OPTIMIZING CROP N USE EFFICIENCY USING POLYMER-COATED UREA AND OTHER N FERTILIZER SOURCES ACROSS LANDSCAPES WITH CLAYPAN SOILS

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled:

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a candidate for the degree of Master of Science in Soil, Environmental and Atmospheric Sciences

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TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

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ABSTRACT

Development of improved management practices to increase nitrogen use efficiency (NUE) within agricultural fields is needed to improve crop production and reduce nitrogen (N) loss. Field studies planted to corn were conducted in 2005 and 2006 in the claypan region of north central and northeast Missouri to determine the effects of landscape position and soil depth to the claypan on crop growth and N uptake, and to examine the use of a variable-source N fertilizer application strategy to optimize crop N fertilizer use. Treatments at the northeast Missouri site consisted of a control and 168 kg N ha^{-1} of urea, polymer-coated urea (PCU), a 50% urea/50% PCU mixture, or anhydrous ammonia applied in 457 m long strips that included variation in elevation and claypan depth. At the north central Missouri site, N fertilizer treatments of 168 kg N ha^{-1} of urea or PCU were broadcast surface-applied within three different cropping/tillage systems and at different landscape positions representing the summit, sideslope and footslope positions in the field. PCU treatments showed a consistent 1505 to 1818 kg ha^{-1} increase in corn grain yields in 2005 and 2006, respectively, in the low lying area, possibly due to the wetter conditions in the low-lying area affecting the fate of the applied N. Similarly, anhydrous ammonia application resulted in a 1505 and 1630 kg ha^{-1} yield increase in 2005 and 2006, respectively, in the low-lying area. At the north central Missouri site in

2006, the corn grain yield of the PCU-treated area was 1191 kg ha^{-1} higher than that of the urea-treated area only at the footslope landscape position in the no-till cropping system. These results suggest that a variable source N fertilizer application approach based on identifying areas in a field which are periodically wet due to their lower elevation, may improve NUE.

CHAPTER I

LITERATURE REVIEW

Problems associated with excessive reactive N in the environment

Excessive reactive nitrogen (N) in the environment has had major negative effects on both air and water quality in the United States and around the world (Crutzen, 1981; Bouwmann, 1990; Vitousek et al., 1997; Malakoff, 1998; Smith et al., 1999). For example, a considerable amount of N leaches through the soil or runs off into streams and rivers, and eventually can make its way to the Gulf of Mexico contributing to the western hemisphere's largest hypoxic zone (Malakoff, 1998). It has been reported that about 1.82 million metric tons of N enters the Gulf hypoxic zone annually (Malakoff, 1998). The size fluctuates, but has reached up to 20,000 km^2, which is second only to the hypoxic zone of the Baltic Basins (about 70,000 km^2) (Rabalais et al., 2002). A major source of N entering into the Gulf of Mexico has been attributed to agricultural activities occurring in the watershed of the Mississippi River (Goolsby et al., 1999). The negative environmental consequences of this hypoxic zone include a reduction in fish growth rates, increased fish mortality, and altered flow of carbon within the food web (Breitburg, 2002), which causes decreased aquatic biodiversity (Galloway and Cowling, 2002).

The input rate of N into the terrestrial N cycle has been doubled by humans and this rate is still increasing (Vitousek et al., 1997). Nitrate (NO_3^-) leaching in northern Missouri has caused 20 to 25% of the drinking water wells in this region to have concentrations of NO_3^- (Wilkinson and Maley, 1996) greater than 10 mg L^{-1} (USEPA, 1992). Past research (Spalding and Exner, 1993) has suggested a linkage between NO_3^-

found in drinking water and health risks. Among the diseases potentially associated with NO_3^- in drinking water are hypertension, non-Hodgkin's lymphoma, central nervous system birth defects, and some cancers (Spalding and Exner, 1993).

Harmful effects of increased N in the environment include acidification of soil and groundwater resources, eutrophication, invasion of weeds, loss of biodiversity, depletion of ozone, increased ozone-induced injury to crop, forest and other ecosystems, and increased stratospheric haze and production of airborne particulate matter (Galloway and Cowling, 2002). Solving these problems of low use efficiencies and excesses of N in the environment is complex and will require multidisciplinary contributions from soil science, agronomy, atmospheric science, ecology, and hydrology (Mitsch et al., 2001).

Low nitrogen use efficiency

The application of N fertilizer for agronomic crop production generally results in the loss of some N into the environment and inefficiency in the use of the added N. Nitrogen recovery efficiency (NRE) is the proportion of applied fertilizer N that is contained in above ground plant biomass at the end of the growing season (Cassman et al., 2002). Average maize (*Zea mays* L.) NRE in the United States and around the world is approximately 37%, indicating that a significant amount of applied N fertilizer is lost or immobilized in the environment with current management practices (Cassman et al., 2002; Raun et al., 2002).

Another method of calculating nitrogen use efficiency (NUE) is to determine the grain yield per unit N applied to the soil (Moll et al., 1987). Some improvement in N yield efficiency in maize systems has been observed over the last 25 years as evidenced by a 51% increase in the ratio of maize grain yield per unit of applied N fertilizer from

42.6 kg grain kg^{-1} N in 1980 to 64.4 kg grain kg^{-1} N in 2005 (Fixen and West, 2002; Fixen, 2006). This increased N yield efficiency may be due to several factors, including improvements in plant genetics, tillage methods, and water nutrient management practices (Stewart et al., 2005). The low NUE in current crop production systems may need to be increased through research in order to improve economic returns from crop production and reduce the potential negative impacts of excess N.

Factors affecting N uptake in a claypan soil

Claypan soils are characterized by a subsoil layer which has an abrupt increase in clay content of at least 100% compared to the horizon above it and very slow permeability (Myers et al., 2007). The depth to claypan layer can vary across landscapes from 10 cm at the backslope position to as deep as 40 cm at footslope positions (Jiang et al., 2007).

The Central Claypan Region of the Midwest is an area of approximately 4 million hectares and includes the states of Missouri, Illinois, and Kansas (Anderson et al. 1990). Large portions of this claypan soil region are used to produce maize annually. Consequently, the soils in this area receive high inputs of N fertilizer.

Leaching of N through a claypan soil is typically reduced due to restricted water movement through the soil matrix of the clay layer (Jung et al., 2006). In claypan soils an argillic horizon (130-460 mm deep) exists that can have clay content greater than 460 g kg^{-1}, reducing the permeability of the soil (Jamison and Peters, 1967). Blevins et al. (1996) found that 30% of N fertilizer remained in the saturated zone and 5% remained in the unsaturated zone after 16 months (2 growing seasons). Less than 2% of the applied N was lost to runoff, and 27.3% was removed with the grain. The remaining N must have leached or was lost to the atmosphere. Blevins et al. (1996) also found the concentration of NO_3^- to be increasing in groundwater after two growing seasons indicating the lasting presence of unused N in the soil.

Approximately 20-30% of N_2O emitted from the earth's surface annually comes from agricultural soils and about 70% of anthropogenic N_2O emissions are the result of agricultural activities (Mosier 1994; Delgado and Mosier, 1996). The rate and total amount of N_2O emissions from soils depends upon several factors, including temperature, pH, irrigation amounts and timing, water holding capacity of the soil, N fertilizer rate and application method, tillage practices, soil total organic C concentrations, soil type, oxygen concentration, and chemical use (Freney, 1997). Bailey, et al. (2005) found in a claypan soil cropped to maize that as high as 10% of applied fertilizer N was lost to the atmosphere as N_2O. This amount of cumulative soil N_2O loss is relatively high compared to what has been found in other well-drained environments (Pathak, 1999), possibly due to the very slow permeability of the claypan soil increasing the amount of time the surface soil is saturated.

Denitrification occurs primarily in soils with high water contents. Restrictive claypan soils may lead to increased denitrification by limiting drainage, thus decreasing the amount of oxygen in the soil. With less oxygen in the soil, microorganisms obtain the oxygen they need from NO_2^- and NO_3^-, resulting in the formation of N_2O and N_2, which enter the atmosphere (Killpack et al., 1993). However, Pomes et al., (1988) observed that denitrification in claypan soils was usually low.

Other processes which may contribute to N losses in agricultural fields with claypan soil are runoff and leaching. The claypan argillic horizon may cause a perched water table and induce lateral flow of water (Blanco-Canqui et al., 2002). During the spring when rainfall is typically high in Missouri, lateral flow may be a significant cause of runoff (Minshall and Jamison, 1965; Wallach and Zaslavsky, 1991). Clays in the Central Claypan Region commonly exceed 50% smectites (Alberts et al., 1996) resulting in diminished infiltration capacity and therefore surface ponding and runoff. Preferential flow paths developed from biological (e.g., worm burrowing or root growth) or physical processes (e.g., desiccation) can function as channels for flow from surface to ground water (Puckett, 1995). Wilkinson et al. (1999) found that drainage through flow paths to the underlying till reduce vertical transport and horizontal movement of N allowing some of the N quick access to shallow ground water. Pomes et al. (1998) stated that because denitrification in claypan soils is typically low, excess N remaining in the cropped soil that is not utilized by later crops can leach from the soil for months or years.

The topsoil depth to the claypan layer is influenced by factors, such as slope and soil management practices. For example, agricultural tillage practices can affect topsoil erosion, thus changing the topsoil depth to the claypan. Soil hydraulic properties, including hydraulic conductivity (K_{sat}), soil water retention, soil bulk density, and pore size distributions, are influenced by slope positions and management practices (Jiang et al., 2007). No-till management generally results in higher K_{sat}, as shown in a clay loam (Gantzer and Blake, 1978) and in a silt loam and a sandy loam (Azooz et al., 1996). This effect is due to improved structure formation and pore networks, resulting in greater macropore flow (Jiang et al., 2007). Furthermore, studies have shown that water retention is also higher for conservation tillage than for tilled soils due to better soil structure and pore arrangements (Blevins et al., 1971; Gantzer and Blake, 1978;

Lindstrom et al., 1984; Hill et al; 1985). Jiang et al. (2007) found that conservation tillage at the backslope landscape position, where topsoil depth was the shallowest, may result in degradation of soil physical properties as much as a system under conventional tillage. Additionally the backslope (shallower) position was more affected by claypan-controlled hydraulic properties than the summit or footslope landscape positions (Jiang et al., 2007). Because N is a mobile nutrient, these soil hydraulic properties can greatly affect the fate of applied N fertilizer. Soil management and slope position are important factors in claypan soils with cropping systems where N fertilizer is applied.

Land topography variability

Various land formations exist across cropped landscapes. Terrain characteristics are strongly related to the soil and crop yields (Kaspar et al., 2003). Several studies focus on the importance of understanding landscape terrain and its relationship with soil moisture variability (Famiglietti et al., 1998; Mohanty et al., 2000; Qiu et al., 2001). Because N is a mobile nutrient, soil water variability directly affects N cycling in the soil. Landscape characteristics, such as curvature, slope, and landscape position, can impact soil water and thus soil N status. Soil properties such as clay content, pH, and sand content have been shown to correlate with landscape position (Ovalles and Collins, 1986). Timlin et al. (1998) observed correlations between magnitude in curvature and maize grain yields, as well as grain yield correlation with depth to fragipan in drier than normal years. A soybean [*Glycine max (L.) Merr*.] and maize study by Kravchenko and Bullock (2000) showed that various soil properties were responsible for 30% of yield variability, and elevation had the most influence on grain yield out of curvature, slope, and flow accumulation. Furthermore, lower elevations within the field had the highest yields. Understanding how land topography affects soil properties and fertilizers may be an integral part of increasing NUE.

Current and future work to reduce N loss

Over the past 50 years, extensive research was conducted to increase NUE and reduce loss of N into the environment. A review by Dinnes et al. (2002) focused on several management strategies to reduce N loss including better N application timing, improved interpretation of soil and plant tests to enhance nutrient recommendations, proper calibration of application equipment to ensure the desired fertilizer rates are applied, nitrification inhibitors, tillage impacts on N, use of cover crops and diversified crop rotations, and plant residue management.

Fertilizer application timing

Randall et al. (1997) stated that N fertilizer application timing and rate are the primary factors which determine loss of nitrate into surface waters. The risk for N losses to leaching, denitrification, volatilization, and immobilization increases with time between application and plant uptake (Dinnes et al., 2002). However, the most important factor to reduce N loss is application of the proper N rate (Power and Scheppers, 1989). Fall application of fertilizer was intended to reduce soil compaction (Dinnes et al., 2002); however, Sanchez and Blackmer (1988) reported 49 to 64% of fall applied N was not subject to plant uptake, but was lost through other pathways. Spring application of N was shown to increase NUE by 20% (Randall et al., 1992; Randall, 1997). It is generally agreed upon that application according to crop need is the best method (Aldrich 1984; Fox et al., 1986; Olsen and Kurtz, 1982; Randall et al., 2003). According to Roberts et al. (2006) the time of greatest N requirement for maize was 6 to 8 weeks after planting and through the end of vegetative growth. Development of a way to supply N fertilizer at the time of planting, as well as later in the growing season for vegetative growth is an important goal for increasing grain yield and NUE.

