially, there are two ways in which organic matter can be added into the soil system: it can be introduced into the soil in the form of manure, compost, organic fertilizer, sludge, or organic wastes; or it can be raised in place in the form of cover crops, pastures, or cash crop residues. Through photosynthesis, plants convert carbon dioxide (CO_2) into organic forms of carbon. Plants will deposit the carbon in the soil through their roots and in plant residues. When most of the crop biomass is harvested and carried out of the field, the opportunity to return organic matter to the soil is lost. This situation is aggravated by excessive or unnecessary tillage, which results in the breakdown of soil organic carbon and the release of CO_2. The result of these practices is a depletion of carbon in the soil.

No-tillage management has been promoted as a practice capable of offsetting greenhouse gas emissions because it results in the sequestering of carbon in soils (Six et al., 2004). Cropping systems based on high crop residue addition and no-tillage tend to accumulate more carbon in the soil than is lost into the atmosphere (Greenland and Adams, 1992).

Although crop residues are placed on the soil surface in a no-till system, higher levels of soil organic matter are maintained with this system due both to the addition of plant roots and to lower soil temperatures (Sprague and Triplett 1986). The decomposition process is promoted by a high O_2 concentration in the soil, and optimal water content and temperatures, which promote the growth of soil microorganisms and increase enzyme activity. Tillage loosens the soil, allowing O_2 penetration, and results in higher soil temperatures because the soil surface becomes uncovered. Conventional tillage practices incorporate residues into the soil and eventually result in lower soil organic matter levels, due to higher residue decomposition rates, when compared with no-till systems. Reducing tillage intensity reduces the rate of soil organic matter decomposition and mineralization; thus, soil organic matter levels can be maintained. In fact, soils managed with no-tillage for extended periods usually have higher soil organic matter contents (Blevins et al., 1977).

In a no-till system, organic matter is concentrated in the 0 to 5 cm surface layer (Blevins et al., 1985), although increased organic matter can be measured deeper in the profile after decades of continuous no-till cropping (Dick et al., 1999). This stratification of soil organic matter could result in very different biological, chemical, and physical soil properties by depth.

Allmaras et al. (2004) conducted a thirteen-year field experiment with continuous corn in the northern portion of the U.S. corn belt. They showed that nitrogen fertilization, corn residue management, and tillage system all significantly influenced the carbon cycle and carbon storage in the soil. They found significant increases in the total soil organic carbon stored within the top 30 cm of soil under no-till management. After 13 years, a no-tillage system resulted in the retention of 24% of the available C in the soil organic carbon pool, while moldboard and chisel plow tillage caused the retention of 11 and 14% respectively.

Tisdale et al. (1999) conducted a 12-year experiment using three crop rotations (i.e., continuous soybean, continuous sorghum, and soybean-sorghum). They found that under conventional tillage systems, soil organic matter increased only slightly when compared with a no-till system where all the residue was left on the soil surface. Under no-tillage, the level of soil organic matter increased by 45% when the quantity of residue was increased from 1 to 3 t/a/yr. Therefore, the quantity of residue retained on the soil is very important to maintaining or increasing soil organic matter.

Hargrove (1982), after a 5-year double-cropping experiment with wheat and soybeans, found that the nutrient concentration near the soil surface (i.e., the top 0-7.5 cm) was greater with no-tillage than with conventional tillage. Edwards et al. (1992), after 10 years of experimentation, described a clear differentiation between plots with no-tillage and conventionally plowed plots. In no-till plots, organic matter accumulated in large quantities in the upper soil layer (the top 20 cm). The overall increase in organic matter in no-till plots was 56% greater than the amount that accumulated in conventionally tilled plots. In addition, the quantities of available nutrients within the upper 45 cm showed a distinct stratification in the no-till plots.

In a review, Titi (2003) confirmed that there is an increase in soil organic matter in the top layers of no-tilled soils. In some studies, the observed increases in topsoil organic matter were accompanied by depletions in organic matter in deeper soil layers, while in other studies the deeper soil organic matter levels remained constant. Thus, no-till can result in either an altered vertical distribution of soil organic matter, or in a net accumulation of soil organic matter in the profile.

Soil Erosion

An important practice in no-till farming is being able to plant through the previous crop residues in an untilled soil. Weeds are controlled by herbicides, cover crops, and by the mulch formed from the previous crop residues. The mulch reduces the impact of raindrops on the soil, leading to a reduction in soil sealing, increased water infiltration, reduced runoff and consequently, reduced erosion. No-till also results in an increase in soil macropores, due to better soil structure formation, thus directly increasing water infiltration and reducing soil erosion. Surface residues also play an important role, protecting the soil from the erosive impact of winds.

Several studies illustrate the negative impact of soil erosion on cropland productivity. Schertz et al. (1989) compared crop growth on slightly eroded and severely eroded phases of three soils. They found that corn yields on severely eroded soils were 9% to 34% lower than those on slightly eroded soils, while soybean yields were 14% to 29% lower. Anderson (1990), found that the use of tillage resulted in extensive wind and water erosion, and that eliminating tillage increased proso millet grain yields from 2290 ka ha^{-1} to 2730 kg ha^{-1}.

Many research studies have shown the effects of no-till systems on erosion control. West et al. (1991), Stone (1996), and Meyer et al. (1999) all showed that water-related soil losses were greatly reduced (i.e., the average reduction of the three studies was 80%) when no-till practices were used instead of fall plowing. They attributed tillage-induced erosion to increased detachability of the soil after tillage.

Dickey et al. (1986), in a review of research on soil erosion reported that erosion was reduced 92%, 96%, and 64%, respectively, by corn, wheat, and soybean residues when compared with moldboard plow tillage. Soybean residue was less effective than corn or wheat residue because of its fragile nature and smaller quantity. It is accepted that erosion control by no-till practices depends on the type and amount of residues on the soil surface.

A dramatic decrease in erosion has taken place in the United States since 1982. U.S farmers can credit much of this reduction to the adoption of conservation tillage. Water erosion on cultivated cropland fell from an average of 9.8 Mg/ha/year in 1982 to a 6.9 Mg/ha/year in 1997, a 30% decrease in amounts of soil loss (Fawcett and Towery, 2001).

Soil Moisture and Structure

Reduced-tillage and crop residue management systems were initially developed to protect the surface from erosion by water or wind, but they also increase soil water content under a wide range of climates and cropping systems. This is due to decreases in evaporation losses and increases in rainfall infiltration. In a four-year study, Phillips (1984) found that soil water evaporation was reduced from no-tillage corn plots during May through September, such that the average annual evaporation was reduced by 15 cm. Therefore, more water was available for transpiration in the no-till plots, resulting in higher corn yields.

Soil moisture retained through reduced tillage systems assumes great importance in regions of low rainfall and high evapotranspiration, on soils low in water-holding capacity, and in years with below normal rainfall. In semiarid regions, where soil water conservation is a priority, water conservation improves when surface residue cover is maintained. In a 20 crop-year study at four Great Plains locations, Greb (1983) determined that as the mulch rate increased from 0 to 6.6 Mg/ha, the net soil water gain increased by 5 cm.

Soil aggregation is the cementing of soil particles into a secondary unit or granule (Sprague and Triplett, 1986). A high level of aggregation is considered an indication of good soil structure and a positive influence on plant growth. The stability of aggregates in water is used as an index of: the resistance of soils to dispersion, a soil's susceptibility to compaction, the degree of soil aeration, soil drainage, water intake rate, susceptibility to soil erosion, and plant emergence. Thus, the degree of aggregation is an excellent indicator of the physical condition of the soil.

In 5 years of continuous corn, Mannering et al. (1975) showed that soil aggregates in the top 5 cm increased by one-third after chiseling and till-planting, when compared with moldboard plowing, while aggregates were more than doubled in the no-tillage system. In addition, they noticed an increase in aggregation in the 5-15 cm zone in the no-plow systems. Thus, improved soil structure (aggregates) can be provided by a long-term no-till system.

An ideal soil environment, which can be provided by the no-till system (i.e., high organic matter content and 25 to 30% volumetric soil water content; Berry and Jordan, 2001), promotes rapid growth of soil microorganisms and earthworms. The earthworms are also important for the improvement of soil structure, since their channels tend to decrease bulk density and increase aeration and drainage (Allison, 1973).

Costs of Production

A number of economic benefits are associated with the use of no-till production agriculture in the United States. Reduction in labor, energy, and machinery costs are associated with no-till farming, relative to conventional tillage systems and other types of conservation tillage.

Smart and Bradford (1999), compared the effects of conventional and conservation tillage on corn yields and production costs during the transition from conventional to reduced tillage. They found that grain yields from no-till crops were lower than those from conventional tillage in the first cropping year, but the no-till yields were equivalent to, or up to 12% greater than, conventional tillage yields in years 2 and 3. Production costs were lower for the no-till system than for the conventional tillage system, because of the reduced number of trips (for tillage purposes) over the field. A three year average of net returns from corn grown under a no-till system during the spring cropping season was \$47 ha^{-1} greater than from corn grown under reduced tillage and \$104 ha^{-1} greater than corn grown under a conventional tillage system. Net returns from no-till corn grown during the fall cropping season were \$5 ha^{-1} greater than from corn grown under reduced tillage, and \$104 ha^{-1} greater than from corn grown under a conventional tillage systems. The conservation tillage systems resulted in greater economic returns, compared with the conventional tillage systems, due to both greater yields in dry years and lower production costs in all years.

Many other studies have shown the economic benefits of adopting no-till systems, and have found a strong relationship between farm profitability and early adoption of no-till systems (Kastens et al., 1999). Increased profits from no-till farming depend partly on reduced labor and machinery costs, which more than offset the increases in chemical costs (especially herbicides) and any additional machinery investment costs that are needed for no-till farming. The greatest economic benefits may result from increased timeliness. No-till often results in faster planting, enabling the operator to plant larger areas within optimum planting dates, thus increasing the chances for optimum yields (University of Missouri, 1997).

In an economic study by Massey (1997), budgets covering the costs of producing corn and soybean under two different tillage systems were analyzed. The seeding rate, fertility program, and yields were assumed the same under both systems. The total net costs for no-till corn were \$8.5 ha^{-1} lower than those for corn grown under a conservation-tillage. The adoption of no-till resulted in an increase of \$20 ha^{-1} in costs for herbicides, but this was offset by a decrease of approximately \$29 ha^{-1} in other costs. The reduced costs were for fuel, labor, and equipment usage, including depreciation on equipment. For soybean production, the increase in herbicide costs was projected to be only \$7.4 ha^{-1} when a no-till system was adopted. As for corn, this increase was offset by lower costs for fuel, labor, and repairs, and the final balance was \$21 ha^{-1} lower for the no-till cropping system.

Schlegel et al. (1999) studied the agronomic and economic impacts of tillage and rotation on wheat and sorghum production, and concluded that costs were \$35 to \$47 ha^{-1} greater for no-till wheat than for wheat grown under reduced tillage, primarily because of higher weed control costs. Production costs were similar for sorghum grown under no-till and reduced tillage systems. They suggested using rotations to improve crop yields and thus offset the increase costs of production under no-till systems.

Weed control is a major consideration when farmers are deciding whether to implement conservation tillage. However, confidence in weed control has increased since the introduction of herbicide-tolerant genetically engineered crop varieties. The use of these varieties allows for economical control of weeds without relying on tillage, and can explain in part why no-till farming has become increasingly popular.

Many economic analyses do not place value on the soil saved due to reduced erosion. If some value were placed on reduced soil erosion, the economics of no-tillage production would be further improved. Furthermore, the decreased time needed to perform fieldwork may lead to increased time for management of the farm, and may produce additional economic benefits from no-till production.

NITROGEN

Function in Plants

Nitrogen is one of the most important nutrients and is required for the survival of all living organisms. It is also central to the production of all crop plants. Plants normally contain 1 to 5% N by weight and absorb N as both nitrate (NO_3^-) and ammonium (NH_4^+). Both ions move into plants by mass flow, which supplies, for example, 99% of the total nitrogen taken up by a corn plant (Tisdale et al., 1999). Before the NO_3^- can be used in the plant, it must be reduced to NH_4^+ or ammonia (NH_3). NH_3 produced is assimilated into amino acids that are incorporated into proteins and nucleic acids. Enzymes are proteins that catalyze all plant growth reactions, and a shortage of enzymes causes stunted growth when N is deficient. In addition, N is a structural component of chlorophyll, which is the primary absorber of light energy needed for photosynthesis. An adequate supply of N is associated with high photosynthetic activity, vigorous vegetative growth, and a dark green plant color (Tisdale et al., 1999).

From an agronomic standpoint, N is the element that is of primary importance for the achievement of maximum crop yields. Although all plant nutrients are required in optimum amounts to achieve high potential yields, nutrients other than N can be more readily adjusted to optimum concentrations in the soil, because they are either held by the soil exchange complex, or have low solubility, and are not so susceptible to loss from the rooting zone. On the other hand, most N fertilizers are highly soluble and may be readily leached, volatilized as NH_3 , or denitrified when in the NO_3^- form.

Stanford and Legg (1984) posited that the most critical factor in promoting high yields is the supply of nutrients, especially N, in accordance with crop demand, without creating toxic conditions. Nitrogen-fertilized maize plants have greater root development and use considerably more water in drought conditions (Gardner et al. 1985). Nitrogen fertilization seems to promote deeper and more profuse rooting early in the season, probably due to increased leaf area, and more assimilate for root growth.

Nitrogen Sources

Nitrogen accounts for 78% of the atmosphere, in the form of elemental nitrogen (N_2) gas. Anhydrous ammonia is itself a fertilizer, and is the basic industrial material from which other nitrogen fertilizers are made. Most of the NH_3 in the world is produced synthetically by reacting N_2 from the air and H_2 gas (Haber-Bosch process). NH_3 production is an energy intensive process, because high temperatures are needed, and because it requires large quantities of hydrogen, which is usually derived from natural gas, or methane (CH_4). From NH_3, many different fertilizer N-containing compounds are manufactured.

Several different kinds of nitrogen fertilizer have been used in agriculture. Among the dry solid forms are ammonium nitrate, ammonium sulfate, calcium nitrate, and urea. The available liquid forms of N fertilizer are anhydrous ammonia, aqua ammonia, and urea ammonium nitrate solution (UAN).

- Ammonium nitrate contains 33 to 34% nitrogen and is manufactured by passing ammonia gas into nitric acid. In ammonium nitrate, one-half of the nitrogen is in the form of ammonium and the other half is in the nitrate form. Because it is entirely available to plants as soon as it dissolves, ammonium nitrate is one of the quickest-acting nitrogen fertilizers. It is very hygroscopic, and requires extra care in storage and handling. It can be explosive under certain conditions, and is more prone to leaching and denitrification than products containing predominantly NH_4. Further, it is more corrosive to handling and application equipment than urea. Recently, there have been problems related to security in the shipping and handling of ammonium nitrate, because it can be used to make a powerful explosive. New legislative and regulatory initiatives could seriously affect the manufacture, transportation, and sale of ammonium nitrate. For example, new U.S. Coast Guard regulations require that each vessel or facility have a security plan, maintenance and security records, training records, a facility or vessel security officer, and a commanding security officer for all vessels (Funderburg, 2004). Some facilities have decided to discontinue shipping the product due to the increased costs and liability associated with these regulations. Consequently, these new regulations and laws are likely to have the effect of making ammonium nitrate both less available, and more expensive, relative to other nitrogen fertilizer products.

- Ammonium sulfate handles well because it does not readily absorb water. In addition, it is a sulfur source, which can be beneficial in some situations. However, ammonium sulfate has a relatively low N concentration (21% N) and it has a stronger acid-forming reaction in soil than other N fertilizers.

- Calcium nitrate (15% N) contains all its N in the nitrate form, and, therefore, it is highly susceptible to leaching and denitrification losses as soon as it is applied. It is also used as a soluble source of calcium.
- Urea is made by combining liquid ammonia and liquid carbon dioxide at very high temperatures and pressures. The resulting product is crystalline and completely water-soluble. Commercial grades carry 45 to 46% N, which allows for substantial savings in handling, storage, and transportation costs relative to other dry forms of N. In addition, urea has fewer tendencies to stick and cake than ammonium nitrate. These characteristics have made urea the principal form of dry N fertilizer applied in the United States, approaching 16% of total N use (Tisdale et al., 1999).
- Anhydrous Ammonia contains 82% N, which is the highest amount of any N fertilizer. Because it is a gas at atmospheric pressure, it must be placed below the soil surface using knives, and even so, some may be lost to the aboveground atmosphere during and after application. In addition, ammonia is can be toxic to living organisms, and application of this fertilizer near living plants may cause temporary or permanent injury to the plants. Applications too close to seeds or seedlings may cause stand problems.
- Aqua ammonia is a liquid, and contains 20 to 25% nitrogen. High costs of transportation and delivery limit its production. It is used for direct soil application, or in the production of liquid fertilizer mixtures. It is usually injected into soil to depths of 2 to 4 inches, to avoid losses from volatilization.
- UAN solutions are mixtures of urea and ammonium nitrate in water, and have nitrogen concentrations between 28% and 32%. They are generally

sprayed or dribbled onto the soil surface, but may be injected into the soil. Under certain conditions, N loss due to ammonia volatilization may be as high as 25%.

Nitrogen Trade

Nitrogen is an important nutrient in terms of world trade and consumption. At present, a supply surplus exists, and will increase slowly until 2007/08. The forecast is for world demand for nitrogen fertilizer to increase at an annual rate of 1.2 %, or 5.2 million ton. However, it is forecast that the world supply will rise by 8.5 million ton by 2007/08 (FAO, 2003).

Over the past five years, several anhydrous ammonia plants in the U.S have shut down due to high natural gas prices. Each ton of ammonia requires 25 to 34 million metric Btu (British thermal units) of natural gas, plus additional energy for handling and shipping (Reetz and Bruulsema, 2004). With lower production capacity, more N fertilizer must be imported, mainly in the form of urea, since much of the N fertilizer produced in the rest of world is urea. In the U.S., new urea production plants are being built, and urea use is increasing.

Importance of Urea

Urea is the most widely used, and its use is the fastest growing, of all dry nitrogen fertilizers. It is the major fertilizer traded in international commerce. In the very near future, urea is expected to account for more than 50% of all nitrogen fertilizers traded, and it has already captured more than 65% of the world trade in dry N fertilizers (Gilgames, 2004).

Urea has a number of advantages over other nitrogen fertilizers. It is safer to ship and handle, it is less corrosive to equipment, it has a higher analysis than any other dry nitrogen fertilizer, and it can be used on virtually all crops. Urea can be stored and distributed through conventional systems. It can be applied in many different ways, ranging from sophisticated aerial applications to hand spreading urea. Urea is also highly water-soluble, so it moves readily into the soil. The high analysis means reduced transportation and application costs per pound of N applied.

Urea is the best nitrogen fertilizer for aerial applications, because the granules are uniform: the applications can be accurately calibrated, and the fertilizer evenly spread. Aerial application of urea to growing crops causes much less leaf burn than either UAN or ammonium nitrate.

Urea contains about one-third more nitrogen when compared with ammonium nitrate, and all its nitrogen is in the ammoniacal form. Until nitrification occurs, the ammonium is less subject to leaching or denitrification than the nitrate portion of ammonium nitrate.

High natural gas prices have promoted the use of urea in the U.S. Anhydrous ammonia was one of the most popular N sources among U.S. farmers in the 90's (USDA, 2005). However, there are hazards related to the management of anhydrous ammonia, and its use is now declining due to the extra costs associated with application, and the closure of some ammonia facilities in the U.S. (GAO, 2003). In addition, the negative environmental consequences related to water contamination from excessive fall fertilizer applications have led to reductions in the use of both anhydrous ammonia and ammonium nitrate. Ammonium nitrate was considered a good N source for fall-application, because it is less likely to be lost via volatilization. However, it use can contribute to the problem of water contamination from nitrate leaching. Due to increased natural gas prices, use of UAN solution has become very costly.

UREA USE IN NO-TILL

When surface applied, urea may be subject to ammonia volatilization. A review by Scharf and Alley (1988) found that an average of 25% of the nitrogen applied as urea is lost via ammonia volatilization. This can be a substantial obstacle to urea use in no-till systems. Wells et al. (2004) reported on several field experiments conducted at the University of Kentucky, comparing urea with ammonium nitrate (AN). The following trends were evident: for conventionally grown corn, if fertilizers were broadcast just before planting and incorporated into the soil, there was little difference between urea and AN. However, if the fertilizers were broadcast at planting and not incorporated into the soil, AN was slightly more effective on poorly drained soils, although there was little difference between urea and AN on well-drained soils.

Minor et al. (1994) studied N fertilizers over three years at three northern Missouri locations, and found that ammonium nitrate gave the best results within broadcast treatments in a corn/soybean rotation system, while urea was usually a desirable second choice. On the other hand, Nelson et al. (2004) studied N fertilizer application in corn in Missouri and found that urea performed better than ammonium nitrate or UAN, when broadcast before planting. Urea also performed well when applied alone or with Agrotain between rows as a sidedress to 2, 3, and 4 ft corn, in a high yield environment. Hanson et al. (1989) compared a broad array of N fertilizers used for surface broadcast application over two years in Missouri. They concluded that ammonium nitrate was clearly the superior N source, and that urea had an intermediate performance. McVay et al. (1991), in a Missouri study, comparing nitrogen sources and application methods for no-till corn, obtained strong indications that ammonium nitrate was as effective as urea. However, they also mentioned that in this experiment the soil conditions were wet, and so the likelihood of N loss from volatilization was reduced. Many other studies in Missouri have found favorable results for ammonium nitrate when compared with urea (Stecker et al., 1992, 1993a, 1993b, 1994, 1995; Stecker 1995).

In summary, variable results have been obtained when fertilizers were topdressed at planting on no-till corn. When low to moderate rates of N were used, urea was more likely to be slightly less effective than AN. When the fertilizers were topdressed over corn 5-7 weeks after planting, the risk increased for urea to be less effective than AN, although the results were variable (Wells et al., 2004).

Ammonia Volatilization from Urea

Ammonia volatilization is the term commonly used to describe the process by which gaseous NH_3 is released from the soil surface to the atmosphere. Volatilization of NH_3 is a mechanism of N loss that occurs naturally in all soils. However, compared with NH_3 volatilization from N fertilizers the amount of NH_3

lost as a result of the mineralization of organic compounds is small (Tisdale et al. 1999). Thus, NH_3 volatilization is mostly discussed in relation to the surface application of N fertilizers.

Several factors affecting ammonia volatilization rate and duration are discussed below.

a) Soil solution pH and N fertilizer source: the equilibrium between NH_4^+ and NH_3 can be represented as: $NH_4^+ + OH^- \rightleftharpoons NH_3 + H_2O$ (equation 1)

Thus, the concentrations of NH_4^+ and NH_3 are determined by the pH of the soil solution. An increase in pH (increasing OH^- concentration) drives the equilibrium to the right, producing more NH_3. When ammonium-containing fertilizers are applied to acidic or neutral soils, little or no NH_3 volatilization occurs, because the soil solution pH is not increased. However, when urea is applied to acidic or neutral soils, the solution pH around the urea granule increases during hydrolysis, as shown in the equation:

$$CO(NH_2)_2 + 3\ H_2O \rightarrow 2\ NH_4^+ + HCO_3^- + OH^- \text{ (equation 2)}$$

In this case, the solution pH can increase to above 7, and the NH_4^+- NH_3 equilibrium shifts to the right (equation 1), to favor NH_3 volatilization loss. In alkaline soils, ammonium sulfate and ammonium nitrate are also subject to NH_3 loss as explained by equation 1.

b) Cation Exchange Capacity (CEC): the adsorption of the positively charged NH_4^+ ion to the exchange complex of soils reduces the amount of NH_4^+ and therefore NH_3 in soil solution. This means that soils with greater CECs may have less NH_3 volatilization. Scharf and Alley (1988) reviewed that some research showed that the more sand in a soil, the greater the chance for ammonia volatilization, because of the low cation exchange capacity that these soils have.

c) Buffer Capacity: the buffer capacity of the soil greatly influences NH_3 volatilization loss. Soil pH change and subsequent NH_3 loss will be much less in a soil with a high pH buffering compared with one with a low pH buffering (Tisdale et al. 1999). The pH buffering capacity of a soil is its ability to resist changes in pH. Similar to the CEC, the buffering capacity is much greater in soils with high clay or organic matter content.

d) Water: the soil moisture content has an important influence on the rate of NH_3 volatilization, because it affects the concentrations of NH_4^+ and NH_3 in soil solution (Haynes and Sherlock, 1986). Ammoniacal N concentrations in soils with high moisture contents will be lower than the concentrations in soils with low moisture contents, and this can lead to lower net losses of NH_3 from wetter soils. Soil water content affects volatilization in a number of different ways depending on the NH_3 source, its time and method of application, its depth of placement (Freney and Simpson, 1983). As an example, Ernst and Massey (1960) and Hauck (1984) found that rapid volatilization from urea appears to occur only when the soil surface is moist, probably because urea hydrolysis requires water, and it occurs very slowly in dry soils. The moisture from dewfall alone can be enough to stimulate ammonia volatilization (Hargrove et al., 1977). However, rainfall or irrigation of 2.5 cm or more can effectively halt ammonia volatilization by washing the urea down into the soil so that even if ammonia forms, it will not escape from the soil (Craig and Wollum, 1982; Bouwmeester et al., 1985; Keller and Mengel, 1986). According to Fox and Hoffman (1981) there is a relationship between timeliness of rainfall after N application, and N loss via volatilization, for no-till corn: "(1) there was insignificant ammonia volatilization loss from unincorporated urea fertilizers if at least 10 mm of rain fell within 48 hours after fertilizer application; (2) if 10 mm or more fell 3 days after urea was applied, volatilization losses are slight (< 10%); (3) if 3 to 5 mm of rain fell within 5 days, or 7 to 9 mm within 9 days, volatilization losses could be moderate (10% to 30%); and (4) if no rain fell within 6 days, the loss could be substantial (>30%)".

e) Temperature: increasing temperature increases the relative proportion of NH_3 to ammonium present at a given pH, decreases the solubility of NH_3 in water, and increases diffusion of NH_3 through the soil. Therefore, the higher the temperature, the greater the potential for NH_3 losses (Freney and Simpson, 1983). Temperature also affects the solubility of the fertilizers added to soil, the urease activity (see below) and the rate of microbial transformations of NH_3.

f) Wind speed: wind can dramatically increase ammonium volatilization rates by carrying ammonia away from the volatilization surface, increasing the diffusion gradient (Kissel et al., 1977).

g) Urease activity: organic N sources (including urea) when applied to the soil, must be mineralized to ammonium before they can be used by plants or lost through volatilization. Urease is an enzyme that hydrolyzes urea into NH_4^+. Urea hydrolysis proceeds rapidly in warm, moist soils, with most of the urea transformed to NH_4^+ in several days (Tisdale et al., 1999). The urease in soils comes from plant residues and from soil bacteria, fungi, and actinomycetes. Thus, the urease activity in a soil increases with the size of its microbial population and with its organic matter content (Barreto and Westerman, 1989). Sandy or calcareous soils tend to have lower activities than heavy-textured or noncalcareous soils (Freney and Simpsom, 1983).

Although urease activity increases markedly as the temperature rises from 10 to 70°C, urease will function at low temperature (Hauck 1984). In the presence of urea, ice will melt at temperatures down to -12°C. Thus, there is the potential for a portion of fall- or early-winter-applied urea to be converted to NH_3 or NH_4^+ before the spring.

Free NH_3 inhibits the enzymatic action of urease. Since significant concentrations of free NH_3 can occur at pH values above 7, some temporary inhibition of urease by free NH_3 occurs after the addition of urea to the soil, because the soil pH near the urea source may reach values of up to 9 (Tisdale et al., 1999). Thus, high rates of urea fertilization in a given area can create conditions restrictive to the action of urease.

Strategies to Reduce Ammonia Volatilization from Urea

Many studies (Touchton and Hargrove, 1982; Mengel et al., 1982; Howard and Tyler, 1989) have shown that better results can be obtained with urea injection than with surface application. Since urea use in agriculture is increasing, strategies to improve urea efficiency, especially in no-till systems, are being tested. These strategies include: treating urea with Agrotain [N-(n-butyl) thiophosphoric triamide or NBPT], knife-injecting urea, and using polymer- or gel-coated urea.

Agrotain (NBPT) is a urease inhibitor. If mixed with urea, it is expected to delay ammonia volatilization, thus increasing the probability that the urea can move into the soil by rainfall or irrigation before significant volatilization losses occur. Tisdale et al. (1999), found corn yield responses to Agrotain of up to 1.3 Mg ha^{-1}, although gains of 0.2 to 0.4 Mg ha^{-1} were more common. The higher yield responses occur under conditions of high N volatilization potential, optimum or lower N application rates, and where urea is broadcast over heavy surface residue environments. Hendrickson (1992) found that in 21 trials, maximum grain yields were obtained from using an average of 83 Kg ha^{-1} less N, when Agrotain was included with the surface-applied urea. In addition, Fox and Piekielek (1993) reported that no-till corn yield increased 0.9 Mg ha^{-1} when Agrotain was included with the surface-broadcast urea. Thus, it appears that the use of Agrotain might be an effective management tool to minimize yield losses due to ammonia volatilization, when urea fertilizers are surface-applied to high residue fields, in years when climatic conditions are conducive to N loss.

The coated-urea products are those in which urea granules are coated with materials, such as sulfur or silicate/polymer combinations. Nitrogen is released from sulfur-coated urea via biological oxidation of the S coating, or physical rupture or fracture of the coating. With polymer-coated urea, N release is dependent on the polymer chemistry, coating thickness, soil moisture, and soil temperature (Blaylock et al., 2005). All these processes contribute to delays in the release of nitrogen into the soil solution and consequently, delays in urea hydrolysis.

Fan et al. (2004), in a three-year field experiment conducted in China, comparing urea with coated urea, found that the maximum wheat yield and nitrogen efficiency were obtained from treatment with coated urea. The coated urea not only resulted in higher yields, but nitrogen fertilizer recovery rates were 16.5 to 68.7% higher than those for uncoated urea. However, Rehm and Sims (2005) compared slow-release fertilizer with urea on hard red spring wheat, and concluded that the slow-release products provided no positive impact on yields. They did find that the use of slow-release N-fertilizers resulted in slightly higher grain protein contents. However, the increases were small, and the premium paid for higher protein grain was not enough to compensate for the higher costs of the slow-release N products. In Missouri, Motavalli et al. (2004) studied the effects of slow-release N fertilizers on corn, and found some evidence that the use of polymer-coated urea did not give significant yield improvements when compared with urea. Traditionally, controlled-release products have not been economical for use with major grain crops, because of the high costs of fertilizers, and low crop prices. However, technological improvements have reduced manufacturing costs for all these products, while high N prices and increased interest in improving N-use efficiency have increased the demand for new products.

SUMMARY

No-till and reduced tillage production systems are widely used today in the United States and around the world, because of their capacity to reduce soil erosion and topsoil loss, and to reduce labor, fuel, and equipment requirements. However, especially for no-till systems, there is a high risk of N loss when broadcast urea is used as the N source. When urea is surface applied, an average of 25% of the N is lost via ammonia volatilization. Depending on soil conditions and weather, losses can range from 0 to 50%. Traditionally, tillage has been used to incorporate urea thereby, avoiding losses of N and yield. This option is not available in no-till and some reduced tillage systems. The loss of N by volatilization can reduce crop yields, or alternatively, increase fertilizer needs and decrease fertilizer efficiency. In addition, the current concern about environmental pollution is a further reason to improve fertilizer efficiency and avoid losses of nutrients into runoff water.

The availability of ammonium nitrate as a granular N source for use in no-till farming has been declining in the United States, while the availability of urea has been increasing. In the past five years, high natural gas prices have led to the temporary or permanent closure of N production facilities in the U.S., and increased imports of N fertilizers. Imported N is mainly in the form of urea, since much of the nitrogen production in the rest of world is in this form.

The objective of this project is to evaluate several strategies to reduce the risk of ammonia volatilization loss from urea when applied to no-till corn, and conventional and no-till wheat. These strategies include: addition of Agrotain (a urease inhibitor) to the urea, use of polymer- or gel-coated urea, and knife

injection of urea. Our goal is to provide crop producers with information that can help them to manage urea reliably and profitably, in no-till systems.

LITERATURE CITED

Allison, F. E. 1973. Soil organic matter and its role in crop production. U.S. Department of Agriculture, Washington, D.C.

Allmaras, R., C. Clapp, and D. Linden. 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68:1366-1375.

Anderson. R. L. 1990. No-till proso millet production. Agron. J. 82:577-580.

Barreto, H. J., and R. L. Westerman. 1989. Soil urease activity in winter wheat residue management systems. Soil Sci. Soc. Am. J. 53:1455-1458.

Berry, E. C., and D. Jordan. 2001. Temperature and soil moisture content effects on the growth of *Lumbricus terrestris* (Oligochaeta: Lumbricidae) under laboratory conditions. Soil Biol. Biochem. 33:133. *In* Titi, A. E. 2003. Soil tillage in agroecosystems. CRC Press, Boca Raton, Florida.

Blaylock, A. D., J. Kaufmann, and R. D. Dowbenko. 2005. Nitrogen fertilizer technologies. http://isnap.oregonstate.edu/WCC103/2005_Proccedings/Blaylock%20Nitrogen%20Fertilizer%20pg8.pdf (28 February 2006)

Blevins, R. L., W. W. Frye, and M. S. Smith. 1985. The effects of conservation tillage on soil properties. *In* D'Itri, F. M. A system approach to conservation tillage. Lewis Publishers, Chelsea, Michigan.

Blevins, R. L., G. W. Thomas, and P. L. Cornelius. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after five years of continuous corn. Agron. J. 69:383-396.

Bouwmeester, R. J. B., P. L. G. Vlek, and J. M. Stumpe. 1985. Effect of environmental factors on ammonia volatilization from urea-fertilized soil. Soil Sci. Soc. Am. J. 49:376-381.

Craig, J. R., and A. G. Wollum. 1982. Ammonia volatilization and soil nitrogen changes after urea and ammonium nitrate fertilization of *Pinus taeda* L. Soil Sci. Soc. Am. J. 46:409-414.

CTIC. 2002. National Crop Residue Management Survey. 2002. http://www.ctic.purdue.edu/core4/ct/ctsurvey/nationaldata.html (5 January 2006).

Dick et al. 1997. Continuous application of no-tillage to Ohio soils. CRS press, p. 178. In: Tisdale S.L., J. L. Havlin, J. D. Beaton, and W. L. Nelson. 1999. Soil fertility and fertilizers: an introduction to nutrient management, p. 459. Prentice Hall, Inc. New Jersey. United States.

Dickey, E. C., D. P. Shelton, and P. J. Jasa. 1986. Residue management for soil erosion control. http://ianrpubs.unl.edu/fieldcrops/g544.htm (2 March 2005).

Ernest, J. W., and H. F. Massey. 1960. The effects of several factors on volatilization of ammonia formed from urea in the soil. Soil Sci. Soc. Proc. 87-90.

Fan, X., L. Fangmin, F. Liu, and D. Kumar. 2004. Fertilization with a new type of coated urea: evaluation for nitrogen efficiency and yield in winter wheat. J. Plant Nutrition 27:853-865.

Fawcett, R., and D. Towery. 2001. Conservation tillage and plant biotechnology: how new technologies can improve the environment by reducing the need to plow. Conservation Technology Information Center (CTIC). Report 10.

Food and Agriculture Organization. 2003. Current world fertilizer trends and outlook to 2007/08. ftp://ftp.fao.org/agl/agll/docs/cwfto07.pdf (5 January 2006).

Fox, R. H., and L. D. Hoffman. 1981. The effect of N fertilizer source on grain yield, N uptake, soil pH, and lime requirement in no-till corn. Agron. J. 73:891-895.

Fox, R. H., and W. P. Piekielek. 1993. Management and urease inhibitor effects on nitrogen use efficiency in no-till corn. J. Prod. Agric. 6:195-200.

Freney, J. R., and J. R. Simpsom. 1983. Gaseous loss of nitrogen from plant-soil systems. Martinus Hijhoff / Dr W. Junk Publishers, the Netherlands.

Funderburg, E. December 2004. Is there a future for ammonium nitrate? Ag news and views. http://www.noble.org/ag/soils/futureammonium/ (19 May 2005).

GAO, 2003. Domestic nitrogen fertilizer production depends on natural gas availability and prices. Report to the ranking democratic member, committee on agriculture, nutrition and forestry, U.S. Senate. GAO-03-1148.

Garner, F. P., R. B. Pearce, and R. L. Mitchell. 1984. Physiology of crop plants. Iowa State University Press. Ames, Iowa.

Gilgames. 2004. http://www.gilgames.com.au/ureaspec.html (5 January 2006).

Greb, B. W. 1983. Water conservation: central great plains. *In* Unger, P. W. Managing agricultural residues. Lewis publishers, Boca Raton, Florida.

Greenland, D. J, and I. Adams. 1992. Organic matter in the soils of the tropics-from myth to complex reality. In: Myths and science of soils in the tropics. Soil Sci. Soc. Am. Special publication no.29.

Hanson, R. G., J. A. Stecker, D. D. Buchholz, N. C. Wollenhaupt, K. A. McVay, W. E. Flanary, and R. L. Smoot. 1988. Evaluation of four nitrogen sources on corn grown under two crop rotations in a conservation tillage system. Missouri Soil Fertility and Fertilizers Research Updates 1988. Agronomy Miscellaneous Publ. #89-01. p.3-12.Univ. of Missouri, Columbia, MO.

Hargrove, W. L. 1982. Proceedings of the minisymposium on legume cover crops for conservation tillage production systems. *In* P. W. Unger 1994. Managing agricultural residues. p. 116. Lewis publishers.

Hargrove, W. L., D. E. Kissel, and L. B. Fenn. 1977. Field measurements of ammonia volatilization from surface application of ammonium salts to a calcareous soil. Agron. J. 69:473-476.

Haynes, R. J., and R. R. Sherlock. 1986. Gaseous losses of nitrogen. In: Mineral nitrogen in the plant-soil system. Ed. Haynes, R. J., and R. R. Sherlock. Academic Press, Orlando, Florida.

Hendrickson, L. L. 1992. Corn yield response to urease inhibitor NBPT: five-year summary. J. Prod. Agric. 5:131-137.

Howard, D. D., and D. D. Tyler. 1989. Nitrogen source, rate, and application method for no-tillage corn. Soil Sci. Soc. Am. J. 53:1573-1577.

Kastens, T. L., K. C. Dhuyvetter, and H. Nivens. 1999. Management factors: what is important, prices, yields, costs, or technology adoption?
http://www.agmanager.info/farmmgt/finance/investment/Briefpap2%20(7-05-02).pdf
(5 January 2006).

Keller, G. D., and D. B. Mengel. 1986. Ammonia volatilization from nitrogen fertilizers surface applied to no-till corn. Soil Sci. Soc. Am. J. 50:1060-1063.

Kissel, D. E., H. L. Brewer, G. F. Arkin. 1977. Design and test of a field sampler for ammonia volatilization. Soil Sci. Soc. Am. J. 41:1133-1138.

Mannering, J. D., D. R. Griffith, and C. B. Richey. 1975. Tillage for moisture conservation. Am Soc. Agr. Eng. Paper No. 75-2523. *In* Sprague, M. A., and Triplett G. B.1986. No-tillage and surface-tillage agriculture: the tillage revolution. John Wiley & Sons, New York, New York.

Massey, R. E. 1997. No-tillage and conservation tillage: economic considerations. University of Missouri Extension G355.

McVay, K. A., J. A. Stecker, D. D. Buchholz, and R. L. Smoot. 1991. Nitrogen fertilizer source, rates, and application methods for no-till corn production. Missouri Soil Fertility and Fertilizers Research Update 1991. Agronomy Miscellaneous Publ. #92-01 p.23-26. Univ. of Missouri, Columbia, MO.