Various versions of the presidedress soil nitrate tests (Magdoff et al., 1984; Fox et al., 1989; Magdoff et al., 1990) and late-spring nitrate tests (Blackmer et al., 1997) have been developed to test effects of mineralization, leaching, or other N losses since N from the previous crop can be determined (Dinnes et al., 2002). Other methods of determining plant available N include the stalk-nitrate test (Varvel et al., 1995) and pre-plant N test (Fuglie and Bosch, 1995). Additionally, use of chlorophyll meters or radiometers, which measure plant greenness and biomass are being tested to evaluate plant N status (Ma et al., 1996). Several studies have shown that these tests have potential to successfully avoid excessive N application more effectively than N applications based on yield-goal (Magdoff, 1991; Durieux et al., 1995; Kanwar et al., 1996; Randall, 1997; Karlen et al, 1998). Moreover, these tests may be useful for evaluating the effectiveness of strategies for improved N management in corn (Magdoff, 1991; Blackmer and Mallarino, 1997).

Effects of cropping systems

Maize is commonly rotated with a legume the following growing season to obtain yield increases that commonly occur due to several benefits of rotation including decreased weed, pest and disease incidence and nutrient carry over from the previous crop. Bacteria that reside in the nodules of legumes have the ability to fix atmospheric N_2 to NH_3 that can be used by the plant. In Missouri and other parts of the North Central Region, the legume in the rotation is often soybean (*Glycine max*) because of its relatively high economic returns. Few studies have examined the extent to which different cropping systems affect nitrate leaching (Zhu and Fox, 2003), but cropping systems may have a large impact on nitrate leaching in non-irrigated fields due to crop differences in rooting depth, root densities, N needs, and uptake efficiencies (Juergens-Gschwind, 1989; Peterson and Power, 1991). Using a legume, such as alfalfa, which has deep roots that quickly decompose after the growing season, may create preferential flow paths in the soil that may increase nitrate leaching (Robbins and Carter, 1980; Carter et al., 1995).

Use of cover crops in the cropping system is another way to utilize unused N from the previous growing season. The amount and rate of nitrate leaching from a soil system is dependent upon several factors, including water percolation in the system. By planting winter cover crops, some of the water that would have moved out of the system will be taken up by these cover crops, thereby reducing nitrate leaching (Meisinger et al., 1990; Dabney et al., 2001). Legume cover crops usually reduce the required amount of N for the next non-legume crop. However, they can sometimes increase yield potential without reducing the economically optimal N fertilizer rate (Dabney et al., 2001). Non-legume cover crops typically have more biomass than legume cover crops, which usually have higher N concentrations. However, observations by Sainju et al. (2002) showed that a non-legume, such as *Lolium pratense* held higher carbon (C) and N than *Vicia villosa* and *Trifolium incarnatum* during a study conducted from 1994-2001. This was probably due to the greater amount of biomass produced by the rye as well as variations in climate (Sainju et al., 2003).

Impact of tillage

Conventional tillage or moldboard plowing is known to aerate the rooting zone in the soil (Dinnes et al., 2002) and increase the population of aerobic bacteria leading to increased oxidation of soil organic matter and N mineralization (Randall et al., 1997). However, conventional tillage practices are rarely used in Missouri due to their negative effects on the soil, which may include soil erosion, decreases in CEC, changes in soil structure, and potential reduction of plant available water (Dinnes et al., 2002). Due to these possible problems with conventional tillage, conservation tillage practices (e.g., no-till) have been widely adopted. Studies have shown soil NO_3^- losses may not differ significantly between no-till and other tillage practices (Randall and Mulla, 2001). However, Rice and Smith (1982) observed that the higher soil water contents in no-tillage soils may cause greater denitrification thereby lowering NO_3^- concentrations, and cause the need for excess N fertilizer application.

Use of site-specific management to improve NUE

Although field soils commonly receive a uniform application of N fertilizer, they rarely result in uniform nitrate concentrations; therefore, less productive areas may be over-fertilized (Power et al. 2000). Less than 30% of a given field's area can be responsible for over 70% of the total field production (Kranz and Kanwar 1995). Site-specific crop management (also called precision agriculture) principles could be used to develop N fertilizer application recommendations based on within-field spatial variability of factors affecting crop N response and environmental N loss.

Extensive research in precision agriculture has been conducted with the object of improving NUE in agronomic systems through site specific N management (SSNM).

Within field variation in soil characteristics decreases NUE when uniform applications of N are applied. Variable rates of N may improve NUE by applying rates based upon spatially variable field characteristics. Carr et al. (1991) had varying results when attempting to use soil surveys to adjust N fertilization rates. Little economic impact was found by Kitchen et al. (1995) when using 1 or 2 years of grain yield data to determine future optimal N rates. A lack of temporal constancy was shown when Lamb et al. (1996), and Jaynes and Colvin (1997) used crop yield data from six years for N fertilization predictions. However, Vetsch et al. (1995) showed evidence for justification of SSNM when variability in check plots of constant rate applied N was compared with the response rate of variable fertilizer rate plots. A study in Nebraska by Ferguson et al. (2002) showed that using reduced variable rate technology (VRT), in which fertilizer was reduced by a fixed amount, lowered grain yields consistently only at one site while at other locations grain yields were lowered by 15 to 20% as compared to the VRT yields. Their results indicate that using SSNM might lower overall N rate, but also showed that for one site the developed state N application algorithm is not applicable for all areas within Nebraska.

Several studies have researched the use of remote sensing for improving crop management (Bastiaanssen et al., 2000; Lamb and Brown, 2000; Pinter et al., 2003), as well as specifically for improving crop N management (Blackmer and White, 1998; Bausch, et al., 2001; 1998; Raun et al., 2002; Scharf and Lory, 2002). Scharf et al. (2002) concluded that aerial photographs could be used to predict sidedress N rates when three conditions were met: i) no N is applied at planting, ii) soil pixels should be taken out of the image, and iii) sufficiently fertilized maize in the same field should be the basis of color expression. Ground-based sensor systems are another method of remote sensing with the potential to improve N management in corn.

Observations from a greenhouse pot experiment planted to maize that assessed he use of canopy sensors (active and passive) and reflectance indices showed that plant N status can be determined through use of wavelength reflectance sensors, which means in-season corn N management may be possible (Soon-dal Hong et al., 2006). Most indices measure ratios of red and near-infrared (NIR) reflectance such as the normalized difference vegetative index (NDVI), which measures wavelength reflectance ratios (e.g. NDVI = [NIR – Red] / [NIR + Red]). Red light is strongly absorbed by chlorophyll, whereas NIR wavelengths are reflected or transmitted by green leaves. Biomass has been correlated to these indices, as well as percentage of green cover, productivity, and photosynthetic activity (Soon-dal Hong et al., 2006).

Field crop indicators and conditions, such as plant biomass, N status, water stress, and many other factors have been related to measurements in visible, NIR, thermal-infrared (TIR), and microwave wavelengths (Moran et al., 2003). Researchers across the nation are evaluating use of crop health sensors for on-the-go detection of N stress in plants and application of N fertilizer. This approach is called variable rate N (VRN) application. Crop health data detected by active (emits light waves) and passive (ambient light waves) light wave reflectance sensors, which typically use visible and NIR wavelengths, is gathered from a strip of corn in the field that has received the optimum rate of N fertilizer. The data from this reference strip is then used as the basis from which the rest of the field is compared. Areas of lower health, receive more N fertilizer, while areas of sufficient health receive little or no additional N based upon algorithms currently under development. In some cases field areas where maize is deficient, the algorithm used may determine that no N should be applied because N may not be the limiting factor to plant health for that area. Development of sensors, algorithms for various crops and locations, and application systems for VRN applications is ongoing and leading to economically efficient and environmentally beneficial methods of N fertilization.

Plant genetics research to improve NUE

Plants vary in their abilities to utilize available N from the soil both among species, and within genotypes of species (Stevenson et al., 1982). Gallis and Hirel, (2003) observed that genetic variation in maize NUE was explained by variation in N-uptake at high N-input; whereas at low N-input, differences in NUE were due to variation in N utilization efficiency. This suggests that N-assimilation may vary depending on the amount of N fertilizer applied. Identification of traits controlling plant N-uptake will be necessary to genetically improve NUE in plants. During silking, plant N status determines the number of kernals (Di Fonzo et al., 1982; Muruli and Paulsen, 1981; Sherrard et al., 1986). Additionally, leaf senescence has been related to post-anthesis N-uptake in grain filling (Di Fonzo et al., 1982; Moll et al., 1987). Through improvements in plant genetics, it also may be possible to extend the life of leaves and allow the plant to take in more N, resulting in greater yields (Gallais and Hirel, 2003).

A way of identifying traits responsible for N-uptake in maize may be through use of Quantitative Trait Loci (QTL) (Agrama, 1999; Gallais and Hirel, 2003; Good, 2004). Mapping of genes related to the intricate process of NUE in plants through QTL allows for ‘candidate’ genes (i.e., genes which may cause observed variation) to be identified.

Although such stresses as drought and phosphorus tolerance have been identified in maize, few genetic studies have focused on improvement of NUE (Gallais and Hirel, 2003). Furthermore, Gallais and Hirel (2003) concluded that the genetic and physiological basis of NUE can be integrated and studied by using molecular markers, genomics, and agronomic combined with physiological studies to identify candidate genes. Identification of genes responsible for control of NUE will lead to the development of high NUE maize lines.

Factors affecting use of N fertilizer

Various N fertilizer sources are available for purchase to agronomic producers. These forms may be solids (e.g., urea or ammonium nitrate), liquids (e.g., UAN [urea ammonium nitrate] solution), or gases (e.g., anhydrous ammonia). Selection of a particular N fertilizer source may be dependent on several factors, including the crop being grown, availability of a particular fertilizer N form, soil chemical and physical characteristics, climatic conditions, availability of application equipment, and price of the fertilizer.

Although an effective solid plant fertilizer N source, ammonium nitrate has become increasingly difficult to purchase in the U.S. market due to its use as an ingredient in bombs. This form of N fertilizer has been popular for use on agronomic crops and pastures. It has many of the same characteristics as urea, but has a lower N analysis (35.5% N) and is more prone to caking than urea because it can absorb water during storage. A primary advantage of ammonium nitrate compared to urea is that it has a lower potential for ammonia volatilization. However, ammonium nitrate may be more susceptible to losses through denitrification (Ryden, 1983) and leaching compared to urea. Incorporation of the fertilizer into the soil reduces the risk of gaseous losses and losses due to runoff.

Anhydrous ammonia is a widely used and effective N fertilizer source for cereal crops; however it is also utilized for illegal production of methamphetamines. Theft of anhydrous ammonia containers for drug use may cause constraints on the availability of anhydrous ammonia fertilizer, bringing about greater demand for other N fertilizer sources. Anhydrous ammonia contains about 82% N, which is the highest analysis of any N fertilizer source. Application is achieved through pulling a nurse tank filled with anhydrous ammonia behind a set of knives which penetrate the soil and are equipped with tubes through which the NH_3 gas flows into the soil. The NH_3 has a high affinity for water; therefore, higher soil water content close to field capacity will increase the amount of applied N retained in the soil. Other factors, such as low temperature and soil texture, will increase the amount and length of time anhydrous ammonia stays in the soil (Havlin et al., 2005).

Research with anhydrous ammonia fertilizer has shown potential for improving NUE (Mullen et al., 2003; Freeman et al., 2007; Teal et al., 2007). Application of anhydrous ammonia to soils kills microbes, which temporarily sterilizes the soil in small bands (Havlin et al., 2005). Biederbeck et al. (1995) observed decreased soil pH in proportion to addition of N fertilizer, with a greater decrease after anhydrous ammonia application than urea. Additionally, increased rates of anhydrous ammonia decreased microbial biomass more than increased rates of urea.

Granular urea (46% N) has been a popular form of N fertilizer in the U.S. and worldwide (Havlin et al., 2005). Urea is often applied uniformly over a field or pasture area. Once applied, the enzyme urease can hydrolyze urea and convert it into NH_4^+, which may then volatilize at the soil surface. In no-till cropping systems urea can be incorporated using light tillage to work the granules below the soil surface to minimize volatilization. Incorporation of urea, especially under cool and dry conditions, will decrease the rate of urease hydrolyzing urea. In addition, an application of urea directly before a rainfall event will inhibit ammonia volatilization losses.

Enhanced efficiency fertilizers

The use of enhanced efficiency fertilizers, such as nitrification inhibitors (NI) urease inhibitors (UI), slow release fertilizers (SRF), and controlled release fertilizers (CRF) are being researched across a variety of cropping systems, landscapes, soil types, and environmental conditions to determine their potential to reduce N losses (Wang and Alva, 1996; Rozas et al., 1999; Dinnes et al., 2002; Tomaszewska and Jarosiewicz, 2002).

Nitrification inhibitors delay the oxidation of NH_4^+ by suppressing the activities of *Nitrosomonas* bacteria. Two nitrification inhibitors primarily are used in the U.S., including nitrapyrin (2-chloro-6-[trichloromethyl]-pyridene), and dicyandiamide (DCD) (Trenkel, 1997). Nitrapyrin is more commonly known as 'N-Serve'® and differs from DCD in that it not only depresses the activity of *Nitrosomonas* bacteria, but it also kills some of the population (Trenkel, 1997). Nitrapyrin is usually mixed with anhydrous ammonia just before the injection of the anhydrous ammonia into the soil. Nitrapyrin degrades after about 30 days in the soil under warm summer growing conditions, but can persist for a longer time under cold, dry, winter conditions, which is why it is commonly applied in the fall. DCD was produced by specifically one manufacturer in the U.S.