Mengel, D. B., D. W. Nelson, and D. M. Huber. 1982. Placement of nitrogen fertilizers for no-till and conventional till corn. Agron. J. 74:515-518.

Meyer, L. D., S. M. Dabney, C. E. Murphree, W. C. Harmon, and E. H. Grissinger. 1999. Crop production systems to control erosion and reduce runoff from upland silty soils. Transactions of the ASAE. 42:1645-1652.

Minor, H. C., J. Stecker, and J. R. Brown. 1994. Fertilizer management for no-till corn and grain sorghum in Missouri. University of Missouri Extension G9176.

Motavalli, P., K. Nelson, S. Anderson, and J. Sadler 2004. Use of slow-release N fertilizer to control nitrogen losses due to spatial and climatic differences in soil moisture conditions and drainage. Missouri Soil Fertility and Fertilizers Research Update 2004. Agronomy Miscellaneous Publ. #05-01 p.114-118. Univ. of Missouri, Columbia, MO.

Nelson, K., B. Burdick, P. Scharf, and G. Stevens. 2004. Rescue N applications for corn: yield response, leaf burn, and yield loss. http://aes.missouri.edu/greenley/fieldday/page55.stm (20 May 2005).

Phillips, R. E. 1984. Soil moisture. *In* Phillips, R. E., and Phillips S. H. no-tillage agriculture: principles and practices. Van Nostrand Company, New York, New York.

Reetz, R., T. Bruulsema, and S. Murrell. 2004. Getting the most from your 2004 nitrogen dollars in the corn belt. http://www.ppi-ppic.org/ppiweb/ppibase.nsf/$webindex/article=6FE22C2F85256CF6000F3C44C1F4CF63 (5 January 2006).

Rehm, G., and A. Sims. 2005. Slow release nitrogen fertilizers for hard red spring wheat: yield and grain protein. University of Minnesota Extension. http://www.extension.umn.edu/cropnews/2005/05mncn06.htm (4 January 2006).

Scarsbrook, C. E. 1965. Nitrogen availability. *In* Bartholomew, W. V., and Clark F. E. 1965. Soil Nitrogen, 481-496. American Society of Agronomy, Madison, Wisconsin.

Scharf P. C. and M. M. Alley. Nitrogen loss pathways and nitrogen loss inhibitors: a review. J. Fert. Issues 5: 109-125.

Schertz, D. L., W. C. Moldenhauher, S. J. Livinsgston, G. A. Weesves, and E. A. Hintz. 1989. Effect of past soil erosion on crop productivity in Indiana. J.Soil and Water Conser. 44:604-608.

Schlegel, A. J., K. C. Dhuyvetter, C. R. Thompson, and J. L. Havlin. 1999. Agronomic and economic impacts of tillage and rotation on wheat and sorghum. J. Prod. Agric. 12:629-636.

Six, J., S. M. Ogle, F. J. Breidt, R. T. Conant, A. R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Global Change Biology 10:155.

Smart, J.R., and J. M. Bradford. 1999. Conservation tillage corn production for a semiarid, subtropical environment. Agron. J. 91:116-121.

Sprague, M. A., and G. B. Triplett. 1986. No-tillage and surface-tillage agriculture: the tillage revolution. John Wiley & Sons, New York, New York.

Stecker, J. A. 1995. Fertilizer nitrogen sources and application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1995. Agronomy Miscellaneous Publ. #96-03. p.8-13. Univ. of Missouri, Columbia, MO.

Stecker, J. A., D. D. Buchholz, R. G. Hanson, N. C. Wollenhaupt, and K. A. McVay. 1993a. Application placement and timing of nitrogen solution for no-till corn. Agron. J. 85:645-650.

Stecker, J. A., D. D. Buchholz, R. G. Hanson, N. C. Wollenhaupt, and K. A. McVay. 1993b. Broadcast nitrogen sources for no-till continuous corn and corn following soybean. Agron. J. 85:893-897.

Stecker, J. A., D. D. Buchholz, G. Smith, W. E. Flanary, and R. L. Smoot. 1992. Fertilizer nitrogen sources for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1992. Agronomy Miscellaneous Publ. #93-04. p.1-7. Univ. of Missouri, Columbia, MO.

Stecker, J. A., B. Chappel, and R. Bottoms. 1994. Urea and ammonium nitrate application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1994. Agronomy Miscellaneous Publ. #95-02. p.31. Univ. of Missouri, Columbia, MO.

Stecker, J. A., B. Chappel, and R. Bottoms. 1995. Urea and ammonium nitrate application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1995. Agronomy Miscellaneous Publ. #96-03. p.14-15. Univ. of Missouri, Columbia, MO.

Stone, R. P. 1996. Control of soil erosion. Ministry of agriculture and food. January 1996. http://www.gov.on.ca/OMAFRA/english/crops/facts/95-089.htm

(2 February 2005).

Tisdale S. L., J. L. Havlin, J. D. Beaton, and W. L. Nelson. 1999. Soil fertility and fertilizers: an introduction to nutrient management. Prentice Hall, Inc. New Jersey, NJ.

Titi, A. E. 2003. Soil tillage in agroecosystems. CRC Press, Boca Raton, Florida.

Touchton, J. T., and W. L. Hargrove. 1982. Nitrogen sources and methods of application for no-tillage corn production. Agron. J. 74: 823-826.

University of Missouri. 1997. Missouri no-till planting systems. University of Missouri Extension. Agricultural publication 164. p. 25.

USDA. U.S fertilizer use and price. 2005. http://www.ers.usda.gov/Data/FertilizerUse/Tables/Fert%20Use%20Table%204.xls (30 December 2005).

West, L. T., W. P. Miller, G. W. Langdale, R. R. Bruce, J. M. Laflen, and A. W. Thomas. 1991. Cropping system effects on interrill soil loss in the Georgia Piedmont. Soil Sci. Soc. Am. J. 55:460-466.

Wells, K. L., L. W. Murdock, and H. F. Miller. 2004. Urea as a source of fertilizer nitrogen for crops in Kentucky. http://www.ca.uky.edu/agc/pubs/agr/agr69/agr69.htm (1 November 2005).

Wells, K. L., W. O. Thom, and H. B. Rice. 1994. Response of no-till corn to nitrogen source, rate, and time of application. J. Prod. Agric. 5:607-610.

CHAPTER II

MANAGEMENT ALTERNATIVES FOR UREA IN NO-TILL CORN

ABSTRACT

No-till and reduced tillage production systems are widely used today in the United States and the world. Urea management in these systems is a challenge. When urea is surface applied, substantial N loss can occur via ammonia volatilization. Traditionally, urea has been incorporated using tillage, thus avoiding losses of N and yield. This option is not available in no-till and some forms of reduced tillage. The objective of this project was to evaluate several strategies to reduce the risk of ammonia volatilization loss from urea applied to no-till corn. The tested strategies included: broadcasting urea with Agrotain (a urease inhibitor), broadcasting urea with Agrotain and dicyandiamide (DCD), broadcasting polymer- or gel-coated urea, knife injecting urea, and tillage to incorporate urea, all in comparison with broadcast urea. Other nitrogen sources were used for comparisons including: anhydrous ammonia, ammonium nitrate (broadcast or knifed in), and urea-ammonium nitrate (UAN) solution (broadcast, knifed in, broadcast with Agrotain, or broadcast with Agrotain and DCD). All treatments were applied pre-plant. Field experiments were conducted over two years (2004 - 2005) with no-till corn following soybean, using N at a rate of 160 kg ha^{-1}. Reflectance measurements were taken during crop development to evaluate N status, and yields were measured at harvest. Nitrogen doubled yields in both years of the experiment. In 2004, relatively higher yields were achieved (up to 10 Mg ha^{-1}). Rain that fell shortly after treatment application probably

minimized ammonia volatilization from broadcast urea. Nonetheless, ammonium nitrate and anhydrous ammonia produced better yields when compared with broadcast urea. None of the urea treatments produced higher yields than broadcast urea. All UAN treatments (UAN, UAN + Agrotain, UAN + Agrotain + DCD, and UAN knifed in) produced lower yields than other N treatments. In 2005, a severe drought resulted in poor pollination and low yields (average 3.35 Mg ha^{-1}). Under these conditions, all treatments, including broadcast urea, resulted in similar yields. Over two years, none of the strategies aimed at improving urea efficiency in no-till corn gave consistently better results than the broadcast urea treatments.

INTRODUCTION

The growth in no-tillage and conservation tillage cropping systems is one of the main developments in crop agriculture during the past 50 years in the United States and many other countries. Adoption of no-till increased from 16.6 million hectares in 1995 to 22.4 million hectares in 2002 in the U.S. Corn production is one of the main crops responsible for this increase, with 0.9 million hectares being converted to no-till corn during the same period (CTIC, 2002).

Nitrogen fertilization is essential for profitable corn production. It also is a major cost of production, and can contribute to degradation of the environment. The economic and environmental costs of N fertilization are growing, and they are likely to become even more important in the future. These costs provide compelling reasons for intensifying efforts to improve N management practices.

Urea is currently the most widely used dry nitrogen fertilizer in the world, and there is some expectation that it will soon represent more than 50% of the total nitrogen fertilizer used in the world (IFADATA, 2005). In 2000, 16% of the total nitrogen fertilizer used in the United States was urea (IFADATA, 2005), and in 2004 its use had increased to 25% (USDA, 2005a). The closure of some North American anhydrous ammonia and ammonium nitrate production facilities is at least partly responsible for this increase in urea usage (GAO, 2003). Urea has gained a competitive advantage over ammonium nitrate because it can be shipped and handled more safely, and it has a higher N analysis (46%).

Due to the process of urea hydrolysis (Figure 1), some loss of N via ammonia volatilization may be expected when urea is surface-applied to soil. However, since the factors affecting ammonia volatilization from broadcast urea are very dependent on environmental conditions and soil characteristics, it is difficult to predict how much nitrogen will be lost via volatilization. Based on results from past research, it is expected that 8% to 33% of the total N applied can be lost by volatilization (Keller and Mengel, 1986; Bundy and Oberle, 1988; Scharf and Alley, 1988; Fox et al., 1996; Palma et al., 1998). Traditionally, the incorporation of urea by tillage has been recommended because the ammonia gases that are formed from urea hydrolysis are likely to be trapped in the soil. This is not possible in no-till systems and some conservation tillage systems.

Losses of nitrogen via ammonia volatilization appear to be greatest when urea is surface applied in a no-till system. The presence of crop residues can increase the potential for ammonia volatilization. This occurs because the crop residues can cause wet, humid conditions at the soil surface, and they can reduce the amount of urea that diffuses into the soil (O'Deen and Follett, 1992). In addition, crop residues have high levels of urease activity (Dick, 1984), the enzymes that catalyze the hydrolysis process. The incorporation of the residue into the soil (tillage) can significantly reduce the amount of ammonia lost from surface-applied urea (Dick 1984; Beyrouty et al., 1988; Barreto and Westerman, 1989; Bergstrom et al., 1998; Bandick and Dick, 1999).

Due to the volatilization potential when urea is surface-applied, ammonium nitrate has been recommended in preference to urea for no-till systems or topdress applications. This recommendation is based on research showing that ammonium nitrate performs better than urea (Table 1). In most cases, losses of N via volatilization were the explanation given for urea's poor performance compared with ammonium nitrate. However, ammonium nitrate use is expected to decrease due to problems with security, closing of production plants, declining availability, and high prices when compared with urea. Anhydrous ammonia, which is currently the most widely used N source for corn production in the U.S. (USDA, 2005a), is also losing popularity because supply is declining and its traditional price advantage is therefore declining as well. With decreased availability of ammonium nitrate and anhydrous ammonia, a substantial research effort has been directed toward strategies to reduce volatilization loss and improve urea performance in no-till corn production.

Urease inhibitors and slow release N sources have been tested to avoid or decrease urea-N losses in surface applications. From the literature it seems that N-(n-butyl) thiophosphoric triamide (NBPT) (commercially known as Agrotain) is the most promising urease inhibitor to improve urea performance when environmental conditions are favorable for N losses via volatilization (Clay et al., 1990; Hendrickson, 1992; Fox and Piekielek, 1993; and Wells et al., 1999). However, addition of NBPT to urea does not always increase yields (Rozas et al., 1999; Murphy and Ferguson, 1997).

Polymer-coated urea is a slow release N source that has been used in the turf and tree nursery markets, but its use for row crops has been restricted previously by its relatively high cost. However, a new polymer-coated urea has been developed that is sold by Agrium under the tradename of ESN. It is expected to be substantially less expensive than previously available products and potentially competitive in the row-crop market. Preliminary evidence indicates no yield benefit to polymer-coated urea when compared with urea (Motavalli et al., 2004). Gel-coated urea, another slow-release N source, is a relatively new product.

For this research, we have used four different nitrogen sources, and a wide range of application methods, to compare with broadcast urea in a no-till system. Our goal is to evaluate several strategies to improve urea efficiency in no-till corn production under growing conditions in Missouri and to compare their performance to other available N sources. This will help corn producers in Missouri decide how to manage nitrogen fertilizer.

MATERIALS AND METHODS

Field experiments were conducted during the 2004 and 2005 crop years at Bradford Research and Extension Center in Columbia, Missouri on a Mexico silt loam soil (fine, smectitic, mesic Aeric Vertic Epiaqualfs). This soil has a high-clay argillic horizon with low saturated hydraulic conductivity and is classified as somewhat poorly drained. The previous crop for both years was no-till soybean, and different experimental areas were used in each year. The corn variety Pioneer 34B20 YGCB RR2 was used in both the 2004 and 2005 experiments. The experiments were planted on 14 May 2004 and 03 May 2005. The plant density was approximately 74600 plants ha^{-1}, with 0.76 m row spacing. Different N fertilizer sources, placements, and additives were the experimental variables.

Treatments and Experimental Design

The experimental design was a randomized complete block with eight replications. Nitrogen treatments were applied pre-plant at a rate of 160 kg N ha^{-1}. The urease inhibitor Agrotain [N-(n-butyl) thiophosphoric triamide or NBPT] and the nitrification inhibitor dicyandiamide (DCD) were used in some treatments. The experimental treatments with fertilizer analysis were:

1. Urea broadcast (46-0-0)
2. Urea knifed in (46-0-0)
3. Urea tilled in (46-0-0)
4. Urea + Agrotain (46-0-0) (Agrotain International, St. Louis, MO)
5. Urea + Agrotain + DCD (46-0-0) (Agrotain International, St. Louis, MO)
6. Polymer-coated urea (44-0-0) (Agrium, Inc., Marion, IN)
7. Gel-coated urea (43-0-0) (Purcell Industries, Florence, AL)
8. Anhydrous ammonia (82-0-0)
9. Ammonium nitrate broadcast (34-0-0)

10. Ammonium nitrate knifed in (34-0-0)
11. Urea ammonium nitrate (UAN) solution (28-0-0)
12. UAN knifed in (28-0-0)
13. UAN + Agrotain (28-0-0)
14. UAN + Agrotain + DCD (28-0-0)
15. Untreated check

Each plot was 3 m by 12 m, and composed of four corn rows. Alleyways and experimental borders were planted with corn to avoid border effects. Dry fertilizers were applied using an Orbit-Air spreader (Gandy Company, Owatonna, Minnesota), liquid fertilizer treatments were sprayed using a portable CO_2-pressurized boom, and knifed in treatments were applied using a custom-made knife applicator. For the tilled-in urea treatments, a field cultivator was passed twice through the plots after the fertilizer was broadcast. In 2004, the broadcast treatments were applied on 27 April, liquid treatments were applied on 3 May, and knifed treatments were applied on 10 May, followed by planting on 14 May. In 2005, the dry treatments were applied on 19 April, the liquid treatments were applied on 20 April, and the knifed treatments were applied on 27 April, followed by planting on 3 May. Rainfall was responsible for some delays in treatment applications.

Reflectance measurements

For both experiments, reflectance measurements were taken using a Cropscan MSR-87 Multispectral Radiometer (Cropscan Inc., Rochester, Minnesota), and the data was used to assess treatment effectiveness along with yields. The design of the radiometer allows for near simultaneous inputs of voltages representing both incident and reflected radiation, which can be used to calculate reflectance from the crop canopy. Measurements were taken while moving the radiometer over one of the two middle rows of each plot, along its complete length. The radiometer was held level 0.5 m above the row using a support pole. Custom software was obtained which allowed the collection of about five measurements per second while walking down the row. About 50 measurements were obtained in each plot and averaged for use in statistical analyses.

For both years, three readings were taken during vegetative stages of growth. In 2004, reflectance measurements were taken on 18 June (plants at V8 stage and 70 cm tall), 25 June (V9 stage and 100 cm tall), and 4 July (V11 stage and 120 cm tall). In 2005, reflectance measurements were taken on 3 June (plants at V6 stage and 50 cm tall), 14 June (V8 stage and 90 cm tall), and 24 June (V10 stage and 210 cm tall).

Harvest

The plots were harvested using a small-plot Gleaner model E combine on 10/05/04 and 09/08/05. Border areas and alleyways were harvested just before harvesting the plots. The middle two rows were entirely harvested (2 rows by 12 m). The combine augered grain to a dump bucket equipped with an electronic scale and moisture meter. Weight and moisture values were recorded 45 seconds after the combine had reached the end of the plot. Yields were corrected to a moisture content of 135 g Kg^{-1}.

Economic analyses

All treatments were submitted to an economic analysis that evaluated the net return to the treatment. Return to N was calculated as:

Return to N = [(plot yield – unfertilized yield) x grain price – treatment cost]. A corn price of \$74.8 $Mg^{-1}$was used, which was the average value for yellow corn #2 at Kansas City – Missouri from June 2004 through August 2005 (USDA, 2005) was used. Treatment cost included both material cost and application cost. Nitrogen fertilizer prices were obtained from local fertilizer dealers in mid-Missouri in early December 2005:

1. Ammonium nitrate: \$1.06 Kg^{-1} N
2. Anhydrous ammonia: \$0.77 Kg^{-1} N
3. Polymer-coated urea: \$1.10 Kg^{-1} N
4. UAN: \$0.90 Kg^{-1} N
5. Urea: \$0.88 Kg^{-1} N
6. Urea + Agrotain + DCD: \$1.05 Kg^{-1} N

Time-averaged N fertilizer prices were not used because it appears that the lower N prices seen in the early part of the experimental period are not likely to come back. The Agrotain price was \$0.14 per Kg of N, obtained from a mid-Missouri fertilizer dealer in December 2005. The costs of fertilizer application were based on the University of Missouri agricultural guide (Plain et al., 2003). Economic evaluations were not made for gel-coated urea since it is a relatively new product in the market and prices for commercialization were not available.

Statistical analyses

Analysis of covariance was used to model treatment effect on yield. The GLM procedure of the Statistical Analysis System (SAS Institute) was used to do the calculation for this analysis. Data from each year were analyzed separately. Nearest neighbor estimates of the position effects of plots (Scharf and Alley, 1993) were used as covariates. Fisher's protected Least Significant Difference with $\alpha = 0.05$ was calculated. When p values are reported, they were calculated in SAS using the pdiff option in the GLM procedure. In addition, linear contrast tests were performed to compare some of the treatments.

Regression was used to relate treatment mean yields to green/near-infrared reflectance ratios. This ratio has been shown to be strongly related to the N status of the crop (Bausch and Duke, 1996; Scharf and Lory, 2002). Regression relating individual plot yields to green/near-infrared reflectance ratios was also performed. Analyses of variance and probability of treatment differences for green/near infrared were calculated using the GLM procedure of SAS. Return to N was statistically analyzed using analysis of variance in SAS, and Fisher's protected Least Significant Difference with $\alpha = 0.05$ was calculated.

RESULTS AND DISCUSSION

2004 Yields

Relatively higher yields were achieved in 2004, with an average yield of 9.0 Mg ha^{-1} (Table 2). Regular rainfall and cool nights during crop development contributed to good yields. Nitrogen applications more than doubled yields ($p < 0.0001$).