Suppression of *Nitrosomonas* bacteria was observed with this NI source, even with repeated applications (Sturm et al., 1994).

Urea applied to soils undergoes transformation from amide-N to ammonium hydroxide and ammonium (Trenkel, 1997). The enzyme urease catalyzes this transformation through hydrolysis. Urease inhibitors slow or stop the hydrolysis of amide-N to ammonium hydroxide and ammonium. Without inhibition of urease, losses from ammonia volatilization can be quite high if the urea has been surface-applied (Grant et al., 1996; Watson et al., 1994). Use of urease inhibitors can reduce the risk of seedling damage, allowing the fertilizer to be in close proximity to the plant, and thereby improving NUE by making the N more easily accessible (Malhi et al., 2003).

Slow- release fertilizers (SRF) release nutrient(s) slowly over time. Controlled-release fertilizers (CRF) encompass fertilizers that release N into the environment essentially in a controlled manner, or due to some factor that causes the fertilizer to release (Shaviv, 2001). The terms CRF and SRF are generally interchangeable. Urea-formaldehyde, other urea-aldehydes and synthetic N compounds, sulfur-coated urea (SCU), and polymer-coated urea (PCU) are examples of SRF products. The Tennessee Valley Authority (TVA) has been developing SCU since 1961 (Salman, 1988). The inexpensive cost of sulfur and efficient coating process was the reasoning behind the TVA choosing it as a coating material (Salman, 1988). By coating fertilizers with polymers or sulfur (or both), release of N can be delayed, allowing for N to be available later in the growing season when plants may require greater N uptake. Diffusion of water through polymer coated fertilizers causes release of N. The diffusion rate depends upon such factors as the chemistry of the polymer, thickness, and ambient temperature. Use of these products may potentially reduce environmental losses, and increased economic returns by improving NUE through continued research.

Problems with SRF or CRF products include increased costs and inconsistency in product manufacturing (Shaviv, 2001). For example, the cost of coated fertilizers is generally higher than conventional fertilizers since the consumer must pay for the cost of the coating and the process of coating. Inconsistent coating can lead to fertilizer timing release problems. With SCU, damaged or cracked coatings will immediately release their fertilizer when in contact with water (Jarrell et al., 1979). Additionally, when an almost perfect coating is obtained, it was known as "locked off," or releases the fertilizer too late (Goertz, 1995).

Although benefits exist for the use of CRF or SRF, their use with agronomic crops is still quite limited due to cost (Shaviv and Mikkelsen, 1993). Shoji et al. (2001) observed a reduction of N_2O emission from a barley field on a clay soil in Colorado, using NI and CRF by 81% and 35%, respectively. Similiarly, SCU has been shown to reduce N concentrations in rice floodwater compared to urea and ammonium sulfate treatements (Craswell et al., 2005). Use of CRF and SRF in several studies beyond the agricultural realm has also shown success (Zhang et al., 1998; Carrow, 1997; Zachary and Petrovic, 2004).

Objectives

The objectives of this research were to: 1) evaluate the interactive effects of landscape position and soil depth to the claypan on NUE and agronomic responses of maize to conventional and slow release N fertilizer sources, and 2) determine the use of a variable-source application strategy to optimize N fertilizer use efficiency and increase economic returns.

Hypotheses

The hypotheses were: 1) interactive effects of landscape position and N treatment will cause differences in crop response to N; 2) spatial variability in soil water content across the field will cause variability in crop response to N treatments; 3) elevation and topsoil depth to the claypan layer will be the main driving factors of spatially variable soil water content; 4) lower elevations and areas of shallow topsoil depth to claypan will be relatively wetter areas in the field; 5) polymer coated urea (PCU) will increase crop yields and NRE compared to conventional fertilizers in wetter field areas; and 6) suitable areas in the field for optimum yields and economic return for PCU application will be delineated using elevation, topsoil depth, grain yield, N treatment, and soil water content data using available algorithms in a geographic information system (GIS).

Arrangement of the Thesis

This thesis contains three chapters which have been organized in a standard research journal format. Separate chapters are provided on results of field experiments conducted in Northeastern Missouri at Novelty, and in North Central Missouri at Centralia. An additional chapter summarizes the GIS analysis that was conducted. A final concluding chapter is added to provide a synthesis of the thesis research.

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CHAPTER 2

EFFECT OF LANDSCAPE POSITION AND N FERTILIZER SOURCE ON MAIZE N RESPONSE IN A CLAYPAN SOIL IN NORTHEAST MISSOURI

ABSTRACT

Improvement of N fertilizer recovery efficiency (NRE) is necessary to reduce the detrimental effects of excess N entering the environment, and to increase economic efficiency of applying N fertilizer to crops. A two-year field trial was established in 2005 at the Greenley Memorial Research Center in Northeast Missouri to determine the interactive effects of topography and topsoil depth on N fertilizer use efficiency in maize (*Zea mays L.*) in a claypan soil. The study was a split-plot design with four replications, which traversed three landscape positions (summit, sideslope, and low-lying). Nitrogen fertilizer treatments consisted of a non-treated control, pre-plant applied urea, polymer-coated urea (PCU), 50% PCU/50% urea mix, or anhydrous ammonia at a rate of 168 kg N ha^{-1}, followed immediately by incorporation to a depth of approximately 15 cm using a field cultivator. Anhydrous ammonia treatments were knife injected on 76 cm spacings. Maize was planted at 74,100 plants ha^{-1}. Anhydrous ammonia and PCU treatments showed a 1475 and 1535 kg ha^{-1} yield increase over urea, respectively, in the low-lying landscape position in 2005. These increases were repeated in 2006 with anhydrous ammonia and PCU yielding 1659 and 1814 kg ha^{-1} greater than urea, respectively, in the low-lying landscape position. In-season gravimetric soil water content data from several dates in 2005 and 2006, show the low-lying landscape position was significantly wetter than the summit and/or sideslope positions. These results suggest that a variable source

N (VSN) fertilizer management strategy based on identification of wetter field areas due to elevation differences may improve maize NRE.

INTRODUCTION

Agronomic crop production has long employed a wide range of management practices designed primarily with the goal of increasing economic returns, sometimes at the cost of incurring detrimental effects to the environment. However, management plans are progressively attempting to incorporate ways of reducing negative environmental effects, while simultaneously improving economic returns. For example, research to increase nitrogen use efficiency (NUE) in maize (*Zea mays L.*) attempts to improve upon both environmental quality and economic returns.

Atmospheric losses of N may result from denitrification or volatilization of ammonia. Nitrate-N may be lost by surface runoff or it may move into groundwater and streams. Once N has become mobilized, it can travel long distances, such as to the Gulf of Mexico where it may contribute to the world's second largest hypoxic zone (Rabalais et al., 2002). Howarth et al. (2002) stated that over 60% of coastal rivers and bays in the U.S. have been contaminated by excess nutrients. Galloway and Cowling, (2002) named several harmful effects associated with excess N in the environment, including elevated levels of ozone in the troposphere, higher amounts of particulate matter in the atmosphere resulting in reduced visibility, increased surface water and soil acidity, greater hypoxia and eutrophication in coastal marine waters, and the potential to impact global temperatures, and rising global temperatures due to climate change.

Raun et al. (2002) reported that the average world NUE in cereal crops was only 33%. In 1999, the world food consumption of N fertilizer was 85,529,551 Mg (FAO, 2001), of which monetary loss from unused N totaled $15.9 billion (Raun and Johnson, 1999). Raun et al. (2002) reported that only three years later, the loss was up to $20 billion. Losses of labeled ammonia N (^{15}N) in maize (*Zea mays L.*) have been reported to be between 52 and 73% (Francis et al., 1993). These losses were due to the low plant use efficiency associated with N. The N recovery efficiency (NRE [the amount of N taken up by the plant compared with the amount of N applied]) of several crops, including maize, is generally below 50%.

Conservation tillage methods are widely used today. Conservation tillage has been defined as any method of tillage and planting that results in residue coverage of at least 30% of the soil surface after planting for the purpose of reducing soil erosion by water or wind erosion and sustains a minimum of 182 kg ha-1 on the soil surface of flat small grain residue equivalent on the soil surface in the critical erosion period (Mannering et al., 1987). Conservation tillage encompasses a variety of tillage methods and has become a popular method of tillage because use of conservation tillage incorporates many benefits from tillage and no-tillage systems, including better yields, reduced soil erosion, improved water infiltration, increased areas in cropland due to the ability to grow crops on more severe slopes, and lower labor costs than conventional tillage.

However, conservation tillage does have disadvantages. Lower spring soil temperatures in no-till soils inhibit seed germination and early growth of plants. Cooler temperatures can also slow the release of plant nutrients, such as N, P, and S, and provide more favorable conditions for diseases and pests (Havlin et al., 2005).

The tillage method used in a given cropping system can affect NO_3^- dynamics. A study by Dou et al. (1995) showed NO_3^- remaining in a 0- to 120-cm soil profile of no-till plots to be one-half that of NO_3^- remaining in conventionally tilled plots. Additionally, a long-term study in Minnesota (Randall and Iragavarapu, 1995) showed NO_3^- concentrations in the 0- to 150-cm profile were significantly lower for no-tillage than for conventional tillage plots for 5 of 11 years, whereas the other 6 years showed no significant difference. Furthermore, subsurface drainage in the no-till treatments had 12% greater flow than tillage treatments, which showed 5% greater nitrate loss. From this study the authors concluded that precipitation had more of an effect on nitrate dynamics than tillage system. Other studies suggest that N management practices probably have more of an effect on nitrate dynamics than tillage systems (Randall and Mulla, 2001; Weed and Kanwar 1996).

Spatial variability in soil properties across a cropped hillslope may contribute to spatial variability in crop yield. Properties, including topsoil depth to claypan, pH, and sand content, have been shown to strongly correlate to landscape position (Ovalles and Collins, 1986). Timlin et al. (1998) concluded that factors which affect soil water holding capacity and drainage, such as topography, soil depth, soil curvature, and organic matter content, would have the greatest impact on maize grain yield variability.

Modern commercial maize production requires large N fertilizer inputs per unit of cropped land. Various N fertilizer sources are available to producers for application to meet crop N requirements. Some common N fertilizer sources include anhydrous ammonia (gas), ammonium nitrate (solid), urea ammonium nitrate (liquid), urea (solid), and various coated urea (solid) fertilizers. Coated fertilizers have been termed slow release fertilizers (SRF), meaning that release of N occurs more gradually over the length of the growing season as opposed to a faster release soon after application (Shaviv, 2001).

Application of anhydrous ammonia is a preferred method of N fertilization because it is marketed as the most economically beneficial N fertilizer source (Johnston et al., 1997). Initial application usually sterilizes bands of the soil, which may reduce activity of denitrifying microorganisms. Anhydrous ammonia contains about 82% N, which is the greatest analysis of any common N fertilizer source. Often, it can be applied in the fall with ideal conditions (cold and dry) and will mostly be available the following spring. Unfortunately, anhydrous ammonia is utilized in the manufacture of methamphetamines, and is frequently stolen for this use, which may or may not impact future cost and availability of the fertilizer.

Urea is a popular and effective source of fertilizer N (46.6% N) and is used extensively throughout the world. Adverse effects to seedlings, germination, and damage to early plant growth, as well as hydrolysis of urea causing reduced pH, increased ammonium ions in the soil, and ammonia volatilization, are common problems found with the use of urea (Bremmer and Krogmeier, 1989). When applied, urease may transform urea into ammonium (NH_4^+), which is further changed to ammonia (NH_3) and can bind to the soil, or may be subject to atmospheric loss. Previous studies have attempted to use soil urease inhibitors such as phenylphosphorodiamidate (PPD) or N-(n-butyl) thiophosphoric triamide (NBPT), to reduce the loss of ammonia through volatilization, but limited success was observed (Bremner and Chai, 1986; Chai and Bremner 1987).

In order to mitigate the deleterious effects of urea, materials to coat the fertilizer prills have been tested. Sulfur coated urea (SCU) was developed in 1961 by the Tennessee Valley Authority (TVA) laboratories (Salman, 1988). Problems with SCU have been related to inconsistent coating, which either causes N to be released immediately when contacted by water, or to not release until much later after N is needed by the plant. Coating the SCU with a polymer was attempted to improve its performance. Polymer sulfur coated urea (PSCU) showed improved N release characteristics over SCU; however, about 20% of applied N was released initially followed by a "tailing" of about 30% (Shaviv, 2001). Christianson (1988) studied the release of N from a combination of diisocyanate and polyol when subjected to temperature, pH, moisture, and organic carbon differences. It was found the release was mainly due to temperature increase and somewhat due to moisture increase. Wang and Alva (1996) observed a decrease in N leaching losses when using isobutylidene diurea (IBDU) in sandy soils. Owens et al., (1999) also observed decreased leaching losses when a methylene urea was applied in a forage crop. Polyolefin coated urea was used by Shoji et al. (2001) in barley and potato along with nitrification inhibitors (NI) and urea treatments to attempt to improve NUE. Total N fertilizer losses from the NI and urea treatments were 10 and 15%, respectively. The PCU averaged only a 1.9% loss. Total soil N_2O emissions from the PCU treatments were one third as much of the urea treatment loss through N_2O emission. Reduced N_2O losses were observed by Merchan-Paniagua et al. (2006) in northeast Missouri on a claypan soil in maize under wet growing conditions in treatments which were not artificially drained. Continued SRF research to improve coatings and application strategies may be a practical means of improving NUE.