During the early stages of plant development, growth was slow and the plants appeared to be stressed, with purple coloration of the leaves and stems. After these stress symptoms were observed, we learned that the experimental area had received a fall application of Chlorimuron-ethyl (Canopy XL) prior to its acquisition for the research farm. The stress associated with this herbicide injury probably limited yields, which were good but lower than many nearby fields.

A high-yielding environment is favorable for differences between treatments to be expressed. However, weather was also favorable for minimizing volatilization loss from the broadcast urea treatment. Within 3 days after application of dry broadcast treatments, the experimental area received 33 mm of rainfall. This amount of rain is enough to move the urea into the soil (Craig and Wollum, 1982; Bouwmeester et al., 1985; Keller and Mengel, 1986), and thus volatilization losses from broadcast urea treatments should have been minimized.

Despite conditions unfavorable for ammonia volatilization, the anhydrous ammonia and ammonium nitrate (both broadcast and knifed in) treatments gave higher yields than broadcast urea at a 95% level of confidence (Table 2). In previous research, ammonium nitrate has usually produced higher yields than urea in no-till corn experiments (Table 1). This yield difference has generally been attributed to N loss from ammonia volatilization when urea was applied. Consistent with this explanation, rainfall soon after treatment application has been associated with nearly-equal yields for urea and ammonium nitrate (Fox and Hoffman, 1980; Oberle and Bundy, 1987; McVay et al., 1991). Why that did not happen in this experiment is unclear, but it is possible that the 33 mm of rainfall was enough to transport the urea deeper in the soil where urease activity greatly decreases (Dick, 1984), so that urea is less likely to be converted to ammonium and taken up by plants. In this case, the gel- and polymer-coated urea treatments should have prevented leaching of urea, however, we did not observe greater yields from those treatments.

Ammonium nitrate (broadcast and knifed in) and anhydrous ammonia also gave better yield responses than the urea treatments that were incorporated (knifed in and tilled in urea). This result conflicts with the idea that lower corn yields with urea are mainly due to ammonia volatilization. Previous studies have usually shown that incorporation of urea has avoided or diminished N losses via volatilization, and produced similar yields for urea and ammonium nitrate (Nelson and MacGregor, 1973; Fox et al., 1986; Howard and Tyler, 1989; and Wells et al., 2004). In an overall view of the literature, this type of result appears to be rare but not unheard of (Stevenson and Baldwin, 1969). Urea leaching is again a possible (but not convincing) explanation since rain within 3 days of application was 33 mm for tilled-in urea and 22 mm for knifed-in urea.

None of the strategies designed to improve urea performance showed statistically better yield responses than broadcast urea (Table 2). This was expected based on the rainfall soon after broadcasting urea. The reduced risk of ammonia volatilization, caused by the rainfall, resulted in similar yields for all urea treatments.

The addition of Agrotain and Agrotain + DCD to the urea treatments resulted in yields not statistically different from ammonium nitrate (broadcast and knifed in). These two treatments gave nearly identical yields, which were about 0.5 Mg ha^{-1} higher than broadcast urea. Although the statistical evidence for higher yields than broadcast urea is weak (p = 0.3 for urea + Agrotain and 0.4 for urea + Agrotain + DCD), it is reinforced by the consistency between the two treatments. That same consistency suggests that there was no benefit to the DCD and that any possible yield benefit can be attributed to the Agrotain. Agrotain has often been shown to increase yield from broadcast urea (Clay et al., 1990; Hendrickson, 1992; Fox and Piekielek, 1993; and Wells et al., 1999), but this is attributed to its ability to reduce ammonia volatilization. In this study, where rain shortly after urea broadcasting and the failure of urea incorporation (tillage and knifing) to increase yield both suggest that ammonia volatilization was minimal, it is difficult to understand why Agrotain might increase yield. However, it is consistent with the UAN treatments, in which Agrotain increased yield significantly and Agrotain + DCD showed a tendency toward increased yield. A linear contrast showed that the addition of Agrotain improved yields from urea by 0.53Mg ha^{-1} and UAN by 0.92 Mg ha^{-1} with 93% certainty.

The urea-ammonium nitrate solution (UAN) treatments gave the lowest yields among N sources. In particular, the UAN + Agrotain + DCD and UAN treatments yielded significantly less than the broadcast urea treatment (90% and 98% confidence, respectively). The presence of crop residues may have caused N immobilization. The problem with immobilization is aggravated for the UAN solution because its dispersion, by spraying, results in a large amount of the solution being deposited over the residues where soil microorganisms' concentration may be high. The poor performance of the UAN treatments is supported by the high level of significance obtained when contrasting them with the remaining treatments ($p < .0001$). Hanson et al. (1988) also reported that broadcast urea gave higher yield than UAN in a no-till corn experiment in Missouri. On the other hand, urea and UAN solution often give similar yields in no-till corn (Bandel et al., 1980; McVay et al., 1991; Stecker et al., 1992). Unlike urea and ammonium nitrate, knifing increased yield from UAN solution. This indicates that knife application was effective in reducing the loss process. This is consistent with immobilization being the main loss process from broadcast UAN, since the N would have much less contact with residue when knifed.

2004 Reflectance Measurement: Relationship to Treatment Yield

A good correlation between treatment mean yields and green/NIR ratios was obtained with the third reflectance measurements (Figure 2C). Over the whole experiment, the reflectance values followed a pattern, with the first reflectance readings giving the highest green/NIR values (Figure 2A), the second giving intermediate values (Figure 2B), and the third (Figure 2C) giving the lowest values. Thus, the plants became darker green as the growing season progressed, due to nitrogen uptake, maturing photosystems, and denser canopy.

The regression analysis for the measurement on 4 July (last measurement) was highly significant using all data ($p < 0.0001$) and remained significant when the check treatment was omitted ($p = 0.02$). The 25 June measurement had a significant correlation between green/NIR ratios and yields only when the check plots were included ($p = 0.04$), and the first measurement (18 June) did not result in a significant correlation between yields and leaf color

($p \geq 0.3$). It is possible that the plants had not expressed the treatment effects yet when the first measurements were taken. On the other hand, individual plot reflectance was always a significant predictor of yield ($p < 0.0001$ with and without check plots for all treatment and measurement timings). Discussion of reflectance measurements in the rest of this section will focus on 4 July measurements unless otherwise stated.

The anhydrous ammonia and broadcast ammonium nitrate treatments gave the highest yields and the lowest green/NIR values, confirming that nitrogen was more available from these treatments than from any others.

The addition of Agrotain to urea produced some positive effects on the plants' appearance, based on reflectance measurements ($p = 0.1$) (Figure 2C). This bolsters the weak evidence ($p = 0.3$) that Agrotain produced a yield response when added to urea. Similarly, the UAN + Agrotain treatment gave higher yields (93% confidence) than UAN alone, and reflectance measurements supported this result with 93% confidence (Figure 2C). Reflectance measurements also suggested that Agrotain + DCD increased N availability from UAN (Figure 2C), but this was at best weakly expressed in yield (Table 2).

Gel- and polymer-coating did not improve the efficiency of urea, based on yield results, but they did give lower reflectance values than uncoated urea (Figure 2C). This suggests that nitrogen was better available to the plants from these products, and encourages further research with them.

On the first measurement date, reflectance from all four knifed treatments was about the same as from the check plots (Figure 2A). This suggests that few roots had reached the mid-row N bands by this date. However, by a week later, crop reflectance from knifed treatments was significantly lower than from check plots, and about the same as from the tilled-in urea treatment (Figure 2B). By 4 July (Figure 2C), the knifed treatments had about the same average reflectance as other treatments, indicating full exploration of the fertilizer bands by crop roots. By this date, the two knifed treatments that would produce higher yields (ammonium nitrate and anhydrous ammonia) also gave lower green/NIR reflectance than the lower-yielding knifed treatments (urea and UAN). The reason for lower N availability from knifed urea and UAN than from knifed ammonium nitrate and anhydrous ammonia is unclear, but the fact that it happened is supported by evidence from both yields and reflectance measurements.

Knifing improved yield ($p = 0.02$) and suggested improvement in green/NIR reflectance ($p = 0.2$) for UAN, but did not improve either yield or reflectance for urea or ammonium nitrate. This is consistent with minimal urea loss by volatilization, substantial immobilization of broadcast (but not knifed) UAN, and minimal immobilization of granular N sources.

Economic Return to Nitrogen in 2004

This experiment resulted in a mean return to nitrogen of \$230 ha^{-1} (Table 3). The good yields and large yield responses to N were responsible for the positive net return involved with N fertilizer application.

Anhydrous ammonia and ammonium nitrate (both knifed in and broadcast), the three best yielding treatments, provided the highest return to N. However, only the anhydrous ammonia and broadcast ammonium nitrate treatments gave significantly higher return to N when compared with broadcast urea ($p = 0.002$, and $p = 0.07$, respectively), despite the extra costs involved with knife injection of anhydrous ammonia and higher costs of ammonium nitrate.

No Agrotain treatment was significantly more profitable than the same N source without Agrotain, but all four Agrotain treatments produced higher estimates for return to N than the corresponding untreated N sources. The probability of this happening if there was no true economic benefit to Agrotain is 0.06, supporting the idea that Agrotain use was profitable in this experiment. Agrotain was the only urea management strategy for which there was evidence of a profitable response. Neither of the coated urea products improved profitability relative to broadcast urea, nor did either of the incorporation strategies.

Broadcast urea (\$229 ha^{-1}) provided a better return to N than UAN (\$133 ha^{-1}) ($p = 0.01$) and UAN + Agrotain + DCD (\$138 ha^{-1}) ($p = 0.02$) due to the low yields associated with these treatments.

2005 Yields

In 2005, yields were severely drought-limited, resulting in an average yield of 3.5 Mg ha^{-1} (excluding check plots). The experimental area received 100 mm of rainfall during the early stages of plant development, before the plants reached the V15 stage. Only 17 mm of rain fell in the experimental area between the VT stage and the R6 stage (physiological grain maturity). In some individual plots, yields were as low as 0.2 Mg ha^{-1} due to a complete failure of pollination, which was probably caused by the late emergence of silks. The treatments mean yield for all treatments are presented in Table 4.

Three replications, located in lower, eroded areas of the landscape, had average yield below 1.0 Mg ha^{-1} and so there was almost no chance for an effective treatment to be expressed as a yield increase. The other five replications were used for statistical analyses, and there were no significant differences between yields for most treatments that received nitrogen (Table 4).

We did not expect differences in yields between the treatments aimed at avoiding N losses via ammonia volatilization, because within 3 days after the dry broadcast treatments were applied, the experimental area received 42 mm of rainfall and 49 mm within 5 days. However, nitrogen application did result in yield increases of 1.9 Mg ha^{-1} to 2.5 Mg ha^{-1}compared with control plots.

Tilled-in urea gave yields which were about 0.25 Mg ha^{-1} higher ($p = 0.4$) than broadcast urea. This was the only treatment for which there was even weak evidence of yield improvement relative to broadcast urea. Thus, none of the strategies for using urea in no-till corn produced a yield benefit in this experiment.

As observed in 2004, the reflectance of all knifed treatments on the first measurement date was about the same as from the check plots (Figure 3A), evidencing the slow N availability from knifed treatments. Since the yields were determined early in the season, due to the drought, knifed treatments had lower yields when compared with other treatments (96% of certainty based on linear contrast between knife and other treatments).

2005 Reflectance Measurement: Relationship to Treatment Yield

The reflectance pattern observed in the previous year was also observed in 2005. Plants were lighter in color at the time when the first readings were taken (i.e., had higher green/NIR ratios), and the lowest green/NIR values at the time when the third readings were taken (Figure 3). Treatment mean reflectance was a significant predictor of treatment mean yield for the 3 June (Figure 3A) and 24 June (Figure 3C) measurements when the unfertilized treatments were included ($p = 0.008$ and $p < 0.0001$, respectively) and when they were not included ($p = 0.09$ and $p = 0.02$, respectively). The contrast between treatment mean yield (and individual plot yield) and green/NIR reflectance on the 14 June measurement was not significant (Figure 3B). Discussion of reflectance measurements in the rest of this section will focus on 24 June measurements (Figure 4) unless otherwise stated.

As the crop developed, UAN + Agrotain and ammonium nitrate gave the lowest green/NIR ratios (Figure 4), but $p > 0.25$ for difference from broadcast urea. As in 2004, ammonium nitrate was one of the lowest reflectance treatments at the third measurement, and was among the higher-yielding treatments. UAN + Agrotain was also among the lowest-reflectance treatments for the first two measurements in 2004, but fell to average reflectance at the third measurement.

Polymer-coated urea showed the same efficiency in delivering nitrogen to the plants as urea + Agrotain and was the only treatment with at least 3% higher yield and 3% lower green/NIR reflectance than broadcast urea (Figure 4). Polymer-coated urea may have retained N in the upper root zone better than other treatments during the heavy rains shortly after treatment application.

Gel-coated urea, however, gave similar reflectance values results to those of the broadcast urea treatments, and the same was true for yield.

Economic Return to Nitrogen in 2005

Drought severely affected treatment effectiveness and this was reflected in return to N. In 2005, the mean return to nitrogen was -\$6 ha^{-1} (Table 5).

There was weak evidence that tilled-in urea and polymer-coated urea may have produced higher yields than broadcast urea. Even if these yield increases were real, they were not large enough to pay for the additional treatment cost (Table 5.).

Broadcast urea (\$20 ha^{-1}) resulted in better return to N than knifed UAN (-\$19 ha^{-1}), UAN + Agrotain + DCD (- \$25 ha^{-1}), and urea + Agrotain + DCD (- \$21 ha^{-1}) with 90% certainty. Since yields were drought-limited, the extra costs of additives and incorporation decreased the return to N for these treatments.

None of the treatments tested gave a statistically better return to N than broadcast urea. Only anhydrous ammonia gave a numerically higher return to N due to its low total cost of N. Water limitations on yield not only prevented strategies for efficient urea use from being profitable, they prevented N fertilizer from being profitable.

CONCLUSIONS

The objective of this study was to find management alternatives that would improve the efficiency of urea in no-till corn production. In the first year, relatively higher yields were obtained due to well-distributed rainfall, and some treatments gave significantly higher yields than broadcast urea. In the second year, very low yields were obtained due to a severe drought, and there were no significant differences between the yields obtained from the different N treatments.

Of the treatments tested to improve no-till corn yields with urea, only Agrotain produced good evidence that it increased N delivery to the crop and yield. Agrotain also increased yield with UAN solution, but yields were still no better than unamended urea. Treatments based on UAN were significantly lower-yielding ($p < 0.0001$) than all other treatments, probably due mostly to N immobilization on residue. Despite good evidence of yield increases due to Agrotain, economic benefits were minimal or nonexistent in these two experiments because the treatment cost offset the yield gains.

Over the two years of experimentation, polymer- and gel-coated urea produced yields similar to broadcast urea. Neither tillage nor knife injection of urea gave higher yields than broadcast urea. The rain that fell shortly after application of dry materials in both years may be responsible for the similar results between these treatments and urea since volatilization losses from broadcast urea would be expected to be low. Given this situation, the yield responses to Agrotain were somewhat unexpected.

Ammonium nitrate (broadcast and knifed in) and anhydrous ammonia gave statistically higher yields than broadcast urea in 2004. Over the two years of the study, only anhydrous ammonia and broadcast ammonium nitrate resulted in greater return to N than broadcast urea. These sources continue to be excellent for use in no-till corn production, and out-performed all of our strategies for improved management of urea.

LITERATURE CITED

Avnimelech, Y., and M. Laher. 1977. Ammonia volatilization from soils: equilibrium considerations. Soil Sci. Soc. Am. J. 41:1080-1084.

Bandel, V. A., S. Dzienia, and G. Stanford. 1980. Comparison of N fertilizers for no-till corn. Agron. J. 72:337-341.

Bandick, A. K., and R. P. Dick. 1999. Field management effects on soil enzyme activities. Soil Biol. Biochem. 31:1471-1479.

Barreto, H. J., and R. L. Westerman. 1989. Soil urease activity in winter wheat residue management systems. Soil Sci. Soc. Am. J. 53:1455-1458.

Bausch, W. C., and H. R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Trans. ASAE. 39:1869-1875.

Bergstrom, D. W., C. M. Monreal, and D. J. King. 1998. Sensitivity of soil enzyme activities to conservation practices. Soil Sci. Soc. Am. J. 62:1286-1295.

Beyrouty, C. A., L. E. Sommers, and D. W. Nelson. 1988. Ammonia volatilization from surface-applied urea as affected by several phosphoroamide compounds. Soil Sci. Soc. Am. J. 52:1173-1178.

Bouwmeester, R. J. B., P. L. G. Vlek, and J. M. Stumpe. 1985. Effect of environmental factors on ammonia volatilization from urea-fertilized soil. Soil Sci. Soc. Am. J. 49:376-381.

Bundy, L. G., and S. L. Oberle. 1988. Evaluation of methods for control of ammonia volatilization from surface-applied urea-containing fertilizers. J. Fert. Issues 5:24-30.

Clay, D. E., G. L. Malzer, and J. L. Anderson. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. Soil Sci. Soc. Am. J. 54:263-266.

CTIC. 2002. National Crop Residue Management Survey. 2002. http://www.ctic.purdue.edu/core4/ct/ctsurvey/nationaldata.html (5 January 2006).

Craig, J. R., and A. G. Wollum. 1982. Ammonia volatilization and soil nitrogen changes after urea and ammonium nitrate fertilization of *Pinus taeda* L. Soil Sci. Soc. Am. J. 46:409-414.

Dick, W. A. 1984. Influence of long -term tillage and crop rotation combination on soil enzyme activities. Soil Sci. Soc. Am. J. 48:569-574.

Fox, R. H., and L. D. Hoffman. 1980. The effect of N fertilizer source on grain yield, N uptake, soil pH, and lime requirement in no-till corn. Agron. J. 73:891-895.

Fox, R. H., J. M. Kern, and W. P. Piekielek. 1986. Nitrogen fertilizer sources, and methods and time of application effects on no-till corn yields and nitrogen uptakes. Agron. J. 78:741-746.

Fox, R. H., and W. P. Piekielek. 1993. Management and urease inhibitor effects on nitrogen use efficiency in no-till corn. J. Prod. Agric. 6:195-200.

Fox, R. H., W. P. Piekielek, and K. E. Macneal. 1996. Estimating ammonia volatilization losses from urea fertilizers using a simplified micrometeorological sampler. Soil Sci. Soc. Am. J. 60:596-600.

GAO, 2003. Domestic nitrogen fertilizer production depends on natural gas availability and prices. Report to the ranking democratic member, committee on agriculture, nutrition and forestry, U.S. Senate. GAO-03-1148.

Hanson R. G., J. A. Stecker, D. D. Buchholz, N. C. Wolenhaupt, K. A. McVay, W. E. Flanary, and R. L. Smoot. 1988. Evaluation of four nitrogen sources on corn grown under two crop rotations in a conservation tillage system. Missouri Soil Fertility and Fertilizers Research Updates 1988. Agronomy Miscellaneous Publ. #89-01 p.3-12. University of Missouri, Columbia, MO.

Hargrove, W. L., and D. E. Kissel. 1979. Ammonia volatilization from surface application of urea in the field and laboratory. Soil Sci. Soc. Am. J. 43:359-363.

Hendrickson, I. L. 1992. Corn yield response to urease inhibitor NBPT: five-year summary. J. Prod. Agric. 5:131-137.

Howard, D. D., and M. E. Essington. 1998. Effects of surface-applied limestone on the efficiency of urea-containing nitrogen sources for no-till corn. Agron. J. 90:532-528.

Howard, D. D., and D. D. Tyler. 1989. Nitrogen source, rate, and application method for no-tillage corn. Soil Sci. Soc. Am. J. 53:1573-1577.

IFADATA. Nitrogen, phosphate, and potash statistics. 2005. http://www.fertilizer.org/ifa/statistics/ifadata/DATA/world.xls (30 December 2005).

Keller, D. G., and D. B. Mengel. 1986. Ammonia volatilization from nitrogen fertilizers surface applied to no-till corn. Soil Sci. Soc. Am. J. 50:1060-1063.