Work to improve NUE by use of variable-rate technology (VRT) has shown success (Paz et al., 1999; Koch et al., 2004; Miao, et al., 2007). On-the-go detection of crop health through wavelength reflectance sensors, followed directly by calculation of appropriate N rate and application of determined N rate, has shown promise for NUE improvement (Sudduth et al., 2007). Lee et al. (1999) found that crop canopy sensors detect plant color based on N content, not based on corn variety. These methods, termed variable-rate N (VRN), have generally increased use of applied N as well as economic returns. However, VRN algorithms do not account for variation in soil properties which may affect crop growth and response to applied N.

Application of several sources of N fertilizer within a field based upon in-field variation of soil properties may be a practical way to improve crop NRE. This research attempts to develop a variable-source N (VSN) fertilizer strategy based upon field areas deemed most suitable for a given N fertilizer source. The objectives of this study were: (i) to determine the interactive effects of landscape position and soil depth to the claypan horizon on NRE and agronomic response of corn to conventional and slow-release N fertilizers and (ii) to examine the use of a variable-source strategy to optimize NRE and increase economic returns.

MATERIALS AND METHODS

Experimental design

This research was conducted in northeast Missouri at the Greenley Memorial Research Center (40° 1' 17" N 92° 11' 24.9" W) in Knox Country near the town of

Novelty (Figure 2.1). The experiment stretched across a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs) and a Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiqualfs). Table 2.1 shows general soil characteristics of the experimental field. Before initiation of the research, soil apparent electrical conductivity (EC_a) data was gathered from the experimental field using an EM-38 (Geonics Limited, Ontario, Canada) in the vertical orientation, which is accurate to 1.5 m deep. This data was mapped and is shown in Figure 2.2. Strong correlations between EC_a and topsoil depth to claypan has been observed (Sudduth et al., 2003), and may influence spatial variation in water content.

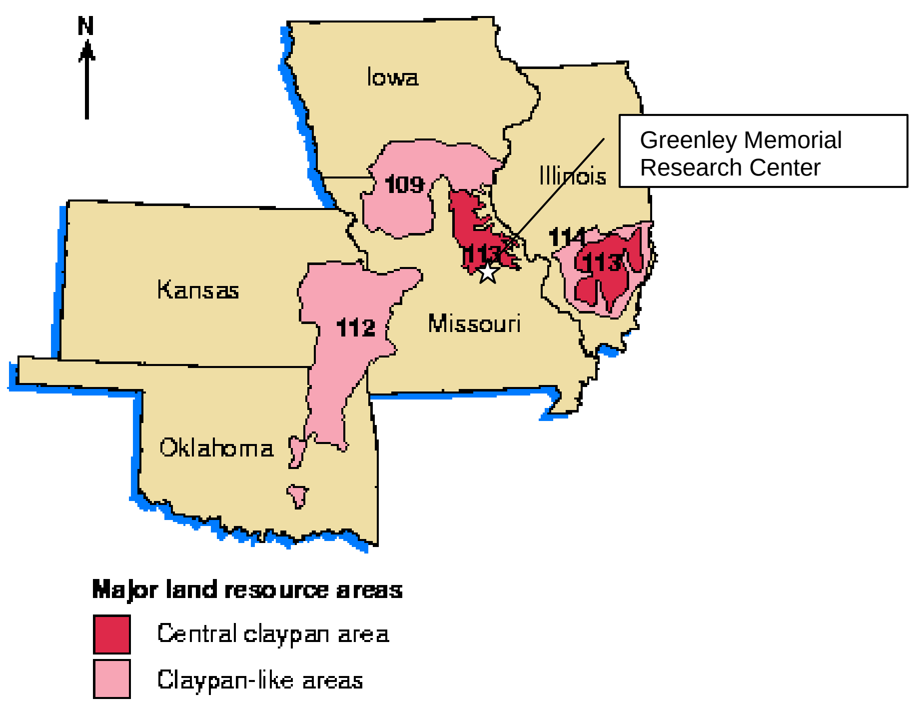

Figure 2.1 Map of the central claypan area and claypan-like areas. The Greenley Memorial Research Center is located in northeast Missouri on a claypan soil. The central claypan comprises an area of about 4 million hectares (Anderson et al., 1990).

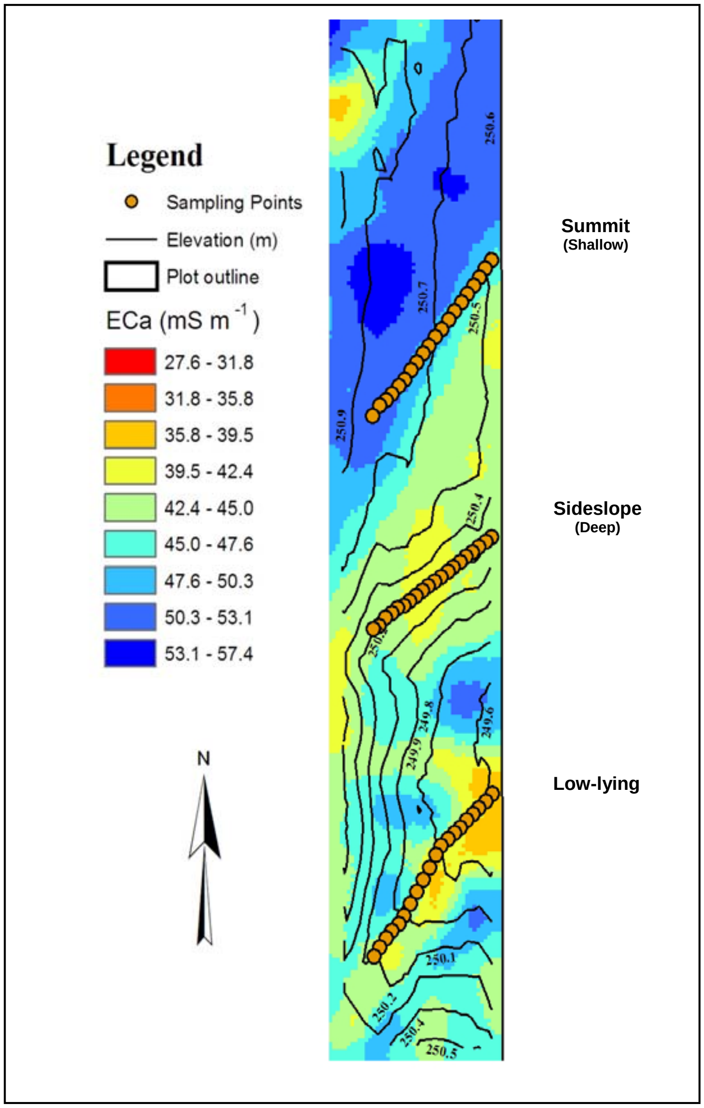

Figure 2.2 Soil EC_a map showing shallow depth to claypan at the summit, deep at the sideslope, and intermediate at the low-lying landscape position. Lines represent elevation breaks. Rows of yellow points were placed using differential GPS (DGPS) along each landscape position (summit, sideslope, and low-lying). These points were sampled for shallow depth (0- to 10-cm) moisture content periodically throughout the 2005 and 2006 growing seasons and represent the location of grain and silage harvests.

Table 2.1 General soil characteristics of the field area collected from each landscape position at three depths.

Depth	Landscape Position	pH	Bulk dens.	Organic matter	Neut. acidity	CEC	Bray I P	Exchangeable Ca	Exchangeable Mg	Soil test K	Inorganic N NO_3^--N	Inorganic N NH_4^+-N
- cm -			Mg/m^3	-- % --	-- $cmol_c\ kg^{-1}$ --		---- mg kg^{-1} ----					
0-10	Summit	6.7	1.31	2.7	0.375	14.8	31.0	2406	229	193	30.0	9.0
	Side Slope	6.6	1.38	2.6	0.250	13.3	35.0	2148	203	244	24.0	3.0
	Low-lying	7.0	1.34	2.7	0.000	15.5	47.0	2601	234	230	16.0	8.0
	DMRT $_{(0.05)*}$	NS	NS	NS	NS	1.6	NS	278	NS	31	NS	NS
10-20	Summit	6.8	1.48	2.1	0.375	14.0	8.3	2338	187	130	48.4	8.4
	Side Slope	6.6	1.48	1.6	0.625	11.8	6.0	1929	146	128	8.6	7.1
	Low-lying	6.9	1.52	2.1	0.375	15.5	13.9	2594	212	152	4.7	10.5
	DMRT $_{(0.05)}$	NS	NS	0.5	NS	2.5	NS	355	55	NS	25.0	NS
20-30	Summit	6.2	1.29	1.9	2.375	16.0	6.3	2359	231	142	14.1	5.2
	Side Slope	5.5	1.36	1.5	5.500	18.0	4.0	2059	191	143	3.4	11.0
	Low-lying	6.1	1.50	2.0	2.750	18.0	6.4	2558	242	131	1.6	8.0
	DMRT $_{(0.05)}$	NS	NS	NS	NS	NS	1.4	733	NS	NS	NS	NS

The experimental design consisted of four replications of five treatments arranged in a split-plot design. Nitrogen fertilizer treatments were broadcast-applied with a Gandy Orbit-Air (Owatonna, MN) and maize was planted on April 27, 2005 at a planting rate of 74,100 seeds ha^{-1}. In 2006, N fertilizer treatments were applied and maize was planted at the same planting rate as the initial year on April 13, 2006. DEKALB maize hybrid C60-19 (Roundup Ready®, European Corn Borer resistant) was planted in 2005. In 2006 DEKALB C60-18 (Roundup Ready®, European Corn Borer Resistant, Rootworm resistant) was planted. Weeds were controlled with an application of atrazine applied at 2.2 kg ai ha^{-1} and 840 g ae ha^{-1} on April 27, 2005, and on April 14, 2006.

Nitrogen fertilizer treatments of 168 kg N ha^{-1} consisted of polymer-coated urea (PCU [ESN® by Agrium Inc., Calgary, Alberta, Canada]), urea, 50% PCU/50% urea mix by weight, anhydrous ammonia, and a control of no N. Treatments were applied in strips of approximately 457 m length by 3 m (6 maize rows) width that crossed three landscape positions (summit [SU], sideslope [SS], and low-lying [LL]). PCU, urea, and 50% PCU/ 50% urea treatments were broadcast-applied and incorporated to an approximate depth of 15 cm using a field cultivator. Other tillage included fall chisel plowing and spring field cultivating. Anhydrous ammonia was knifed into the soil with a 76 cm spacing between injection bands. To supply recommended levels of soil P and K, fertilizer was applied on April 26, 2005 at 3.0 kg N ha^{-1}, 14.7 kg P_2O_5 ha^{-1}, and 9.0 kg K_2O ha^{-1}. On November 1, 2005, fertilizer was applied to supply P and K at a rate of 4.3 kg N ha^{-1}, 11.1 kg P_2O_5 ha^{-1}, and 22.2 kg K_2O ha^{-1}. Additional N was supplied with these applications because diammonium phosphate was used as the P source.

Soil sampling and analysis

Shallow depth soil samples (0-10 cm) were periodically collected for gravimetric water content from sampling points at each landscape position at ten dates during the growing season in 2005 and nine dates in 2006 (Figure 2.2). Bulk density samples were collected from the control treatments at each landscape position using the core method (Blake and Hartge, 1986) with a Uhland probe and a 7.62 by 7.62 cm ring. Samples were obtained at depths of 0-10, 10-20, and 20-30 cm. The soil collected from the bulk density core samples was also used for general soil characteristics analysis of untreated soil using standard analytical procedures at the University of Missouri Soil Testing Laboratory described in Nathan and Sun (2006) (Table 2.1).

Plant sampling and analysis

One in-season maize plant sampling of the total aboveground portion of the plant was collected on June 21, 2005. Ten plants were selected from one of two interior maize rows and the aboveground plant tissue was collected. Plant tissue gravimentric moisture content was obtained after drying the sample in a forced-air oven at 60 °C and samples were ground using a Thomas-Wiley mill® with a 2 mm sieve. The samples were digested in sulfuric acid using a block digester and subjected to total Kjeldahl N (TKN [Zellweger Analytics, 1996]) analysis using flow-injection analysis (FIA) to determine N uptake and nitrogen recovery efficiency (NRE).

The following equations show how N uptake and NRE were calculated:

$$N\ uptake = (Harvested\ silage\ wt.) * \frac{(\%\ silage\ N\ content)}{100}$$

[2.4]

$$NRE = \frac{N\ uptake_{(+\ N\ source)} - N\ uptake_{(-\ N\ source)}}{Total\ N\ added * 100}$$

Above-ground biomass (silage) was harvested after the maize reached physiological maturity in both years from each plot in 6 m lengths from one inside row of the four plot rows. Silage plants were chopped with a Vermeer® (Vermeer Corp., Pella, IA) chipper, and a sub-sample was collected to determine moisture content and total N content of the harvested silage.