Mengel, D. B., D. W. Nelson, and D. M. Huber. 1982. Placement of nitrogen fertilizers for no-till and conventional till corn. Agron. J. 74:515-518.

McVay, K. A., J. A. Stecker, D. D. Buchholz, and R. L. Smoot. 1991. Nitrogen fertilizer source, rates, and application methods for no-till corn production. Missouri Soil Fertility and Fertilizers Research Update 1991. Agronomy Miscellaneous Publ. #92-01 p.23-26. Univ. of Missouri, Columbia, MO.

Motavalli, P., K. Nelson, S. Anderson, and J. Sadler 2004. Use of slow-release N fertilizer to control nitrogen losses due to spatial and climatic differences in soil moisture conditions and drainage. Missouri Soil Fertility and Fertilizers Research Update 2004. Agronomy Miscellaneous Publ. #05-01 p.114-118. Univ. of Missouri, Columbia, MO.

Murphy, T. L., and R. B. Ferguson. 1997. Ridge-till corn and urea hydrolysis response to NBPT. J. Prod. Agric. 10:271-282.

Nelson, W. W., and J. M. MacGregor. 1973. Twelve years of continuous corn fertilization with ammonium nitrate or urea nitrogen. Soil Sci. Soc. Amer. Proc. 37:583-586.

Oberle, S. L., and L. G. Bundy. 1987. Ammonia volatilization from nitrogen fertilizers surface-applied to corn (*Zea mays*) and grass pasture (*Dactylis glomerata*). Biol. Fertl. Soils 4:185-192.

O'Deen, W. A., and R. F. Follett. 1992. Ammonia emission from soybean-amended calcareous soil with various soil temperature and moisture levels. Agron. J. 84:893-896.

Palma, R. M., M. I. Saubidet, M. Rimolo, and J.Utsumi. 1998. Nitrogen losses by volatilization in a corn crop with two tillage systems in the Argentine Pampa. Comm. Soil Sci. Plant Anal. 29:2865-2879.

Plain, R., J. White, and J. Travlos. 2003. 2003 custom rates for farm services in Missouri. Agricultural MU guide G302, Univ. of Missouri, Columbia, MO.

Raun, W. R., D. H. Sander, and Olson. 1989. Nitrogen fertilizer carriers and their placement for minimum till corn under sprinkler irrigation. Agron. J. 81:280-285.

Rozas, H. S., H. E. Echeverria, G. A. Studdert, and F. H. Andrade. 1999. No-till maize nitrogen uptake and yield: effect of urease inhibitor and application time. Agron. J. 91:950-955.

Scharf, P. C., and J. A. Lory. 2000. Calibration of remotely-sensed corn color to predict nitrogen need. Proceedings of the Fifth International Conference on Precision Agriculture. ASA-CSSA-SSSA, Madison, WI.

Scharf, P. C., and M. M. Alley. 1988. Nitrogen loss pathways and nitrogen loss inhibitors: a review. J. Fert. Issues 5 :109-125.

Scharf, P. C., and M. M. Alley. 1993. Accounting for spatial variability in field experiments increases statistical power. Agron. J. 85:1254-1256.

Stecker, J. 1994. Fertilizer nitrogen sources and application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1994. Agronomy Miscellaneous Publ. #95-02 p.16-21. Univ. of Missouri, Columbia, MO.

Stecker, J. 1995. Fertilizer nitrogen sources and application times for no-till corn. Missouri Soil Fertility and Fertilizers research Update1995. Agronomy Miscellaneous Publ. #96-03 p.8-13. Univ. of Missouri, Columbia, MO.

Stecker, J. A., D. D. Buchholz, R. G. Hanson, N. C. Wollenhaupt, and K. A. McVay. 1993a. Broadcast nitrogen sources for no-till continuous corn and following soybean. Agron. J. 85:893-897.

Stecker, J. A., D. D. Buchholz, R. G. Hanson, N. C. Wolenhaupt, and K. A. McVay. 1993b. Application placement and timing of nitrogen solution for no-till corn. Agron. J. 85:645-654.

Stecker, J. A., D. D. Buchholz, G. Smith, W. E. Flanary, and R. L. Smoot. 1992. Fertilizer nitrogen sources for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1992. Agronomy Miscellaneous Publ. #93-04 p.1-7. Univ. of Missouri, Columbia, MO.

Stecker, J., B. Chappel, and R. Bottoms. 1994. Urea and ammonium nitrate application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1994. Agronomy Miscellaneous Publ. #95-02 p.31. Univ. of Missouri, Columbia, MO.

Stecker, J., B. Chapel, and R. Bottoms. 1995. Urea and ammonium nitrate application times for no-till corn. Missouri Soil Fertility and Fertilizers Research Update 1995. Agronomy Miscellaneous Publ. #96-03 p.14-15. Univ. of Missouri, Columbia, MO.

Stevenson, C. K., and C. S. Baldwin. 1969. Effect of time and method of nitrogen application and source of nitrogen on the yield and nitrogen content of corn (*Zea mays* L.). Agron. J. 61:381-384.

Tisdale S. L., J. L. Havlin, J. D. Beaton, and W. L. Nelson. 1999. Soil fertility and fertilizers: an introduction to nutrient management, p. 86-153. Prentice Hall, Inc. New Jersey. United States.

Touchton, J. T., and W. L. Hargrove. 1982. Nitrogen sources and methods of application for no-tillage corn production. Agron. J. 74:823-826.

USDA. 2005a. U.S. fertilizer use and price. 2005.
http://www.ers.usda.gov/Data/FertilizerUse/Tables/Fert%20Use%20Table%204.xls (30 December 2005).

USDA. 2005b. Cash prices of corn at principal markets, United States, by month. 2005.
http://www.ers.usda.gov/data/feedgrains/standardreports/Cash_Corn_Prices.xls (5 December 2005).

Varsa, E. C., S. A. Ebelhar, P. R. Eberle, E. Gerhard, and T. Wyciskalla. 1993. Evaluation of nitrogen management practices in no-till corn production. Department of crop Sciences, University of Illinois, Urbana-Champaign.

Wells, K. L., J. E. Dollarhide, and H. E. Burkwhat. 1999. Field evaluation of Super Urea for production of no-till corn. Agronomy note, vol 31, number 1.
http://www.uky.edu/Ag/Agronomy/Extension/agr_notes/agvl31_1.pdf (20 November, 2005).

Wells, K. L., L. W. Murdock, and H. F. Miller. 2004. Urea as a source of fertilizer nitrogen for crops in Kentucky.
http://www.ca.uky.edu/agc/pubs/agr/agr69/agr69.htm (1 November 2005).

Wells, K. L., W. O. Thom, and H. B. Rice. 1992. Response of no-till corn to nitrogen source, rate, and time of application. J. Prod. Agric. 5:604-610.

Zhang, F., A. F. Mackenzie, and D. L. Smith. 1993. Corn yield and shifts among corn quality constituents following application of different nitrogen fertilizer sources at several times during crop development. J. Plant Nutrition 16:1317-1337.

Table 1. Studies comparing ammonium nitrate and urea performance on no-till corn.

Study	Date published	Years of experimentation	N rate used (Kg/ha)	Source with better result	Observations
Bandel et al.	1980	3	45, 90, 135, 180	ammonium nitrate	
Fox and Hoffman	1980	4	0, 50, 101, 202	ammonium nitrate same as urea	rain
Fox et al.	1986	3	59, 97,171	ammonium nitrate	
Fox et al.	1996	3	134	ammonium nitrate	
Hanson et al.	1989	2	654, 107, 161	ammonium nitrate	
Howard and Tyler	1989	3	56, 112, 168, 224	ammonium nitrate	
Howard and Essington	1988	6	168	ammonium nitrate	
McVay et al.	1992	4	80, 160	ammonium nitrate same as urea	wet soil
Mengel et al.	1982	3	0, 165	ammonium nitrate same as urea	
Nelson and MacGregor	1973	12	106	ammonium nitrate same as urea	
Oberle and Bundy	1987	2	0, 56, 112	ammonium nitrate same as urea	rain
Raun et al.	1989	3	90, 180	ammonium nitrate same as urea	irrigated
Stecker	1995	1	134, 161	ammonium nitrate	early preplant
Stecker	1994	1	120, 180	ammonium nitrate same as urea	
Stecker et al.	1993a	3	67, 135, 202	ammonium nitrate	
Stecker et al.	1993b	2	54, 107, 161, 214	ammonium nitrate	
Stecker et al.	1994	2	89, 134	ammonium nitrate	
Stecker et al.	1995	2	100, 150	ammonium nitrate	
Touchton and Argrove	1982	3	90, 180, 270	ammonium nitrate	
Varsa et al.	1998	4	125,161	ammonium nitrate	
Wells et al.	1992	3	0, 71, 143	ammonium nitrate	
Zhang et al.	1993	3	90, 180	ammonium nitrate same as urea	

Table 2. Treatment least square mean yields for the corn 2004 experiment.

Treatment	Yield LSMean Mg ha^{-1}
Anhydrous ammonia	10.29
Ammonium nitrate	10.10
Knifed ammonium nitrate	10.03
Urea+Agrotain	9.35
Urea+Agrotain+DCD*	9.27
Polymer-coated urea	9.21
Urea tilled in	9.08
Urea	8.82
Knifed UAN	8.82
Knifed urea	8.76
Gel-coated urea	8.61
UAN+Agrotain	8.52
UAN+Agrotain+DCD	7.97
UAN	7.60
Check	3.77
$LSD_{(0.05)}$	0.84

* DCD = dicyandiamide

Table 3. Return to nitrogen applied in the 2004 corn experiment.

Treatment	Return to N
	$ ha^{-1}
Anhydrous ammonia	347
Ammonium nitrate	297
Knifed ammonium nitrate	285
Urea+Agrotain	247
Urea+Agrotain+DCD	236
Urea	229
Urea tilled in	228
Polymer-coated urea	224
Knifed UAN	219
Knifed urea	218
UAN+Agrotain	180
UAN+Agrotain+DCD	138
UAN	133
$LSD_{(0.05)}$	61

Table 4. Treatment least square mean yields for the 2005 corn experiment.

Treatment	Yield LSMean Mg ha^{-1}
Urea tilled in	3.86
Polymer-coated urea	3.77
Ammonium nitrate	3.64
UAN+Agrotain	3.63
Urea	3.61
Urea+Agrotain	3.60
Anhydrous ammonia	3.55
Gel-coated urea	3.50
Urea+Agrotain+DCD*	3.41
UAN+Agrotain+DCD	3.37
Knifed ammonium nitrate	3.30
Knifed urea	3.29
Knifed UAN	3.21
UAN	3.20
Check	1.33
$LSD_{(0.05)}$	0.57

* DCD = dicyandiamide

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Table 5. Return to nitrogen applied in the 2005 corn experiment.

Treatment	Return to N $ ha^{-1}
Anhydrous ammonia	24
Urea	20
Urea tilled in	19
Polymer-coated urea	-2
Urea+Agrotain	-2
UAN+Agrotain	-4
Ammonium nitrate	-5
Knifed urea	-10
UAN	-15
Knifed UAN	-19
Urea+Agrotain+DCD	-21
UAN+Agrotain+DCD	-25
Knifed ammonium nitrate	-37
$LSD_{(0.05)}$	38

Figure 1. The urea hydrolysis process that occurs when urea is applied to the soil.

Equation 1.

Urea Hydrolysis

$$(NH_2)_2CO + 2H_20 \xrightarrow[\text{Urease}]{\text{Soil}} (NH_4)_2CO_3$$

Urea, Water, Ammonium Carbonate

Equation 2.

$$(NH_4)_2CO_3 + 2H^+ \longrightarrow 2NH_4^+ + CO_2\uparrow + H_20$$

Ammonium Carbonate, Ammonium, Carbon Dioxide (gas), Water

Equation 3.

$$NH_4^+ + OH^- \longrightarrow NH_3\uparrow + H_2O$$

Ammonium, Hydroxyl, Ammonia, Water

Figure 2. Interaction between Green and Near-Infrared (NIR) ratios and mean yields for the three different reflectance measurements taken during the 2004 corn experiment.

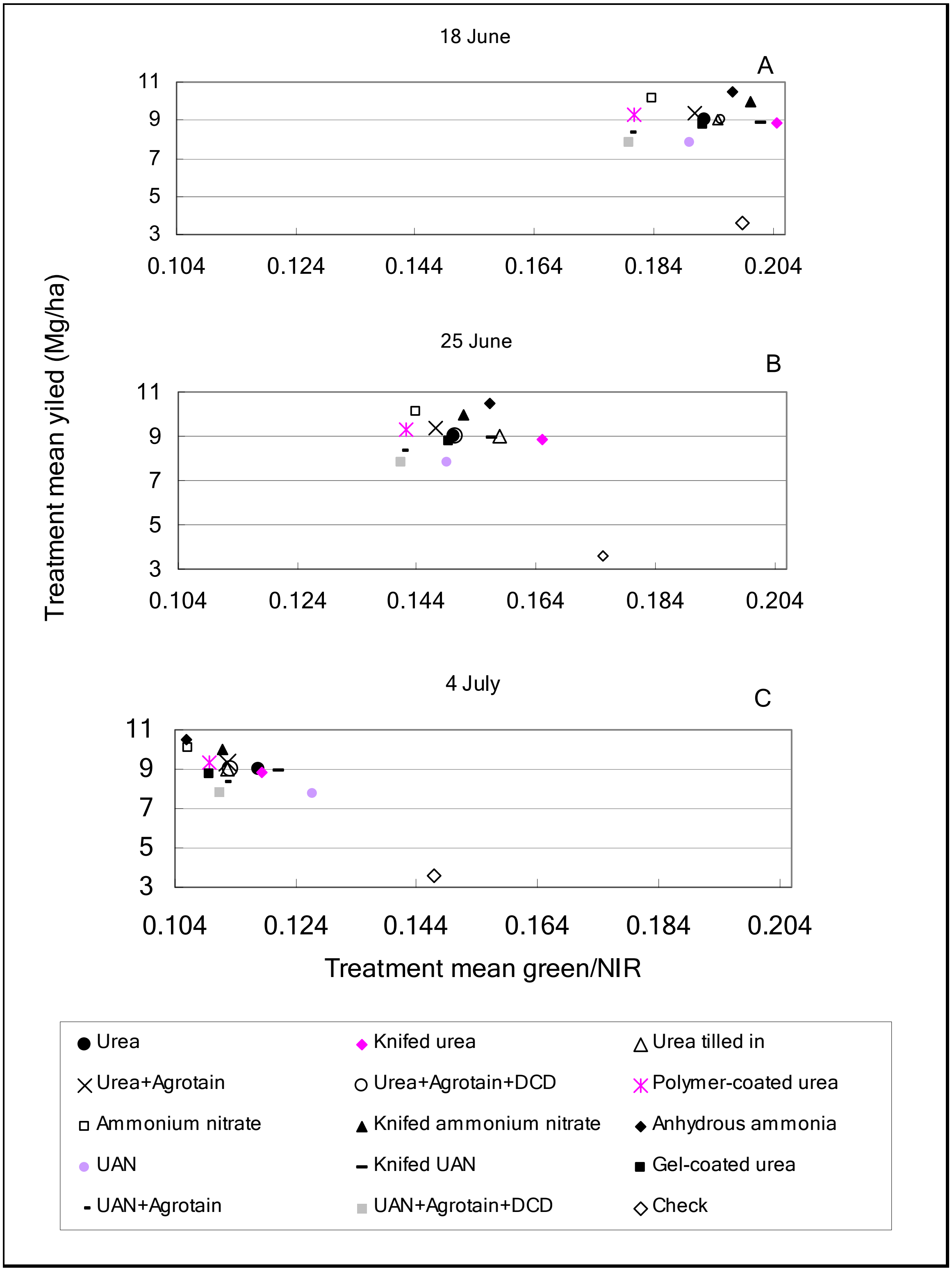


Figure 3. Interaction between Green and Near-Infrared (NIR) ratios and mean yields for the three reflectance measurements taken during the 2005 corn experiment.

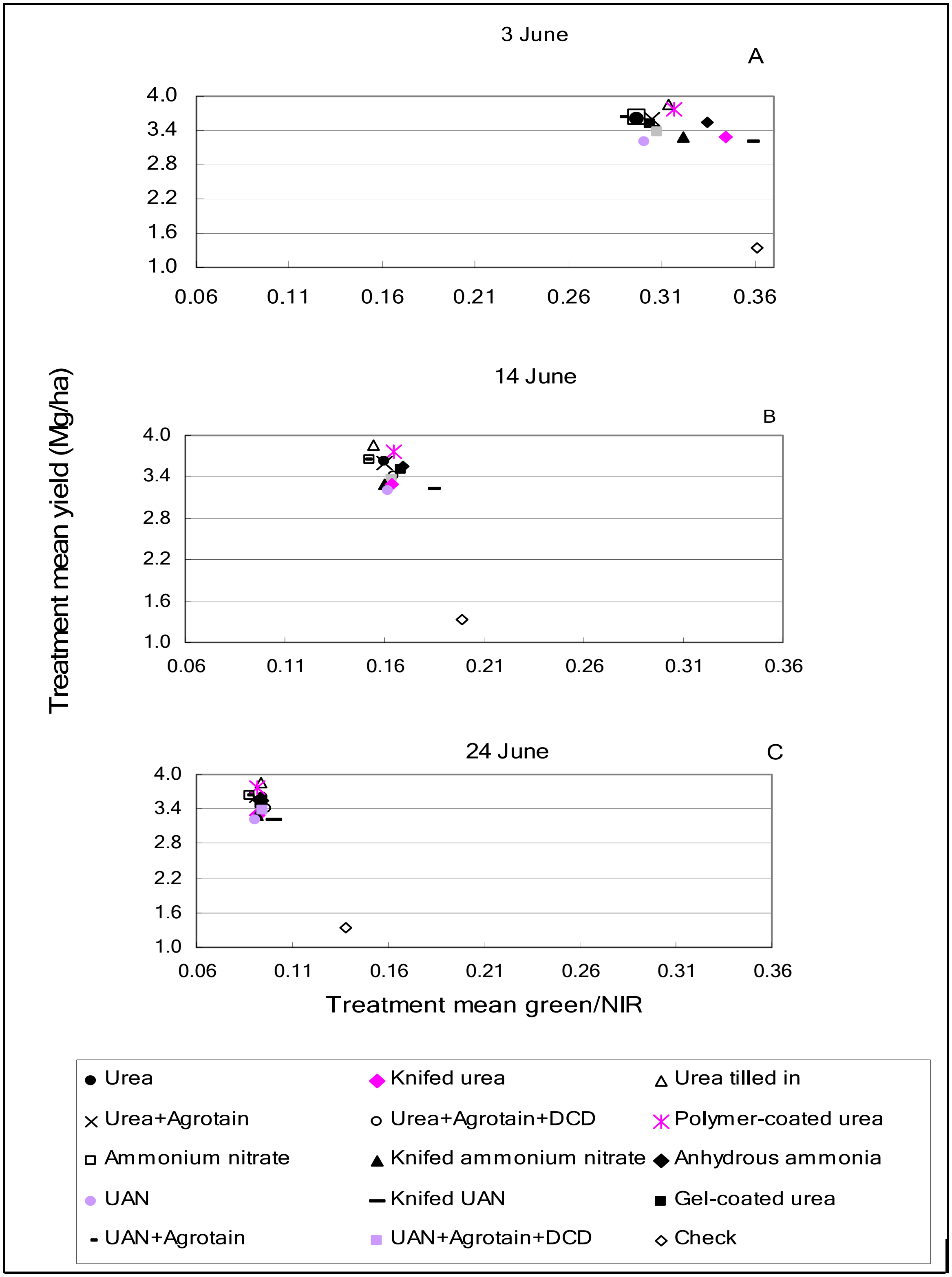
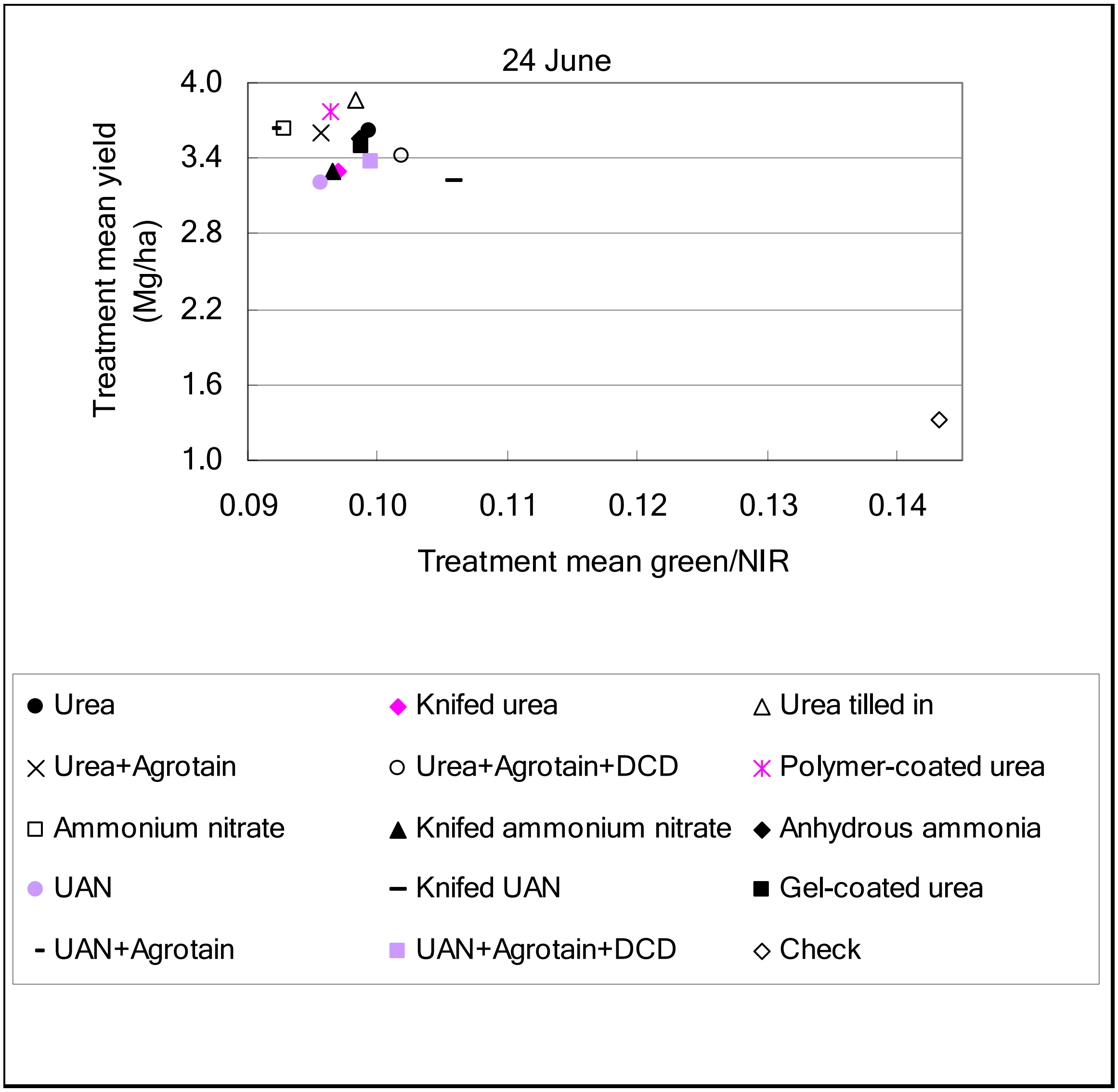


Figure 4. Interactions between Green/NIR ratios and mean corn yields for the reflectance measurements taken on 24 June 2005. This figure is the same as figure 3C but allows a change of scale to improve visibility of the data.



CHAPTER III

MANAGEMENT ALTERNATIVES FOR TOPDRESSING UREA ON WINTER WHEAT

ABSTRACT

Urea production and use are increasing worldwide. Traditionally, urea has been incorporated to avoid losses of N by ammonia volatilization. However, this option is not available when topdressing wheat. The objective of this project is to evaluate several strategies designed to reduce the risk of ammonia volatilization loss from urea topdress applied on wheat. The tested strategies included treating urea with Agrotain (a urease inhibitor) or Agrotain + dicyandiamide (DCD), and use of coated urea products. Ammonium nitrate and urea-ammonium nitrate (UAN) solutions were used in the trials as well. Fertilizers were applied at a rate of 80 kg N ha^{-1}. Reflectance measurements were taken during crop development to complement yield as a measure of treatment effectiveness. Nitrogen more than doubled wheat yields in both years. In 2004, wheat yields were low and none of the strategies designed to reduce N loss resulted in higher wheat yields with 95% confidence. However, the weather was favorable for ammonia volatilization and there was evidence from both yield (72% confidence) and reflectance (97% confidence) that urea + Agrotain + DCD was more effective than urea in delivering N to the crop. With excellent yields in 2005, urea + Agrotain (5.4 Mg ha^{-1}), urea + Agrotain + DCD (5.4 Mg ha^{-1}), and ammonium nitrate (5.5 Mg ha^{-1}) produced higher yields when compared with broadcast urea (5.1 Mg ha^{-1}). The addition of a timing effect for the 2005 experiment resulted in a significant and large yield response (1.4 Mg ha^{-1}) when treatments were applied in March

compared to in January. Application of polymer- and gel-coated urea did not improve wheat yield relative to urea in either year. All UAN treatments showed lower yield responses and higher reflectance values in both years. Agrotain + DCD was the most effective treatment for increasing yield and profitability from urea over the two study years.

INTRODUCTION

Increased production costs and environmental awareness have promoted the development of methods to increase the efficiency of applied nutrients. Nitrogen is often the most limiting nutrient for cereal grain production, and application of nitrogen fertilizers represents one of the highest input costs in agricultural systems. Adequate N must be available to the wheat plant at all phases of development. Shortage of N can result in reduced tillering, reduced head size, poor grain fill, reduced yields, and low grain protein content (Stewart et al. 2005, Conley et al. 2003).

Urea is the most widely used dry nitrogen fertilizer and its use is growing. Nitrogen fertilizer imports to the U.S. are increasing due to high prices for natural gas in North America. Urea is the major fertilizer traded in international commerce, and is the dominant N form in increased imports. It is expected to soon account for more than 50% of all nitrogen fertilizers traded, and has already captured more than 65% of the world trade in dry N fertilizers (Gilgames, 2004).

In Missouri, where the climate is humid, most winter wheat is topdressed in early spring. All-preplant N management used to be more common, but failed too often due to overwinter N losses. Fall application of N prolongs exposure to the environment before crop uptake, increasing the risk of N loss through immobilization, leaching, or denitrification.

When surface applied, urea is susceptible to loss by ammonia volatilization (Keller and Mengel, 1986; Scharf and Alley, 1987; Bundy and Oberle, 1988; Beyrouty et al., 1988). Traditionally, urea has been incorporated with tillage to avoid this loss. However, this option is not available when topdressing wheat. Thus, ammonia volatilization is potentially a serious issue for urea topdressed on winter wheat. Volatilization loss of N from urea may be particularly high in no-till wheat, since surface residue accumulation increases the activity of urease (McInnes et al., 1986; and Barreto and Westerman, 1989). Ammonium nitrate is a good N source for top dressing wheat, but problems with security, closing of production plants, a likely decrease in availability, and higher price than urea is decreasing its popularity. UAN can also be a good N source for topdressing wheat, but tends to perform poorly in no-till due to N immobilization on residue (Stecker, 1993; Stecker and Smoot, 1995; Howard et al., 2002).

Given the increasing prevalence of urea, there is a need to evaluate strategies to minimize N loss when it is used to topdress winter wheat. Some strategies to reduce N loss are now available. Agrotain [N-(n-butyl) thiophosphoric triamide or NBPT] is a urease inhibitor that can be coated on or cogranulated with urea. It slows down the urea hydrolysis process and can be effective in reducing ammonia volatilization (Clay et al., 1990) and increasing yields of corn and wheat (Hendrickson, 1992; Varsa et al., 1993 and 1996; Hughes et al., 1993; Fox and Piekielek, 1993; Murphy and Ferguson, 1997).

Coating of urea granules can be used to slow the rate at which N is released, which can be beneficial for various reasons including reduced loss of N.

Polymer-coated urea has been used for years in the turf and tree nursery markets but its use for row-crops has been restricted by its high cost. A new polymer-coated urea has been developed by Agrium that is expected to be substantially less expensive than previously available products and competitive in the row-crop market. It is sold under the trade name ESN. Results from studies with polymer-coated urea in wheat have not found higher yields than with urea (Schwab et al., 2003; Nelson et al., 2005). Gel-coated urea (Purcell Industries), another slow-release N source, is a relatively new product and research about its performance has not been published yet.

In this research, urease inhibitor and two coated urea products were evaluated for their performance relative to urea in topdressing wheat. Other nitrogen sources were included to provide wheat producers with appropriate comparisons in deciding whether to use the new urea technologies. Our objective was to find a way to improve topdressed urea efficiency on winter wheat that would also be competitive with other N sources.

MATERIALS AND METHODS

Field experiments were conducted during the 2004 and 2005 crop years at the Bradford Research and Extension Center in Columbia Missouri, on a Mexico silt loam soil (fine, smectitic, mesic Aeric Vertic Epiaqualfs). This soil has a high-clay argillic horizon with low saturated hydraulic conductivity and is classified as somewhat poorly drained. The experiments were set up in different areas each year. The previous crop for both years was no-till soybean. In 2003, the experimental area was disked for leveling purposes and the residues were mixed with the soil. Wheat was planted on 9 October. In 2004, the wheat was no-till planted on 17 October.

Experimental areas received as preplant fertilization: 34 Kg ha^{-1}, 0 kg P_2O_5 ha^{-1}, and 0 kg K_2O ha^{-1} for the 2004 experiment, and 34 Kg N ha^{-1}, 101 kg P_2O_5 ha^{-1}, and 112 kg K_2O ha^{-1} for the 2005 experiment. P and K rates were based on results from the University of Missouri soil test laboratory.

Treatments and Experimental Design

The experimental design was a randomized complete block with eight replications. Plots sizes were 2.0 m by 13.7 m with row spacing of 0.2 m. Wheat variety Roane was used in 2004 and the variety MFA 2020 was used in 2005. To avoid border effects, the same wheat varieties were planted in the alleyways and experiment borders.

Nitrogen treatments were broadcast applied at a rate of 80 kg N ha^{-1}.The urease inhibitor Agrotain [N-(n-butyl) thiophosphoric triamide or NBPT] was used in some treatments. Commercially it is sometimes used in combination with the nitrification inhibitor dicyandiamide (DCD). Polymer-coated urea was obtained from Agrium Inc. (Marion, Indiana), and gel-coated urea was obtained from Purcell Industries (Florence, Alabama). The N treatments used were:

1. Urea (46-0-0)
2. Urea + Agrotain (46-0-0) (Agrotain International, St. Louis, MO)
3. Urea + Agrotain + DCD (46-0-0) (Agrotain International, St. Louis, MO)
4. Polymer-coated urea (44-0-0) (Agrium, Inc., Marion, IN)
5. Gel-coated urea (43-0-0) (Purcell Industries, Florence, AL)
6. Urea ammonium nitrate (UAN) solutions (28-0-0)

7. UAN plus Agrotain (28-0-0)
8. UAN + Agrotain + DCD (28-0-0)
9. Ammonium Nitrate (34-0-0)
10. Untreated check

Dry fertilizer treatments were applied using an Orbit-Air spreader (Gandy Company, Owatonna, Minnesota) and liquid fertilizer treatments were sprayed using a portable CO_2-pressurized boom. In 2004, treatments were applied on 2 April except for gel-coated urea, which was applied on 9 April due to a delay in the shipment of the product. Two additional timings for N application were incorporated into the 2005 experiment. Thus, treatments were applied on 14 January, 18 February, and 17 March. Use of the air spreader was not possible in 2005 because frozen soybean stubble punctured the tires for the first treatments and the ground was too wet during later treatments. Therefore, the dry fertilizers were hand spread. All equipment was cleaned and recalibrated between treatments.

For the 2004 experiment, weed infestation was a problem in some of the plots. Visual observations were made, and the plots were rated according to their weed infestation patterns from 0 (no weeds) to a maximum of 10 (high weed pressure).

Reflectance measurements

For both experiments, reflectance measurements were taken using a Cropscan MSR-87 Multispectral Radiometer (Cropscan Inc., Rochester, Minnesota), and the data used to assess treatment effectiveness along with yields. The design of the radiometer allows for near simultaneous inputs of voltages representing incident as well as reflected irradiation, which can be used to calculate reflectance from the crop canopy. The radiometer was held level by a support pole 1.6 m above the crop canopy in the middle of each plot, which provided a 0.8 m-diameter scanned area. A total of 55 measurements were taken at each wavelength in a five s period and averaged by the software for use in statistical analyses. In each year, three sets of readings were taken: on 23 April 2004 (plants at 3 node stage, 0.35 m tall), 4 May 2004 (boot stage, 0.45 m tall), and 20 May 2004 (early anthesis stage, 0.75 cm tall), and on 8 April 2005 (2 node stage, 0.20 m tall), 23 April 2005 (early boot stage, 0.5 m tall), and 3 May 2005 (early anthesis stage, 0.6 m tall).

Harvest

Plots were harvested using a small-plot Wintersteiger combine. Border areas and alleyways were harvested just before the plots. Yields were corrected to a moisture content of 135 g Kg^{-1}. For the 2004 experiment, the middle six rows (1.2 m by 12.5 m) were harvested on 23 June, and on the next day, the grain was taken to the laboratory to be weighed and tested for moisture. For the 2005 experiment, the middle eight rows (1.6 m by 12 m) were harvested on 26 June and the grain was immediately weighed and tested for moisture using a hand-held moisture meter in the field.

Economic analyses

All treatments were submitted to an economic analysis that evaluated the net return to the treatment. The Return to N was calculated for each plot as:

Return to N = [(plot yield – average unfertilized yield) x grain price – treatment cost].

A wheat price of $145 Mg^{-1} was used, which was the average value for wheat no. 1 at Kansas City – Missouri from April 2004 through August 2005 (USDA, 2005) was used. Treatment cost included both material cost and application cost. Nitrogen fertilizer prices were obtained from local fertilizer dealers in mid-Missouri in early December 2005:

1. Ammonium nitrate: $1.06 Kg^{-1} N
2. Polymer-coated urea: $1.10 Kg^{-1} N
3. UAN: $0.90 Kg^{-1} N
4. Urea: $0.88 Kg^{-1} N
5. Urea + Agrotain + DCD: $1.05 Kg^{-1} N

Time-averaged N fertilizer prices were not used because it appears that the lower N prices seen in the early part of the experimental period are not likely to come back. The Agrotain price was $0.14 per Kg of N, obtained from a mid-Missouri fertilizer dealer in December 2005. The costs of fertilizer application were based on the University of Missouri agricultural guide (Plain et al., 2003). Gel-coated urea is an experimental product and is not commercially available, so it was omitted from the economic analyses.

Statistical analyses

Analysis of covariance was used to model treatment effects on yield. The General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, Cory, NC) was used to do the calculation for this analysis. The two sites were analyzed separately. Nearest neighbor estimate of position effect (Scharf and Alley, 1993) was used as a covariate in both years, grass weed rating was used as a covariate in 2004, and time of application was used as a covariate in 2005. Fisher's protected Least Significant Difference with $\alpha = 0.05$ was calculated. When P values are reported, they were calculated in SAS using the pdiff option in the GLM procedure. In addition, linear contrast tests were performed to compare some of the treatments.

Regression was used to relate treatment mean yields to green/near-infrared reflectance ratios. This ratio has been shown to be strongly related to the N status of the crop (Bausch and Duke, 1996; Scharf and Lory, 2002). Regression relating individual plot yields to green/near-infrared reflectance ratios was also performed. Analyses of variance and probability of treatment differences for green/near infrared were calculated using the GLM procedure of SAS. The economic analysis based on return to nitrogen applied was statistically analyzed using analysis of variance in SAS and Fisher's protected Least Significant Difference with $\alpha = 0.05$ was calculated.

RESULTS AND DISCUSSION

2004 Yields

Average yields for the experiment in 2004 were low (2.5 Mg ha $^{-1}$) and the reasons for this are uncertain. The crop was planted in a timely manner, it showed a normal development during the early stages, tillering was normal, and it generally looked good during the month of March. However, later in development the plants were not as vigorous as normal and showed a sparse canopy. Some grass weeds were observed later in the season and influenced yield, but our opinion is that the weeds were more a result of poor wheat growth than the poor wheat growth was a result of the weeds. Diseases or insect injuries were not found, and fertility was normal. Yield was more than doubled by N application since unfertilized plots yielded 1.2 Mg ha^{-1}. Analysis of covariance showed that weed competition decreased yields from zero to 1.5 Mg ha^{-1} (data not shown).

The mean yields for all treatments are presented in Table 1. None of the treatments gave a statistically higher yield (95% confidence) than the broadcast urea treatment. Weather conditions in March and April appeared to be favorable for ammonia volatilization, but low yields masked potential treatment effects. Urea + Agrotain + DCD had the highest yield for the experiment (2.7 Mg ha^{-1}) and was the only treatment that showed some evidence of improving yield compared to urea, even though it was not strong ($p = 0.28$).

Polymer-coated urea had one of the lowest yields in the experiment (2.28 Mg ha^{-1}), lower than urea with 90% confidence. Polymer-coated urea is formulated to release N slowly, and appears to have released N too slowly to effectively supply the needs of the wheat crop.

The UAN treatments, as a group, had the lowest yields in the experiment by linear contrast ($p = 0.04$). Individually, the UAN + Agrotain + DCD treatment produced lower yields than all urea treatments, ammonium nitrate, and gel-coated urea ($p < 0.01$). Previous research (e.g., Tracy and Buchholz, 1989) has generally shown that UAN gives yields as good as other N sources in clean-tilled wheat, which was the system in this experiment. Poor performance of UAN is often reported for no-till wheat (Stecker, 1993, and Stecker and Smoot, 1995), and is attributed to immobilization of broadcast solution N on residue.

2004 Reflectance Measurements: Relationship to Yield

There was a significant correlation between mean yields and the green/near infrared (NIR) reflectance measurements ($p < 0.0001$ for all three dates) (Figure 1). Measurements started 21 days after most treatment applications and 14 days after the gel-coated urea application. The correlation between green/NIR and yield was still highly significant when check plots were not taken into account ($p = 0.0005$, $p = 0.0006$, and $p = 0.001$ for the three dates, respectively).

As the crop developed, urea + Agrotain + DCD showed evidence, based on reflectance measurements, that plants were better supplied with N than plants treated with urea ($p = 0.18$, $p = 0.05$, and $p = 0.03$ for measurements from 23 April, 4 May, and 20 May, respectively). Probably the short period between treatment application and the first reading caused the relatively low significance at that time. In contrast, reflectance from the urea and urea + Agrotain treatments was not statistically different for any of the three readings ($p = 0.59$, $p = 0.35$, and $p = 0.46$, respectively), which reinforces their similar yields ($p = 0.94$). Grant (1998) reported similar results in low-yield wheat experiments where no overall benefit to using Agrotain was observed. However, it is not clear why only Agrotain + DCD, and not Agrotain, seemed to improve urea performance since environmental conditions were not favorable for nitrate loss.

The low yield with polymer-coated urea was also expressed in the reflectance measurements. This treatment showed higher green/NIR ratios than the other treatments, indicating N deficiency. On 23 April, it was more similar to the unfertilized treatment than to any of the other fertilized treatments (Figure 1A). It seems likely that urea diffusion through the coating was too slow to supply the wheat with enough N early in the season. As the season progressed, the reflectance from polymer-coated urea caught up with some other treatments (Figure 1C), indicating N availability increased over time. Nevertheless, reflectance date support the yield data in suggesting poor performance from this treatment. However, previous research with polymer-coated urea in wheat has shown that it has produced the same yields as urea (Schwab et al., 2003; Nelson et al., 2005).