Grain was harvested from 6 m lengths in two maize rows using a small plot combine (Massey 10, Haven, KS) on September 13, 2005 and September 12, 2006. Moisture was adjusted to a dry-weight basis prior to analysis.

A graph was devised showing increasing net profit differences (i.e., between use of PCU or anhydrous ammonia and urea in the low-lying areas) changing along with increasing market maize prices and fertilizer cost differences. The fertilizer costs represented differences in the price of the N in PCU or anhydrous ammonia that are either greater or less than the price of N in urea. Each fertilizer cost increment was multiplied by 168 to represent the 168 kg N ha^{-1} that would be applied, which effectively shows fertilizer cost difference over or under urea. Application cost differences were not included.

Statistical analysis

All data were analyzed statistically using analysis of variance (ANOVA) in PROC GLM with the SAS statistical computer program (SAS Institute, 1988). Duncan's Multiple Range Test (DMRT) was used to test statistical significance ($p \leq 0.05$) among the treatment means.

RESULTS AND DISCUSSION

Rainfall

Total precipitation received during the 2006 growing season was 146 mm higher than in 2005, which was a relatively dry year for the area (Figure 2.4). A late-season rainfall event in late July, after a long period of high temperatures and little or no rainfall, provided much needed moisture for plant growth. The 2006 growing season not only received a greater amount of precipitation, but rain events were more evenly distributed throughout the season, which probably explains the overall greater grain and silage yields for 2006.

In-season shallow soil water content

Results for water content of shallow soil samples (0- to 10 cm) collected throughout both growing seasons show that the low-lying landscape position was significantly wetter than the other landscape positions, for several dates (Figures 2.5 and 2.6). The 2006 data shows the low-lying position was wetter for 7 of the 9 dates in the control, 8 of 9 dates in the PCU, and 5 of 9 dates in the urea plots. The greater frequency of wetness in the low-lying position can probably be explained by the greater and more evenly distributed precipitation events. Generally, the soil water content was not significantly different across N treatments from the same date.

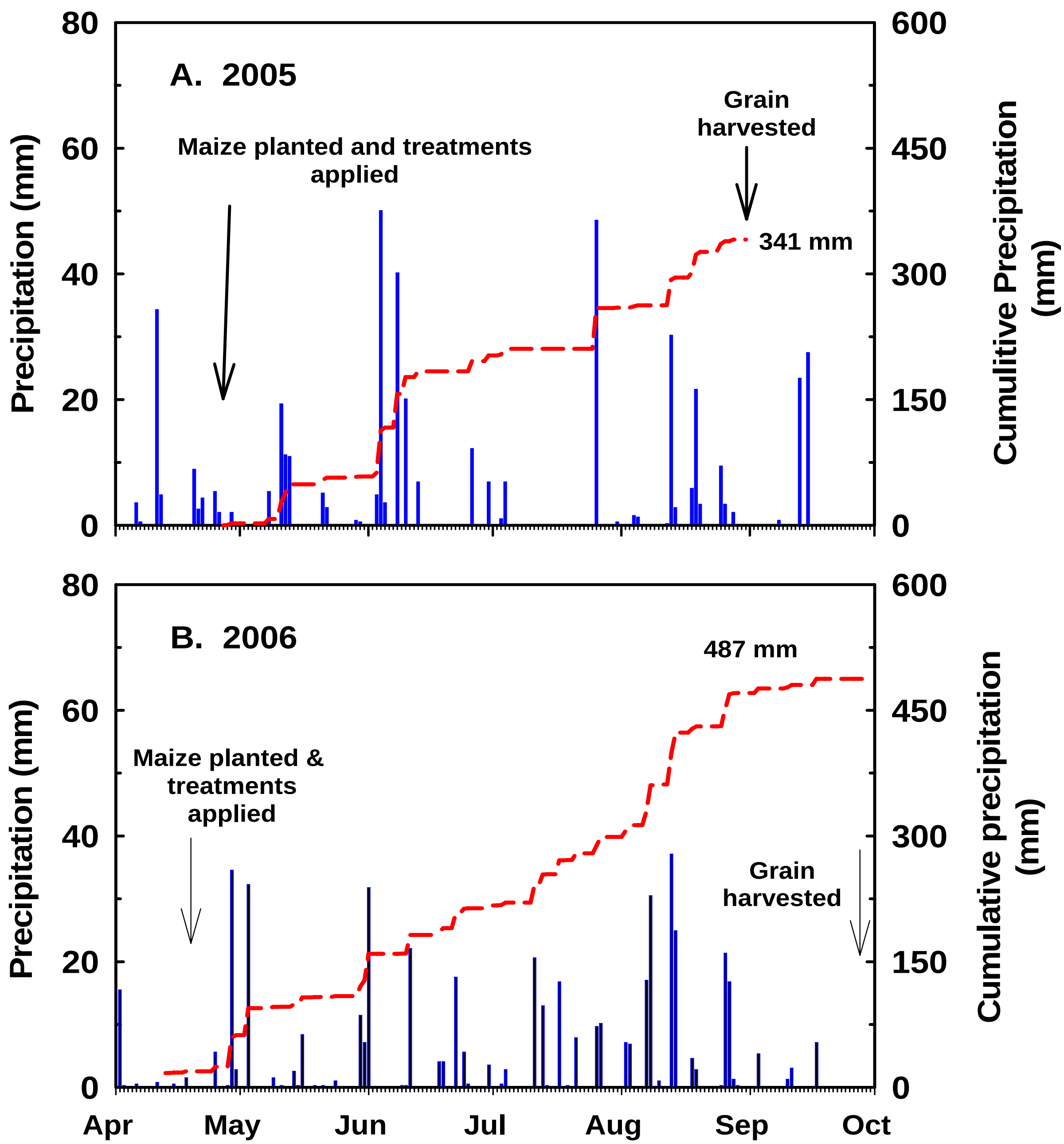

Figure 2.4 Daily recorded precipitation (bars) and cumulative precipitation (segmented

line) for the growing season from planting to grain harvest in 2005 and 2006. Arrows show the time of planting and fertilizer application, as well as the time of grain harvest.

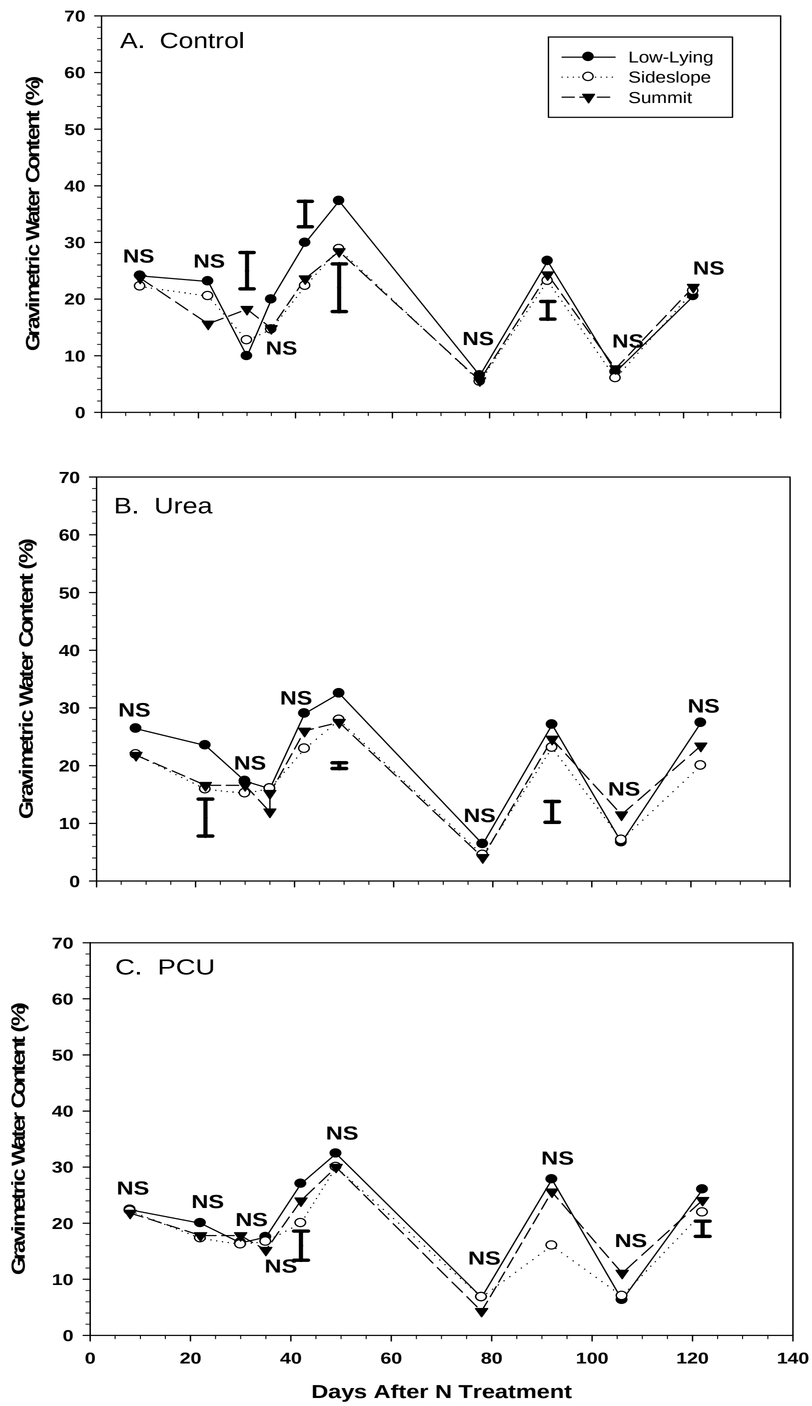

Figure 2.5 Comparison of gravimetric soil water content data (0- to 10-cm) collected throughout the 2005 growing season at each landscape position.

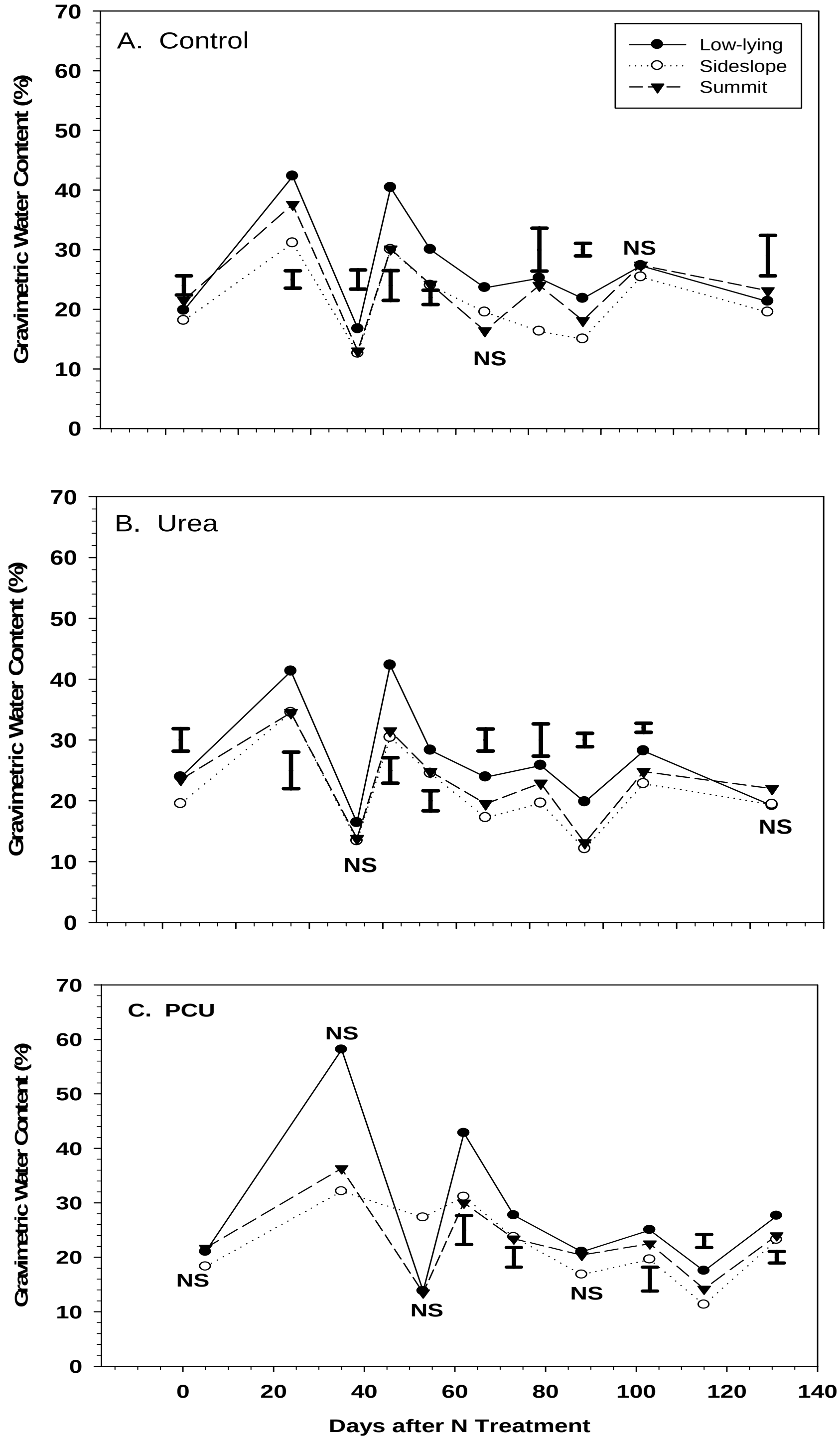

Figure 2.6 Comparison of gravimetric soil water content data (0- to 10-cm) collected throughout the 2006 growing season at each landscape position.

Grain yield

Grain yields in 2005 were lower than 2006 probably due to the poorer rainfall distribution and lower overall precipitation during the growing season in 2005 (Table 2.2). However, both years showed grain yields of PCU and anhydrous ammonia treatments were significantly greater than urea treatments at the low-lying landscape position. The average increase in yield for PCU and anhydrous ammonia treatments at the low-lying position were 1535 and 1475 kg ha^{-1} in 2005, respectively, over the urea treatment. In 2006, results were similar with an average increase in yield for PCU and anhydrous ammonia treatments at the low-lying position were 1814 and 1659 kg ha^{-1}, respectively. Timlin et al. (1998) observed that topography was a major factor determining maize grain yield. The higher grain yields with treatments of PCU and anhydrous compared to urea was probably due to greater soil moisture in this landscape position than the other landscape positions, caused by topographical and soil depth characteristics affecting the fate of applied N. Furthermore, Stone et al. (1985) found that landscape position had a much stronger correlation with grain yield than did erosion class.

Both PCU and anhydrous ammonia treatments yielded significantly greater at the low-lying landscape position, as compared to the respective PCU and anhydrous ammonia treatments at the sideslope and summit positions in 2005. Only one significant treatment difference, excluding fertilized treatments vs. control treatments, was observed, which was a difference of 889 kg ha^{-1} greater yield with the PCU/urea mix over urea in 2006 at the sideslope position. These results suggest that PCU and anhydrous ammonia might increase grain yield compared to urea when applied in field areas which match the characteristics of the low-lying area of this experimental field.

Silage Yield

Similar to grain yields, the 2006 silage yields were generally higher than that of 2005 due to greater total rainfall and more evenly distributed rainfall events (Table 2.3). All N fertilizer treatments had significantly greater silage yields compared to that of the control treatment, except at the sideslope position in 2005 of PCU and PCU/urea treatments. The control was 1.6 Mg ha^{-1} greater at the sideslope landscape position than at the low-lying position in 2005. The PCU was 2.9 Mg ha^{-1} greater at the low-lying landscape position than at the sideslope in 2005, and the PCU/urea mix was 3.2 Mg ha^{-1} greater at the low-lying position than at the sideslope and 2.5 Mg ha^{-1} greater at the low-lying position than at the summit position. These results are most likely due to the same factors which affected the grain yield results (i.e., spatial differences in soil water content).

Table 2.2 Grain yields by landscape position and treatment from 2005 and 2006.

2005

N fertilizer treatment	Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$*
	Landscape position			
	---------------------- kg ha^{-1} ----------------------			
Control	4614	4537	4457	NS
Urea	5816	4960	5818	NS
PCU	5898	4637	7353	1920
PCU/urea	5965	4840	6538	NS
Anhydrous	6312	5561	7293	1567
$DMRT_{(0.05)}$	599	NS	1345	

2006

N fertilizer treatment	Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$
	Landscape position			
	---------------------- kg ha^{-1} ----------------------			
Control	6091	5776	8116	1936
Urea	11949	11048	11038	NS
PCU	12506	11744	12852	NS
PCU/Urea	12624	11937	11860	NS
Anhydrous	12663	11679	12697	NS
$DMRT_{(0.05)}$	1087	870	1150	

*Duncan's Multiple Range Test ($P < 0.05$); NS = not significant

Table 2.3 Silage yield by landscape position and N fertilizer treatment from 2005 and 2006.

2005

N fertilizer treatment	Landscape position: Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$*
	------------------------ Mg ha^{-1} ------------------------			
Control	9.6	10.8	9.2	1.5
Urea	12.3	12.5	12.4	NS
PCU	12.1	11.5	14.4	1.8
PCU/urea	11.7	11.0	14.2	1.9
Anhydrous	13.0	12.3	16.2	NS
$DMRT_{(0.05)}$	2.0	1.5	3.2	

2006

N fertilizer treatment	Landscape position: Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$
	------------------------ Mg ha^{-1} ------------------------			
Control	11.0	11.3	10.1	NS
Urea	19.8	20.6	17.2	NS
PCU	20.5	19.0	19.5	NS
PCU/Urea	20.8	20.7	19.0	NS
Anhydrous	20.7	19.9	18.9	NS
$DMRT_{(0.05)}$	3.5	3.6	4.6	

*Duncan's Multiple Range Test ($P < 0.05$); NS = not significant

N uptake and NRE

Results from the 2005 growing season showed that N uptake for PCU and anhydrous ammonia treatments were significantly greater than urea treatments only in the low-lying position in 2005 by 36- and 47 kg ha^{-1}, respectively (Table 2.4). PCU showed 39 and 56 kg ha^{-1} increase in N uptake in the low-lying position than PCU treatments in the summit or sideslope positions, respectively, in 2005. NRE in the anhydrous ammonia treatments in 2005 was significantly greater than urea in the low-lying area by 28%. PCU in the low-lying area was similar to urea or PCU/urea. PCU, PCU/Urea, and anhydrous ammonia treatments in the low-lying position were all significantly greater than respective PCU, PCU/Urea, and anhydrous ammonia treatments at the summit or sideslope positions by 25%, 17%, and 24% between the summit and low-lying positions, and 35%, 21%, and 32% difference between the sideslope and low-lying positions. Application of a conventional N fertilizer source at the non-low-lying field areas may further improve NRE because of the lack of significant differences between fertilized treatments at the summit and sideslope positions and may also be economically beneficial because PCU is commonly more expensive than conventional N fertilizer sources.

Motavalli et al. (2005) observed significantly less nitrate leaching from PCU fertilized plots than from urea fertilized plots in northeast Missouri. Research has also shown decreased N_2O emission from slow release fertilizers than from conventional fertilizers (Abao et al., 2000; McTaggart and Tsuruta, 2003). PCU and anhydrous ammonia increased efficiency in the low-lying position due to the increased soil moisture content in this position throughout the duration of the growing season, which may have affected the fate of applied N.

Table 2.4 N uptake and N recovery efficiency for 2005 and 2006.

2005

	Landscape position			
N treatment	Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$*
	N uptake			
	----- kg ha^{-1} -----			
Control	45	45	43	NS
Urea	72	62	74	NS
PCU	71	54	110	26
PCU/Urea	69	63	95	NS
Anhydrous	83	69	121	NS
$DMRT_{(0.05)}$	12	13	32	
	NRE			
	----- % -----			
Control	--	--	--	--
Urea	17	10	19	NS
PCU	16	6	41	17
PCU/Urea	15	11	32	12
Anhydrous	23	15	47	20
$DMRT_{(0.05)}$	6	8	23	

*Duncan's Multiple Range Test (P < 0.05); NS = not significant

2006

	Landscape position			
N treatment	Summit	Sideslope	Low-lying	$DMRT_{(0.05)}$
	N uptake			
	----- kg ha^{-1} -----			
Control	44	55	53	NS
Urea	152	158	122	NS
PCU	131	138	133	NS
PCU/Urea	161	165	128	NS
Anhydrous	148	177	127	45
$DMRT_{(0.05)}$	12	13	58	
	NRE			
	----- % -----			
Control	--	--	--	--
Urea	64	58	41	NS
PCU	52	49	48	NS
PCU/Urea	69	65	45	NS
Anhydrous	62	73	44	NS
$DMRT_{(0.05)}$	6	8	NS	

Cost Analysis

Improved maize NRE and grain yield by use of PCU or other N fertilizer sources in field areas of low-lying elevation may potentially increase economic returns. Using grain yield results from this study and a market maize price of \$0.20 kg^{-1}, economic returns were calculated when PCU was applied in the low-lying area versus urea application in the low-lying area. The cost of applying 168 kg N ha^{-1} of urea is about \$161 ha^{-1}, whereas the cost of applying 168 kg N ha^{-1} as PCU is about \$210 ha^{-1}. This is a cost difference of an extra \$47 ha^{-1} to use PCU. Averaging the observed grain yield increase of PCU over urea for 2005 and 2006 in the low-lying area resulted in a mean yield increase of 1675 kg ha^{-1}. When multiplied by the \$0.20 kg^{-1} maize market price, and the \$47 extra cost of applying PCU is subtracted, the benefit from using PCU instead of urea in the low-lying area is \$228 ha^{-1}. These results show an economic advantage to PCU use in low-lying areas.

Anhydrous ammonia similarly increased grain yield in the low-lying area and provided economic benefits over urea application. The cost of applying anhydrous ammonia is about \$247 ha^{-1}, meaning an additional \$86 ha^{-1} cost of application over urea and an additional \$19 ha^{-1} more than the cost of applying PCU. Average observed grain yield increase under anhydrous ammonia treatment over urea for 2005 and 2006 was 1567 kg ha^{-1}. When multiplied by the market price of \$0.20 kg^{-1} and the extra \$86 cost over urea application is subtracted the economic benefit from using anhydrous ammonia is \$227.

The cost of applying the PCU/urea mix is \$186 ha^{-1}, which is a \$25 ha^{-1} additional cost over urea. When the average increased PCU/urea mix grain yield of 771 g ha^{-1} over urea grain yield is multiplied by the cost and the \$25 ha^{-1} extra cost over urea application is subtracted, the economic benefit of the PCU/urea mix on grain yield is \$129.

Figure 2.7 shows potential profit from using anhydrous ammonia or PCU in an area where these fertilizers would result in greater yield than use of urea fertilizer. As fertilizer cost increases the range of profits decreases. The greatest potential profit range resulted from -\$0.10 kg^{-1} fertilizer cost, which is commonly the price difference between anhydrous ammonia and urea.

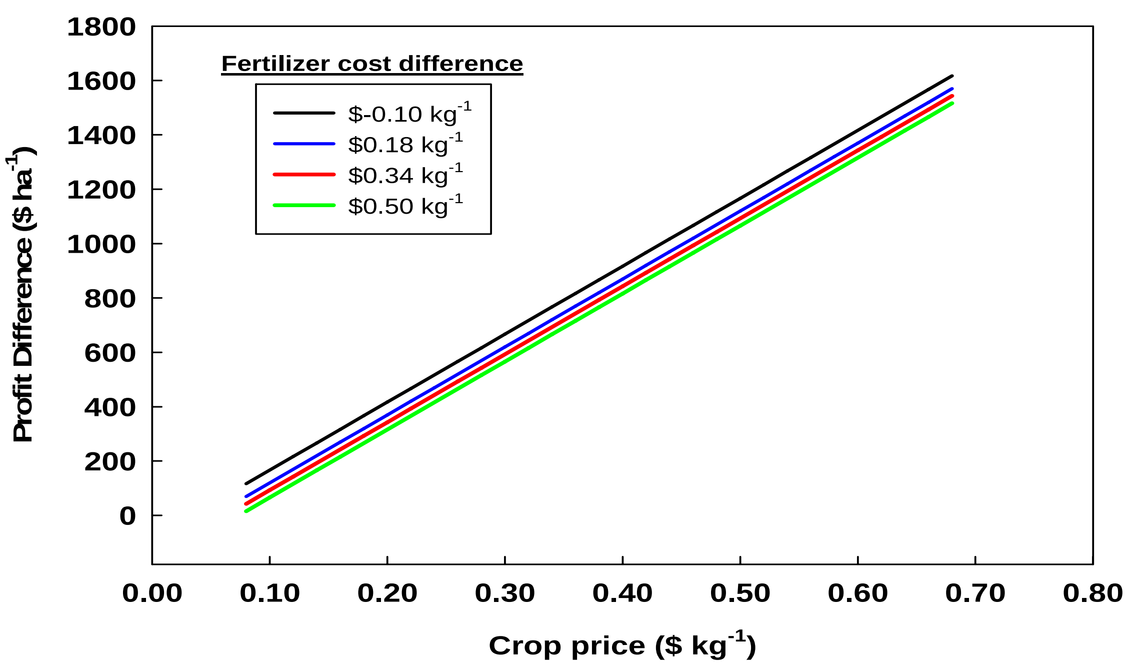

Figure 2.7 Potential net profit difference in low-lying areas at an application rate of 168 kg N ha^{-1} from using anhydrous ammonia or PCU fertilizer compared to urea at different combinations of crop price and differences in fertilizer costs per kg N between anhydrous ammonia or PCU and urea. This figure does not take into consideration differences in fertilizer application cost among the N fertilizer sources.

CONCLUSIONS

Spatial variation in several soil properties, including depth to the claypan, soil exchangeable Ca and CEC, and differences in soil water content, were observed by landscape position across the experimental field. The low-lying landscape position was wetter throughout the 2005 and 2006 growing seasons due to its lower elevation, which may have affected runoff and drainage and possibly N loss.