Economic Return to Nitrogen in 2004

The economic return to nitrogen for this experiment was \$ 60 ha^{-1} on average (table 2). The poor yield performance of some treatments led them to a lower return to N.

None of the treatments resulted in significantly higher return to N than broadcast urea. Only urea + Agrotain + DCD gave a numerically higher return, due to higher yield, which was only weakly supported by yield statistics but more strongly supported by reflectance statistics. This treatment was probably associated with a yield increase, but it is uncertain whether it was large enough to pay for the additional cost of the treatments relative to urea.

The broadcast urea treatment had a better return to nitrogen than the UAN + Agrotain, UAN + Agrotain + DCD, and polymer-coated urea treatments ($p = 0.04$, $p > 0.0001$, and $p = 0.01$, respectively) (Table 2). These treatments had lower yields and extra costs compared to urea, which were responsible for their lower return to N.

Overall, none of the treatments tested gave a better return to N than broadcast urea at the 95% level of confidence. The low yields prevented strategies for efficient urea use from being profitable.

2005 Yields

Excellent yields were achieved for the 2005 wheat experiment, in which the mean yield was 5.0 Mg ha^{-1} (Table 3). This is higher than the average yield for the state of Missouri (3.5 Mg ha^{-1}) between 1999 and 2003 (AgEBB, 2005). Weather conditions were favorable for wheat development, and no diseases or pests were detected. These factors facilitated crop yield responses to N, and yields were increased up to 3.0 Mg ha^{-1} after N application.

Based on some evaluations made during crop development in the previous year, a timing effect was added to the experiment in 2005, to avoid unfair trials for slow-release sources, especially polymer-coated urea. A statistical analysis showed that the timing effect was significant ($p < 0.0001$) and resulted in an average increase of 1.4 Mg ha^{-1} in yields when treatments were applied in March instead of in January (Figure 2). This may have been caused by N loss between fertilizer application in January and the main uptake period in April.

In 2005, some treatments produced better yield responses than urea. Low rainfall after all three treatment application timings meant that there was opportunity for volatilization loss from the urea treatment. Averaged over all three application timings, urea + Agrotain ($p = 0.02$), urea + Agrotain + DCD ($p = 0.03$), and ammonium nitrate ($p = 0.01$) all gave higher yields than urea (Table 3). Thus, the addition of Agrotain did improve urea efficiency under conditions when we would expect some nitrogen losses via ammonia volatilization. This has also been observed in numerous earlier studies (Clay et al., 1990; Hendrickson, 1992; Murphy and Ferguson, 1997; Varsa et al., 1993; Varsa et al., 1996). Since there was no difference in yield between urea + Agrotain and urea + Agrotain + DCD, it is assumed that the addition of DCD did not contribute to reducing loss of N. Thus, these two treatments may be considered equivalent in this experiment. A linear contrast of yield with urea versus these two treatments combined strengthens the conclusion ($p = 0.01$) that Agrotain increased yield in this experiment.

The polymer-coated urea treatment behaved differently than the other N sources, in that it did not show sensitivity to timing effects. Of all the treatments applied in January, polymer-coated urea gave the highest average yield, which was significantly ($p = 0.02$) higher than urea. Thus, based on the 2005 results, polymer-coated urea is a good alternative for nitrogen supply early in the season. Over all timings, polymer-coated urea gave the same yield as urea ($p = 0.92$). This is consistent with past research (Schwab et al., 2003; Nelson et al., 2005). As in 2004, applying polymer-coated urea in March gave lower yield than urea. Gel-coated urea gave the same yield as urea ($p = 0.51$). In spite of favorable conditions for treatments to perform better than urea, gel-coated urea failed to do so.

Unlike urea, the addition of Agrotain or Agrotain + DCD to the UAN treatments did not improve wheat yields. As in 2004, the UAN treatments as a group gave lower yields than other N sources ($p < 0.0001$ by linear contrast). Previous research in Missouri has sometimes shown lower no-till wheat yield with broadcast UAN than with urea (Stecker, 1993). In other cases, yields are similar for the two sources (Tracy and Buchholz, 1989; and Stecker and Smoot, 1994 and 1995).

2005 Reflectance Measurements: Relationship to Yield

Because of the incorporation of three different treatment application times into the experiment, the results were more complex to evaluate than in the previous year. The regression analyses confirmed that treatments that yielded better again had lower green/near-infrared reflectance. Treatment mean reflectance was a significant ($p < 0.04$) predictor of treatment mean yield for all application times and measurement dates when the unfertilized treatment was included. However, when check plots were not considered, only the 23 April and 3 May measurements from treatments applied in March were significant predictors of yield ($p = 0.01$ and $p = 0.0003$, respectively). On the other hand, individual plot reflectance was always a significant predictor of yield ($p < 0.0001$ with check plots for all treatment and measurement timings; $p < 0.04$ excluding check plots for all groups).

For the first reflectance measurement on 8 April, treatments applied in February gave the lowest green/NIR (Figure 3A), probably because some N from January treatments had been lost and March treatments had been applied too recently to be fully expressed. By 23 April, March treatments were about equal with February treatments (Figure 3B), and by 3 May they had lower green/NIR than the corresponding February treatments (Figure 3C), reflecting better N availability and eventual higher yields.

Urea + Agrotain, urea + Agrotain + DCD, and ammonium nitrate resulted in better yields than urea ($p < 0.03$), but only urea + Agrotain + DCD had lower reflectance than urea in the first two readings ($p = 0.06$ and $p = 0.08$, respectively) and this effect was not significant at the third reading ($p = 0.7$) (analysis pooled across application timings). This suggested that urea + Agrotain + DCD was more efficient in delivering N to the crop than ammonium nitrate and urea + Agrotain. As observed in 2004, there was weak evidence that urea + Agrotain + DCD performed better than urea + Agrotain but the reasons are not clear.

Polymer-coated urea resulted in higher green/NIR values than urea or gel-coated urea even though all three treatments gave the same yields. This was especially true for the first measurements, reinforcing the idea that polymer-coated urea releases N too slowly for winter wheat. Polymer-coated urea showed the same pattern as observed in 2004, giving the highest reflectance among all N treatments for the first two readings, and showing a slight improvement in delivering N late in the season, which was evidenced in the 3 May reading (Figure 3C). However, polymer-coated urea applied in March still had a high green/NIR reflectance suggesting that N release and availability were not completed when the 3 May reading was taken.

As observed in 2004, all UAN treatments gave lower yield responses and based on reflectance measurements produced the most nitrogen deficient plants. Green/NIR for UAN treatments was higher than for other N treatments ($p < 0.0001$ by linear contrast) for all three measurement times. These results reinforce the conclusion that N immobilization occurred with UAN treatments in 2005.

Economic Return to Nitrogen in 2005

Due to lower yields when treatments were applied in January or February, the return to N was also low for those treatments. In this analysis, we will consider only the return to N for treatments applied in March, since that was the best application timing and since all UAN treatments were applied only at that time. The return to nitrogen for March-applied treatments was on average \$ 209 ha^{-1} (Table 4).

The addition of Agrotain to urea increased the return to N by \$ 31 ha^{-1} ($p = 0.08$) (Table 4). The increase in yields provided by its addition to urea ($p = 0.02$) was enough to offset its costs and be profitable. A linear contrast of return to N for urea versus both urea treatments containing Agrotain reinforces the conclusion that Agrotain use was profitable in this experiment (average \$23 ha^{-1}benefit, $p = 0.15$)

Polymer-coated urea had lower return to N when compared with broadcast urea ($p < 0.0001$) (Table 4). Higher yields were necessary for the polymer-coated urea to compensate for its high costs, but instead yields were lower for the March application timing.

Urea resulted in better return to N when compared with all three UAN treatments ($p < 0.0001$) because of the lower yields and higher application costs associated with all UAN treatments. The evidence from this experiment suggests that UAN is not a viable alternative to urea for topdressing winter wheat. Return to UAN was not improved by addition of Agrotain or Agrotain + DCD.

CONCLUSIONS

The objective of this project was to evaluate different management alternatives designed to reduce the risk of ammonia volatilization loss for urea topdressed on wheat.

Both treatments combining urea with Agrotain out-yielded urea alone in 2005, when yields were excellent. There was good evidence that use of Agrotain was profitable in 2005. In 2004, when yields were low, there was weak evidence that the urea + Agrotain + DCD treatment increased yield and N availability relative to urea.

After two years of experimentation, polymer- and gel-coated urea only produced the same average yield as urea. However, the polymer-coated urea improved yields relative to urea when applied in January with the introduction of a timing effect on 2005 experiment. For producers who want to topdress early, polymer-coated urea may be a useful product.

The effect of N application timing in 2005 was striking. March application produced better yields than February application, which produced better yields than January application.

UAN treatments gave lower yield than other N treatments in both years of the study. Immobilization of N due to high crop residue could explain this observation in 2005, but in 2004 the experimental area had been clean-tilled and there was no residue to immobilize the UAN. The reason for low yields with UAN in 2004 is unknown.

Over the two years of the study, only the addition of Agrotain and Agrotain + DCD to urea produced evidence that they are more profitable than broadcast urea for topdressing wheat.

LITERATURE CITED

Bandel, V. A., S. Dzienia., and G. Stanford. 1980. Comparison of N fertilizers for no-till corn. Agron. J. 72:337-341.

Barreto, H. J., and R. L. Westerman. 1989. Soil urease activity in winter wheat residue management systems. Soil Sci. Soc. Am. J. 53:1455-1548.

Bausch, W. C., and H. R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Trans. ASAE. 39:1869-1875.

Beyrouty, C. A., Sommers L. E., and Nelson D. W. 1988. Ammonia volatilization from surface-applied urea as affected by several phosphoroamide compounds. Soil Sci. Soc. Am. J. 52:1173-1178.

Blaylock, A. D., J. Kaufmann, and R. D. Dowbenko. 2005. Nitrogen fertilizer technologies. http://isnap.oregonstate.edu/WCC103/2005_Proccedings/Blaylock%20Nitrogen%20Fertilizer%20pg8.pdf (28 February 2006).

Buchholz, D. D., P. W. Tracy, K. A. McVay, S. R. Madely, R. L. Smoot, and C. L. Hoenshell. 1989. Nitrogen rates and timing for winter wheat in Missouri 1989. Missouri Fertility and Fertilizers Research Update 1989. Agronomy Miscellaneous Publ. # 90-01. p.128-149. Univ. of Missouri, Columbia, MO.

Bundy, L. G., and S. L. Oberle. 1988. Evaluation of methods for control of ammonia volatilization from surface-applied urea-containing fertilizers. J. Fert. Issues 5:24-30.

Clay, D. E., G. L. Malzer, and J. L. Anderson. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. Soil Sci. Soc. Am. J. 54:263-266.

Conley, S., W. Bailey, W. Casady, F. Fishel, B. Johnson, R. Massey, P. Scharf, R. Smeda, L. Sweets, and A. Wrather. 2003. Management of soft red winter wheat. MU Extension, Integrated pest management series. University of Missouri, Columbia, Missouri.

Fox, R. H., and W. P. Piekielek. 1993. Management and urease inhibitor effects on nitrogen use efficiency in no-till corn. J. Prod. Agric. 6:195-200.

Franzluebbers, A. J., F. M. Hons, and D. A. Zuberer. 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59:1618-1624.

Grant, C. A. 1998. Using NBPT to increase efficiency and safety of urea fertilizer. (11 January 2005).
http://ssca.usask.ca/98-Proceed/GRANT.html

Hendrickson, L. L. 1992. Corn yield response to the urease inhibitor NBPT: five-year summary. J. Prod. Agric. 5:131-137.

Howard, D. D., M. A. Newman, M. E. Essington, and W. M. Percell. 2002. Nitrogen fertilization of conservation-tilled wheat. I. Sources and application rates. J. Plant Nutrition 25:1315-1328.

Hughes, D. F., N. R. Kitchen, and L. Mueller. 1993. Slow release nitrogen fertilizers in winter wheat. Missouri Fertility and Fertilizers Research Update 1993. Agronomy Miscellaneous Publ. #94-03. p.42-45. Univ. of Missouri, Columbia, MO.

Keller, D. G., and D. B. Mengel 1986. Ammonia volatilization from nitrogen fertilizers surface applied to no-till corn. Soil Sci. Soc. Am. J. 50:1060-1063.

Knowles, T. C., B. W. Hipp, P. S. Graff, and D. S. Marshall. 1993. Nitrogen nutrition of rainfed winter wheat in tilled and no-till sorghum and wheat residues. Agron. J. 85: 886-893.

McInnes, K. J., R. B. Ferguson, D. E. Kissel, and E. T. Kanemasu. 1986. Ammonia loss from applications of urea-ammonium nitrate solution to straw residue. Soil Sci. Soc. Am. J. 50:969-974.

Murphy T. L., and R. B. Ferguson. 1997. Ridge-till corn and urea hydrolysis response to NBPT. J. Prod. Agric. 10:271-282.

Nelson, K., M. Jones, P. Motavalli, and R. Smoot. 2005. The effects of slow-release N fertilizer rate and timing on wheat grain yield compared to other N sources. (26 January 2006).
http://aes.missouri.edu/greenley/fieldday/2005/page58.stm

Plain, R., J. White, and J. Travlos. 2003. 2003 custom rates for farm services in Missouri. Agricultural MU guide G302, Columbia, Missouri.

Rao, S. C., and T. W. Popham. 1999. Urea placement and nitrification inhibitor effects on growth and nitrogen accumulation by no-till winter wheat. Crop Sci. 39:1115-1119.

Sander, D. N. 1988. How to apply fertilizer to wheat.
http://ianrpubs.unl.edu/fieldcrops/g889.htm (20 may 2005).

Scharf, P. C., and J. A. Lory. 2000. Calibration of remotely-sensed corn color to predict nitrogen need. Proceedings of the Fifth International Conference on Precision Agriculture. ASA-CSSA-SSSA, Madison, WI.

Scharf, P. C., and M. M. Alley. 1993. Accounting for spatial variability in field experiments increases statistical power. Agron. J. 85:1254-1256.

Schomberg, H. H., J. L. Steiner, and P. W. Unger. 1994. Decomposition and nitrogen dynamics of crop residues: residue quality and water effects. Soil Sci. Soc. Am. J. 58:372-381.

Schwab, G. J., L. W. Murdock, J. Dolarhide, J. James, and D. Call. 2003. Polymer coated urea affects on wheat yield. http://www.ca.uky.edu/ukrec/RR%202002-03/02-03pg33.pdf (26 January 2006).

Stecker, J. A. 1993. Fertilizer nitrogen sources for no-till wheat. Missouri Soil Fertility and Fertilizers Research Update 1993. Agronomy Miscellaneous Publ. #94-03. p.74-81. Univ. of Missouri, Columbia, MO.

Stecker, J., and R. Smoot. 1994. Fertilizer nitrogen sources for no-till wheat. Missouri Fertility and Fertilizers Research Update 1994. Agronomy Miscellaneous Publ. #95-02. p. 8-15.

Stecker, J., and R. Smoot. 1995. Fertilizer nitrogen sources for no-till wheat. Missouri Fertility and Fertilizers Research Update 1995. Agronomy Miscellaneous Publ. #96-03. p. 30-35. Univ. of Missouri, Columbia, MO.

Stewart, M., R. Mikkelsen, K. Dhuyvetter, and A. Schlegel. 2005. Nitrogen price and fertilization decisions: examples from central great plains. http://www.ppi-ppic.org/ppiweb/ppibase.nsf/$webindex/article=32c4656785256ce10072c7869daaa864 (20 May 2005).

Tracy, P. W., and D. D. Buchholz. 1988. Evaluation of nitrogen sources and rates of spring topdress application on winter wheat (1987-88). Missouri Fertility and Fertilizers Research Update 1988. Agronomy Miscellaneous Publ. #89-01. p.79-80. Univ. of Missouri, Columbia, MO.

Tracy, P. W., and D. D. Buchholz. 1989. Evaluation of nitrogen sources and rates of spring topdress application on winter wheat. Missouri Fertility and Fertilizers Research Update 1989. Agronomy Miscellaneous Publ.#90-01. p.160-165. Univ. of Missouri, Columbia, MO.

USDA. 2005. Cash prices, selected U.S. commodities. http://www.ers.usda.gov/publications/agoutlook/aotables/2005/11nov/aotab18.xls (5 December 2005).

Varsa, E. C., S. A. Ebelhar, P. R. Eberle, E. Gerhard, and T. Wyciskalla. 1993. Evaluation of nitrogen management practices in no-till corn production. http://cropsci.uiuc.edu/research/rdc/dixonsprings/proj_reports/eval_nitro_practices.cfm (10 December 2005).

Varsa, E. C., S. A. Ebelhar, P. R. Eberle, D. Klockenga, and A. Mann. 1996. An evaluation of urease inhibitor technology as a nitrogen management tool in no-till corn and wheat production. http://frec.cropsci.uiuc.edu/1997/report10/ (11 January 2005).

Vaughan, B., D. G. Westfall, and K. A. Barbarick. 1990. Nitrogen rate and timing effects on winter wheat grain yield, grain protein, and economics. J. Prod. Agric. 3:324-328.

Table 1. Least squares mean yields for the 2004 wheat experiment.

Treatment	YIELD LSMean
	Mg ha^{-1}
Urea+Agrotain+DCD*	2.74
Ammonium Nitrate	2.58
Urea+Agrotain	2.58
Urea	2.56
Gel-coated urea	2.55
UAN+Agrotain	2.37
UAN	2.34
Polymer-coated urea	2.28
UAN+Agrotain+DCD	2.13
check	1.41
$LSD_{(0.05)}$	0.30

* DCD = dicyandiamide

Table 2. Return to nitrogen applied in the 2004 wheat experiment.

Treatment	Return to N $ ha^{-1}
Urea+Agrotain+DCD	101
Urea	89
Urea+Agrotain	79
Ammonium nitrate	77
UAN	53
UAN+Agrotain	44
Polymer-coated urea	30
UAN+Agrotain+DCD	10
$LSD_{(0.05)}$	42

Table 3. Least squares mean yields for the 2005 wheat experiments.

Treatment	LSMean yields for average treatment timing Mg ha^{-1}	LSMean yields for treatments applied in March Mg ha^{-1}
Ammonium Nitrate	5.47	6.12
Urea+Agrotain	5.41	6.17
Urea+Agrotain+DCD*	5.38	6.07
Polymer-coated urea	5.15	5.25
Urea	5.14	5.87
Gel-coated urea	5.06	5.91
UAN+Agrotain	3.97	4.58
UAN	3.89	4.49
UAN+Agrotain+DCD	3.83	4.42
Check	3.30	3.30
$LSD_{(0.05)}$	0.22	0.26

* DCD = dicyandiamide

Table 4. Return to nitrogen applied in March in the 2005 wheat experiment.