Due to relatively higher cost compared to conventional N fertilizer, use of enhanced efficiency fertilizers, such as PCU, may be restricted unless the use of these products is both practical and profitable. This research tested the possibility of two strategies to use enhanced efficiency N fertilizers including targeting areas in the field for which there is greater response and mixing the conventional and enhanced efficiency fertilizer together and applying that mix over the whole field. The grain yield, silage yield, NRE, and economic results of this research suggest that applying enhanced efficiency fertilizer, such as PCU, to low-lying areas of the field in claypan soils is a better alternative practice than mixing the N fertilizer products. In addition, application of pre-plant anhydrous ammonia is also an effective practice to increase yield performance and increase NRE compared to when urea is used as a N fertilizer source.

This approach of targeted N fertilizer application based on landscape position was effective in both wet and dry growing seasons. The higher rainfall during the early part of the growing season after N fertilizer application in 2005 and 2006 may account for the observed higher yield response and improvements in NRE observed with use of PCU and the anhydrous ammonia compared to the urea in the low-lying area. Visual observations confirmed that the soil in the low-lying landscape position was saturated at least once during the early growing season period in both years of this research. We speculate that this saturated soil leads to greater N loss, possibly through denitrification, in the urea-treated soils compared to the PCU- and anhydrous ammonia-treated soils.

The ultimate acceptance of this practice by growers of targeted N fertilizer applications based on landscape position will depend on several factors including the increased economic return with use of the practice. Other factors affecting adoption may include market availability of the enhanced efficiency fertilizer, ease of storage and application, access to government subsidies, and changes in fertilizer and maize prices. Based on the economic analysis presented in this research, use of incorporated PCU and pre-plant anhydrous ammonia fertilizer can be profitable compared to urea when used in low-lying areas of a field. However, further research is needed to test whether this proposed practice would work under a variety of environmental conditions and cultural practices. In addition, this research was limited in that it evaluated agronomic response based on categories of landscape position and not as a gradient over the field. We recommend that future research assess the changes in agronomic response over the landscape at a finer scale in order to delineate and map those areas where use of alternative N fertilizer sources may be profitable.

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CHAPTER 3

EFFECTS OF CROPPING SYSTEM, LANDSCAPE POSITION AND N FERTILIZER SOURCE ON MAIZE CROP RESPONSE IN A CLAYPAN SOIL IN NORTH CENTRAL MISSOURI

ABSTRACT

Strategic use of enhanced efficiency fertilizers (EEF) may be a way to reduce applied nitrogen (N) fertilizer loss into the environment and increase maize (*Zea mays L.*) response in claypan soils. A two-year plot experiment was established in 2006 at the USDA Agricultural Research Service Cropping Systems and Water Quality Research Unit (USDA-ARS-CSWQRU) experiment station on a claypan soil located in Central Missouri. Two fertilized treatments of 168 kg N ha^{-1} urea and polymer-coated urea (PCU), and a non-treated control were nested within three long-term USDA cropping system rotations, including CS1 (minimum-till corn/soybean), CS2 (no-till corn/soybean), and CS3 (no-till corn/soybean/wheat) on three landscape positions (summit, sideslope, or footslope) in three replications. In 2006, maize grain yield under PCU treatment was 1203 kg ha^{-1} higher than urea treated at the footslope position in CS2. Maize nitrogen recovery efficiency (NRE) was significantly greater under PCU treatment than urea treatment in 2006 at the summit position in CS3. Differences in spatial variation across the study site, along with misapplication of N fertilizer in 2007 caused crop N response variability in this study. The footslope position generally held less soil gravimetric water content at 0 to 20 cm deep, which contributed to the lack of crop N response differences between the treatments. Further research into the relationships between landscape elevation variability, topsoil depth to the claypan, and soil infiltration

and drainage variability, and silage and grain yield, and NRE is needed to successfully delineate field areas that may be more suitable for PCU than non-coated urea.

INTRODUCTION

Maize (*Zea mays L.*) grain production in the U.S. totaled over 329,791 Mg in 2007 (USDA NASS). This was an increase of about 64,047 Mg over 2006 production (USDA NASS). In addition to the higher maize production, the price of N fertilizer has been increasing due to several factors, including increased global demand for fertilizer, rising demand and subsidies for maize-based ethanol production in the U.S., higher fertilizer transportation costs, the decreasing value of the U.S. dollar causing the cost of imported good such as fertilizer to increase, and higher natural gas prices leading to increased costs of fertilizer production (The Fertilizer Institute, 2008). Despite the increased costs of N fertilizer, sustaining higher levels of maize production has required increased N fertilizer usage. The Fertilizer Institute (2008) reported that from 2001 to 2006, world N demand increased by 14 percent. Furthermore, they projected that by 2001, ethanol production could easily reach 41.6 billion liters, which is more than double current production.

In order to maintain current food supplies and continue increasing ethanol production using maize grain, yields need to be increased. One important way to increase grain yield is to first raise the maize use efficiency of soil inputs, such as N, which is the most limiting nutrient for maize growth and development. An additional benefit of improved N use efficiency is the decreased potential for environmental pollution.

Excess N entering the environment causes negative impacts, such as hypoxia, eutrophication, soil and water acidification, and N_2O emission (Galloway and Cowling, 2002). Nitrogen recovery efficiency (NRE) is a measure of the proportion of the applied fertilizer N that is taken up by the aboveground portion of the plant (Cassman et al., 2002). Cassman et al. (2002) stated that average maize NRE is only about 37%, indicating that a high proportion of applied N fertilizer is lost into the environment or immobilized in the soil under current cropping systems.

Cropping system effects on N

Numerous factors affect the fate of applied N fertilizer in a given cropping system. Geographic location, land topography, climatic conditions, various soil chemical and physical properties, and land management affect N cycling in the soil. Cropping system differences generally result in N cycling differences. Several studies have examined interactions between various cropping systems and the fate of applied N fertilizer (Burle, et al., 1997; Venterea et al., 2005; Russel et al., 2006; Parkin and Kaspar, 2006; Dusenbury et al., 2008).

Use of legumes in rotation is an important cropping system practice to improve N availability in the non-legume phase of the rotation. Greenland (1971) observed improved soil fertility from increased N availability in legume-based pastures. Pavinato (1993) and Teixeira et al. (1994) showed that although legumes increased soil acidity, maize yields were largest in systems including legumes and maize every year. Burle et al. (1997) found that legume-based cropping systems resulted in greater above ground N, as well as soil organic N than non-legume systems, which increased N mineralization and nitrification.

Russel et al. (2006) stated that N fertilization and legumes can increase maize yields; however, each management practice may impact soil status and N cycling dissimilarly. Several benefits come from use of legumes in a cropping system, including: better soil structure, decreased soil loss, increased microbial diversity (Jensen and Hauggaard-Nielsen, 2003), and increased plant N availability through providing more substrates for N mineralization (Sanchez et al., 2001).

Not only does inclusion of legumes in the rotation affect soil properties, but selection of N fertilizer source may significantly impact C and N levels. A long-term study beginning in 1931 by Rasmussen et al. (1980) showed that the addition of 22.4 Mg of manure ha^{-1} over 45 years increased soil C and N, compared to addition of 45 or 90 kg ha^{-1} of chemical fertilizer, or 2.2 Mg of pea vines ha^{-1} during the time period. Russel et al. (2006) researched different N fertilization rates in four different cropping systems and their impacts on soil quality in north central and northeast Iowa. Continuous maize, maize/soybean (*Glycine max (L.)* Merr.), maize/maize/oat (*Avena sativa* L.), and maize/oat/alfalfa/alfalfa (*Medicago sativa* L.) were the four studied systems. Systems containing alfalfa resulted in larger post-harvest N stocks, as well as soil organic carbon concentrations. By comparison of the study to a proximal undisturbed pasture soil, which was low in available N, and had low pH, and high CEC, they concluded that alfalfa included in cropping systems maintains high fertility without diminishing soil quality from excessive addition of N fertilizer.

Tillage in cropping systems is another major factor that may affect soil properties. Several studies have observed tillage impacts on soil N dynamics (Dou et al., 1995;

Aslam et al., 1999; Wienhold and Halvorson, 1999). Detrimental impacts of tillage on soils include possible increased nitrate leaching, reduced cation exchange capacity, lowered water retention capacity, and diminished soil structure (Dinnes et al., 2002). No-till or conservation tillage practices can mitigate these negative effects. According to McLaughlin and Mineau (1995), conservation tillage reduces erosion, improves soil permeability, and decreases runoff. Furthermore, no-till systems can lead to improved soil conditions, such as increased soil organic matter content (Tyler and Overton, 1982; Tyler et al., 1983; Havlin et al., 1990; Hill, 1990) and increased exchangeable cations, cation exchange capacity, and pH (Ismail et al., 1994; Karathanasis and Wells, 1989).

Increased denitrification in no-till cropping systems over tilled cropping systems was observed by Rice and Smith (1982). They concluded that higher soil moisture contents in the no-till system increased denitrification, as well as increased N fertilizer requirements that are commonly reported for no-till soils. However, Angers et al. (1997) found that no significant difference in N concentrations between tillage and no-tillage systems existed at depths of 0 to 60 cm in an eastern Canadian soil.

Land topography effects on N

Agronomic maize production typically occurs over a landscape of variable elevation. Seemingly flat river floodplains can show up to a few meters of topographical variation, which can affect water flow and accumulation. Areas where water might accumulate over time are more susceptible to reducing plant N uptake and increasing N loss. Topsoil depth to claypan, pH, sand and sand content are soil properties that have been shown to strongly correlate to landscape position depending on location (Ovalles and Collins, 1986). Timlin, et al. (1998) concluded that factors which affect water drainage and holding capacity will impact the fate of applied N. These factors include topography, soil depth, soil curvature, and organic matter. Timlin et al. (1998) stated that these factors would have the greatest impact on maize grain yield by influencing water drainage. Terrain attributes, such as erosion class, landscape position, and soil properties, are permanent spatial factors that influence crop yield (Lark et al., 1997; Whelan and McBratney, 1997; Colvin et al., 1999). These factors are long-lasting and need to be observed over long time periods to accurately interpret recurring spatial patterns (Sudduth et al., 1997; Lark and Stafford, 1998). If this can be accomplished, producers will have an advantage that allows them to manage their fields on a site-specific basis (Larscheid et al., 1997). A study by Kaspar et al. (2003) in central Iowa showed that it would be possible to use terrain attributes and yield data from several years to determine a variable rate strategy for crop management.

Timlin et al. (2001) stated that plant available water is the most important factor affecting crop yields. Determination of average water-holding capacity based on landscape position has been shown to strongly correlate with silage yield (Wright et al., 1990). Timlin et al. (2001) concluded that by using soil water retention and a simple water budget model, effects of soil water on yield can be quantified. A strategy for crop management based on spatial soil water patterns over time and crop yields can be developed to increase crop performance, and reduce loss of crop inputs into the environment.

Granular N fertilizers

Granular urea fertilizer is a form of N fertilizer that has been heavily used in maize production for decades. However, use of urea fertilizer has some possible disadvantages due to its potential adverse effects on seed germination and early growth in the soil caused by ammonia produced by urea fertilizer through hydrolysis (Bremner and Krogmeier, 1988). In addition, urea fertilizer is susceptible to ammonia volatilization losses, especially when it is surface-applied (Ernst and Massey, 1960; Ferguson et al., 1984; Beyrouty et al., 1988).

Application of N fertilizer to cropped fields results in some N lost to the environment through leaching, runoff, or gaseous losses to the atmosphere. For example, Bailey et al. (2005) studied N_2O gas flux after N fertilization in Northeast Missouri on a claypan soil and observed that approximately 10% of the applied N to maize was lost to the atmosphere. Delgado and Mosier (1996) reported that approximately 70% of anthropogenic N_2O emissions result from agricultural activities. The N_2O evolved from the applied N fertilizer may further oxidize to NO and NO_2, which are catalysts for O_3 destruction in the stratosphere (Crutzen, 1976).

Slow-release fertilizers (SRF) are being used to attempt to reduce N losses. One example of a SRF is polymer-coated urea (PCU), in which urea prills are coated with a polyurethane or polyolefin coating, which encapsulates the fertilizer and slows its release. Merchan Paniagua et al. (2005) observed reduction in N_2O flux on poorly drained plots in Northeast Missouri with use of PCU in maize during a cropping year with relatively wet conditions. Furthermore, Motavalli et al. (2005) observed maize grain yields in PCU-treated plots equal to grain yields from anhydrous ammonia-treated plots. Additionally, potato yields increased with use of coated urea over conventional urea at rates of 45 and 135 kgN ha^{-1} in a loamy sand soil in Minnesota (Rosen and McNearney, 2005).

The objective of this study was to determine the interactive effects of landscape position, soil depth to claypan, and different established cropping system on maize N response and NRE.

MATERIALS AND METHODS

Experimental Design

This study was conducted on long-term cropped research plots at the USDA-ARS-Cropping Systems and Water Quality Research Unit (CSWQRU) experiment station, (39°38'N, 92°20'W) located in the Goodwater Creek Research Watershed near Centralia, MO (Figure 3.1).