Treatment	Return to N $ ha^{-1}
Urea+Agrotain	325
Ammonium nitrate	316
Urea+Agrotain+DCD	308
Urea	294
Polymer-coated urea	187
UAN	88
UAN+Agrotain	88
UAN+Agrotain+DCD	67
$LSD_{(0.05)}$	30

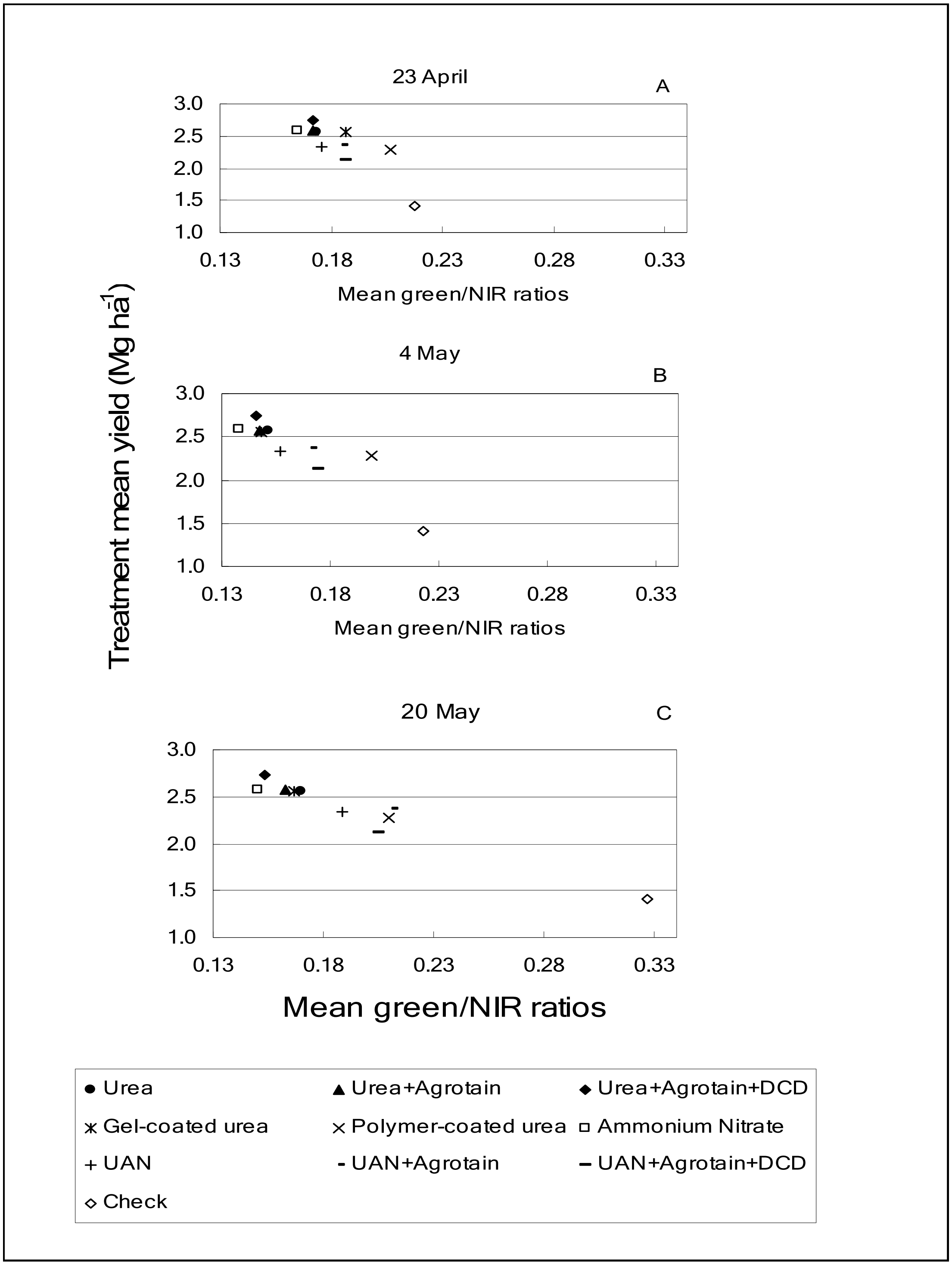
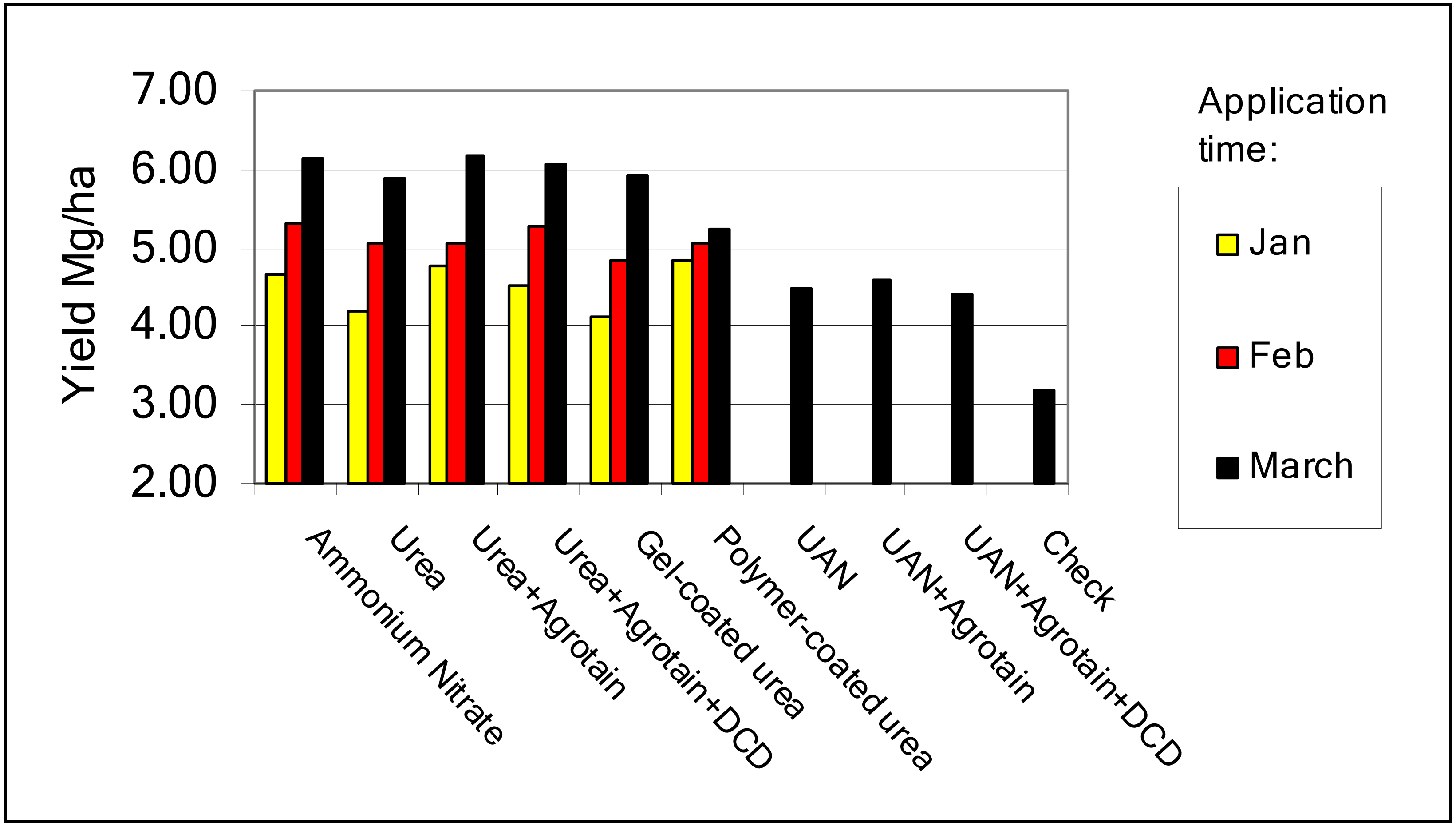


Figure 1. Interaction between Green and Near-Infrared (NIR) ratios and mean yields for the three different reflectance measurements taken during the 2004 wheat experiment.

Figure 2. Mean yields for the 2005 wheat experiment with three different application times for some treatments.



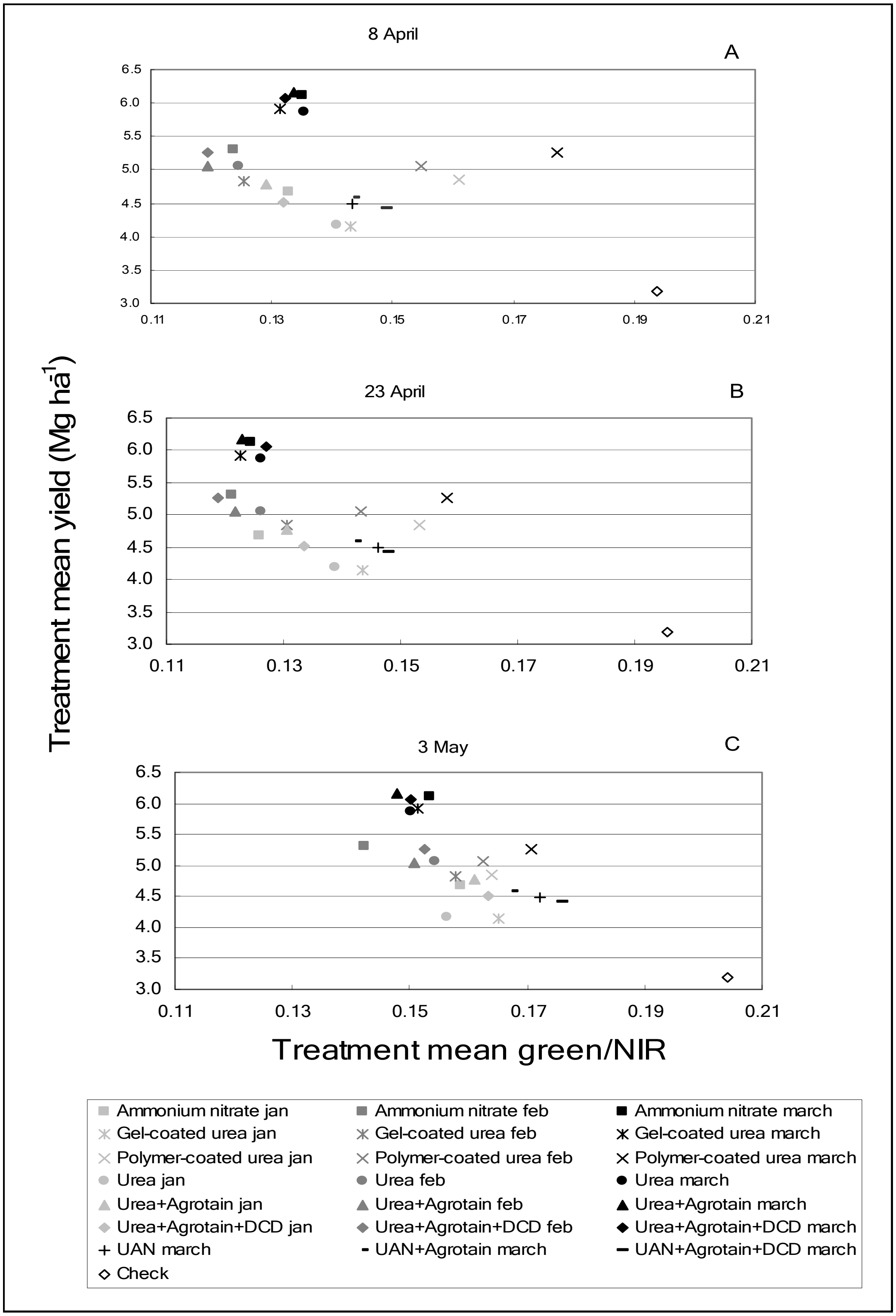
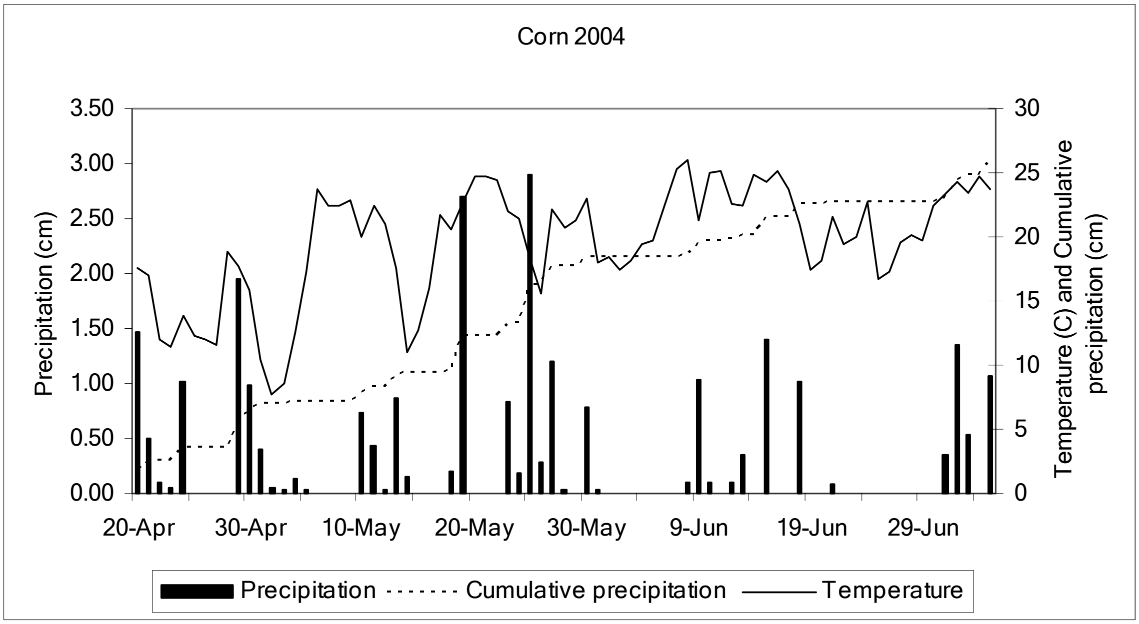
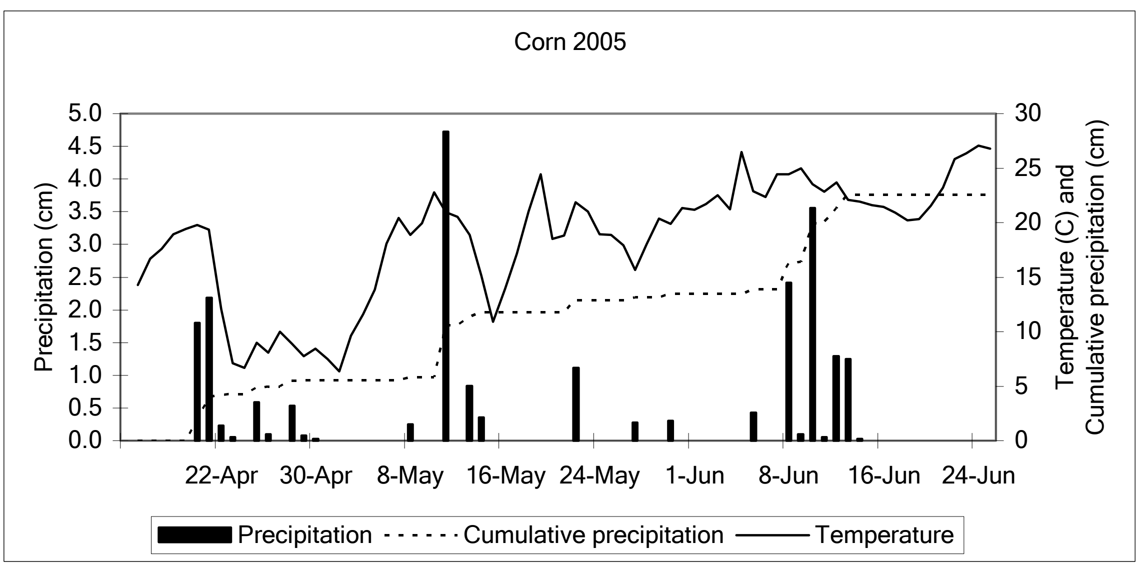


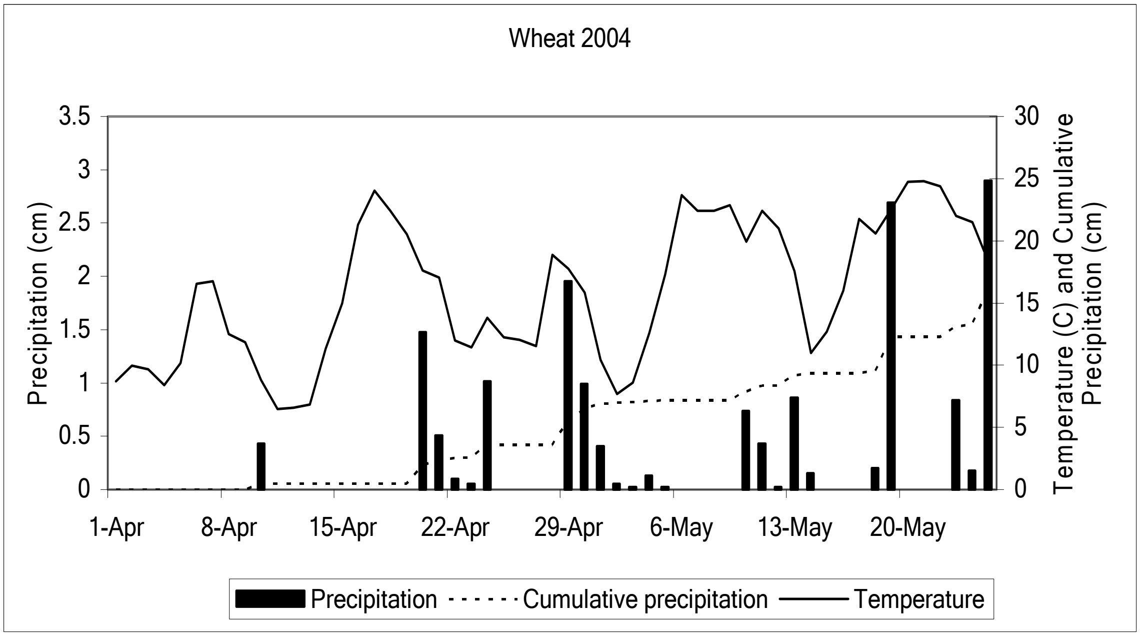
Figure 3. Interaction between Green and Near-Infrared (NIR) ratios and mean yields for the three different reflectance measurements taken during the 2005 wheat experiment.

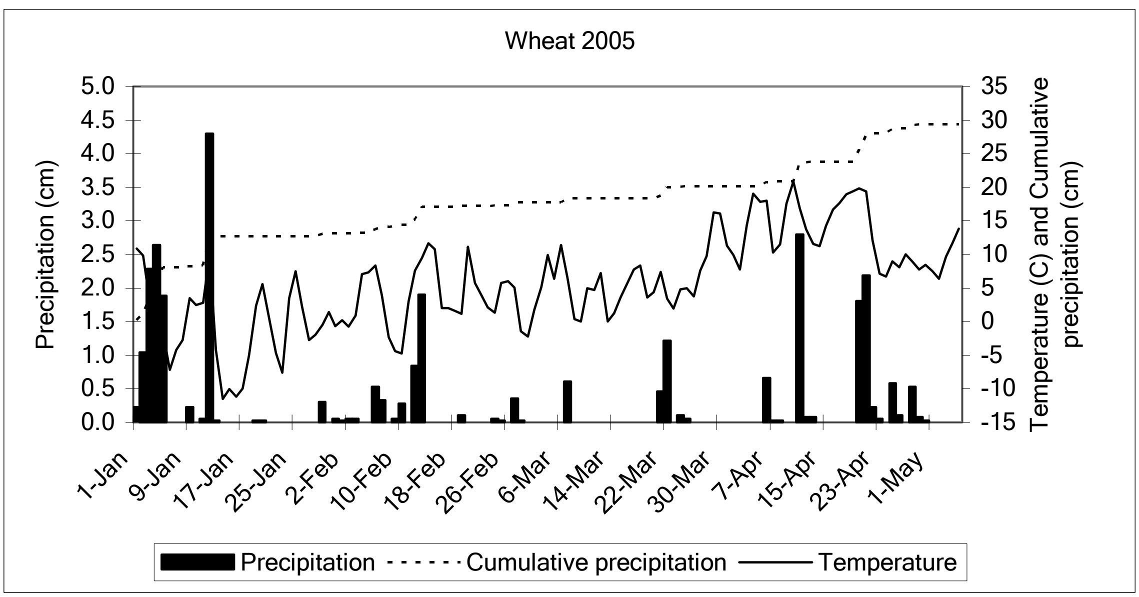
APPENDIX





1. Precipitation (cm), cumulative precipitation (cm), and temperature (C) during the time of development of the 2004 and 2005 corn experiments.





2. Precipitation (cm), cumulative precipitation (cm), and temperature (C) during the time of development of the 2004 and 2005 wheat experiments.