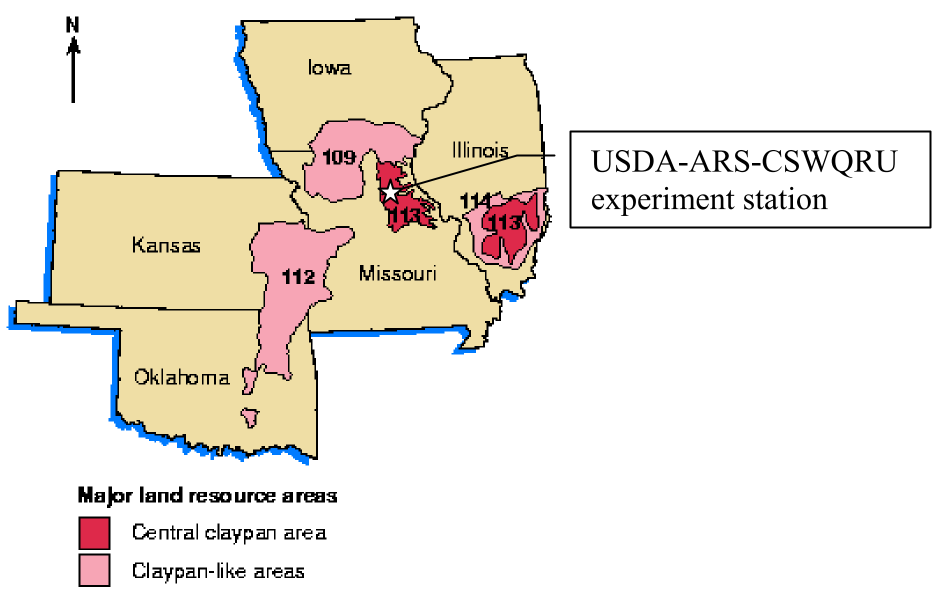

Figure 3.1 Location of the study at the USDA-ARS-CSWQRU experimental station in the Goodwater Creek Research Watershed near Centralia, MO. The site is near the edge of the claypan soil in the central claypan area.

The experimental plots were part of the Agricultural Systems for Environmental Quality (ASEQ) study established in 1996 which examines the effects of cropping system on long-term agronomic response and runoff. The Missouri Management Systems Evaluation Area (MSEA) project provides the basis for the ASEQ project. Soils in the study consisted of an Adco silt loam (fine, smectitic, mesic, Vertic Albaqualfs), and a Mexico silt loam (fine, smectitic, mesic, Aeric, Vertic Epiaqualfs) in the lower-lying landscape of some plots (Missouri Cooperative Soil Survey Website, 2007).

Three cropping systems from the ASEQ study initiated in 1996 were selected and designated as CS1, CS2, and CS3. The CS1 cropping system was a minimum till maize (*Zea mays* L.)/soybean (*Glycene max* L.), CS2 was a no-till maize/soybean rotation, and CS3 was a no-till maize/soybean/wheat (*Triticum aestivum*.) rotation. The cropping system plots traversed three landscape positions (i.e., summit, sideslope, and footslope). At each of the three landscape positions in each cropping system, three N fertilizer treatments were introduced into the ASEQ plots and arranged in a randomized complete block design with three replications. Treatments were 4.5 by 10 m rectangles (e.g., 6 maize rows wide) located on the northern six maize rows of the ASEQ cropping systems, which were 18 m (e.g., 24 maize rows) wide by 190 m in length. The treatments consisted of 168 kg N ha^{-1} applied as urea or polymer-coated urea (PCU[ESN® by Agrium Inc., Calgary, Alberta, Canada]), and a control treatment with no applied N. All three treatments were applied at each landscape position, resulting in 81 total plots in 2006. Due to an error with N fertilizer application, only 72 plots were used in 2007.

Maize was planted on April 14, 2006 at 69,169 seeds ha^{-1}. Starter fertilizer was applied at 0.9 kg N ha^{-1} and 6.3 kg P_2O_5 ha^{-1}. A poor stand necessitated a re-planting on May 16, 2006. Conventional hybrid Master's Choice 'MC 530' was re-planted at 69,169 seeds ha^{-1}. The treatments of PCU and urea fertilizers were hand-spread at 168 kg N ha^{-1} on April 20, 2006. Fertilizer was incorporated with a Troy Bilt® garden tiller (Troy Bilt,, Cleveland, OH) on CS1 only.

Conventional maize hybrid 'NK N67-D6' was planted on May 15, 2007 at 69,169 seeds ha^{-1} and fertilized treatments were hand-spread and incorporated in CS1 only. Starter fertilizer was applied at 0.9 kg N ha^{-1} and 6.3 kg P_2O_5 ha^{-1}. Fertilizer was incorporated into CS1 in the same manner as in 2006.

Several pesticide applications were applied to the plots in 2006. In CS1, on April 14, 2006 a mixed application of 93.54 L ha^{-1} of atrazine, ammonium sulfate, glyphosate, and esfenualerate was applied. On May 23, 2006 after re-plant, CS1 was sprayed with glyphosate and ammonium sulfate to kill any plants remaining from the first planting, which were at the V-2 growth stage. On June 30, 2006 CS1 received an application of atrazine plus nicosulfuron plus mesotrione plus ammonium sulfate, targeting waterhemp (*Amaranthus tuberulatus*), cocklebur (*Xanthium strumarium*), crabgrass (*Digitara sanguinalis*), and morning glory (*Ipomea tricolor*). Henbit (*Lamium amplexicaule* L.) and other winter annuals were controlled in 2007 on CS2 on April 23, 2007 with an application of atrazine, ammonium sulfate, and glyphosate. On April 30, 2007 winter annuals were sprayed using refined soybean oil, atrazine, glyphosate, and ammonium sulfate.

CS1 was the only tilled cropping system and was tilled April 6, 2006, April 17, 2006, and May 17, 2006 with a Sunflower® (Beloit, KS) disk/cultivator. On May 17, 2006 a culti-packer was used to break soil clods and preserve soil moisture. The same disk/cultivator was used in 2007 on April 21, April 23, and May 16.

Apparent electrical conductivity (EC_a) was collected using an EM-38 (Geonics, Ontario, Canada) sensor attached to a wooden cart and pulled by an all-terrain vehicle (ATV). Sudduth et al. (2003) showed strong correlations between EC_a data and topsoil depth to the claypan layer.

Soil sampling and analysis

Soil samples were collected from control treatments to a depth of 20 cm on May 12th, 2006 using a stainless steel push probe. Fifteen samples were randomly collected from each control plot, and combined for a composite sample. These samples were extracted for inorganic N using 2 *M* KCl and a Lachat Flow Injection Ion Analyzer (Lachat Instruments, 1992, 1993). The same method of sampling and analysis was repeated on June 14th, 2006 and included the urea and PCU treatments.

In 2007 soils were sampled in the same manner. The control plots were sampled on May 22, 2007, and all plots were sampled on June 8, 2007. Gravimetric soil water content was collected from 0 to 20 cm deep. Six soil samples were collected and composited every 18 m starting from the summit position, then eight more were taken from the approximate start of the footslope position every 9 m for a total of 14 data points in each transect.

Grain harvest, silage harvest, N-uptake and NRE

Grain was harvested on September 29th, 2006 from the two middle maize rows of the six total rows using a 2-row plot combine equipped with a weigh-bin and moisture tester. Each harvested row was 10 m in length. All grain yields are expressed on a dry-weight basis.

Total above ground plant biomass was collected from one 10 m maize row in each plot on September 5th, 2006 after the maize had reached physiological maturity. This material was chopped using a Vermeer® (Vermeer Corp., Pella, IA) brush chipper. Sub-samples were collected from the chopped bulk row material, weighed and dried at 60°C and then reweighed to determine moisture content. The dried samples were ground using a Thomas-Wiley® mill to pass a 1 mm sieve. The samples were then analyzed for total Kjeldahl N (TKN [Lachat Instruments, 1992, 1993]) using a block digestor and a flow-injection analyzer (FIA) to determine N uptake and nitrogen recovery efficiency (NRE).

The following are equations used to calculate N uptake and NRE:

$$N\ uptake = (Harvested\ silage\ wt.) * \frac{(\%\ silage\ N\ content)}{100}$$

[3.2.]

$$NRE = \frac{N\ uptake_{(+\ N\ source)} - N\ uptake_{(-\ N\ source)}}{Total\ N\ added * 100}$$

This process was repeated in 2007 with grain harvested on September 24th, 2007 and silage harvested on September 4th, 2007.

Statistical analysis

All data were analyzed using the SAS statistical software (SAS Institute, 1988).

Analysis of variance (ANOVA) was conducted using PROC GLM and the multiple comparison test used was Duncan's Multiple Range Test (DMRT) to test for statistical differences among the treatment means at $p \leq 0.05$.

RESULTS AND DISCUSSION

Rainfall

Recorded precipitation in the study area during the 2006 growing season differed from precipitation received during the 2007 season (Figure 3.2). From planting to grain harvest in 2006, 629 mm of precipitation was received, in contrast to the 2007 season from time of planting to grain harvest, only 487 mm of precipitation was received. On June 11 and 12, 2006 a total of 147 mm of precipitation was recorded. This large amount of precipitation over a relatively short amount of time caused severe erosion of sediment from CS1. CS2 and CS3 were not visually affected by this event, probably due to the no-till management providing greater surface residue, which dispersed water droplet impact and reduced lateral flow of water. This heavy rainfall event may have caused variability in crop response to N among cropping systems, especially between the tilled (i.e., CS1) and no-tilled (i.e., CS2 and CS3) cropping systems.

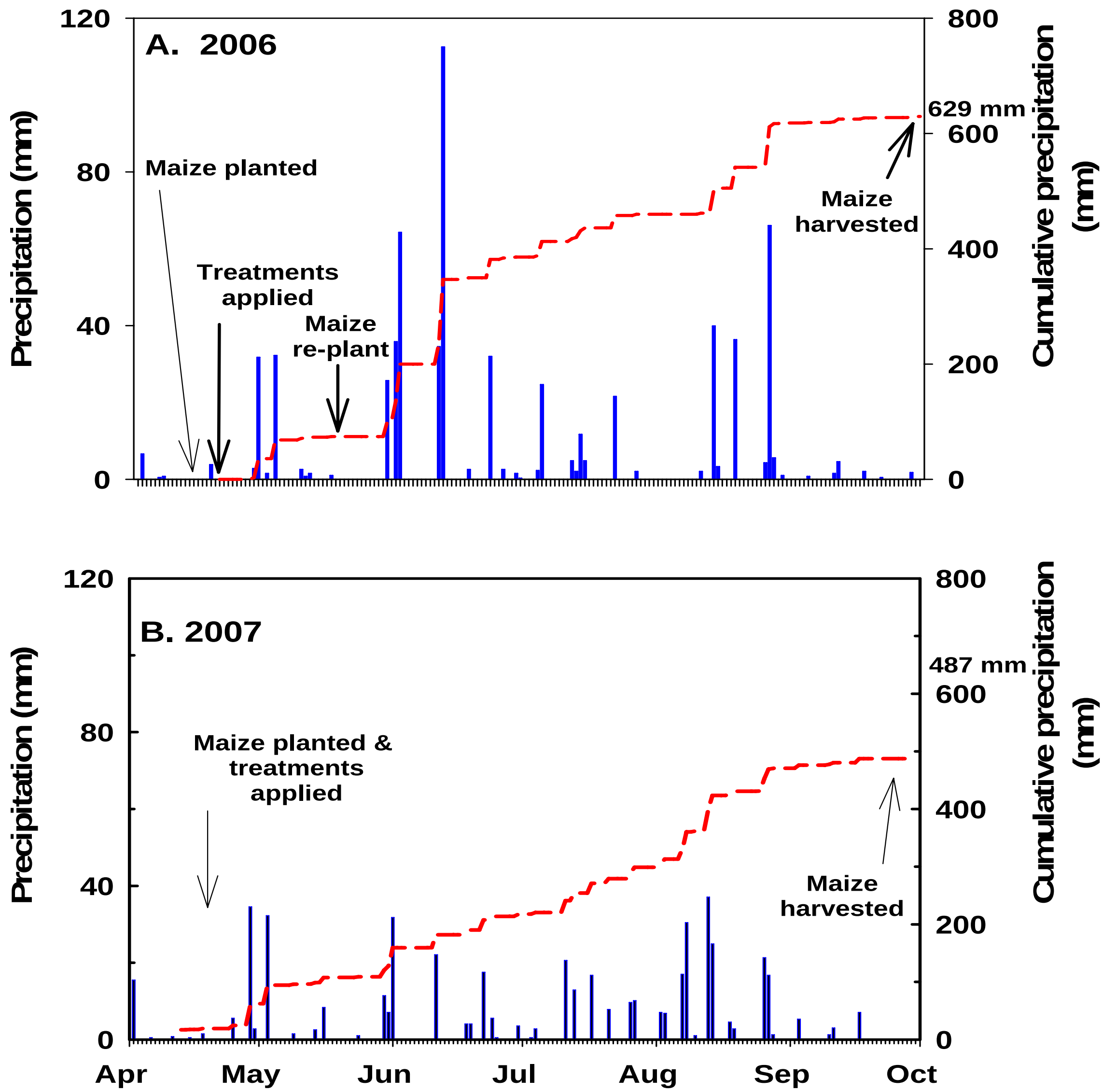

Figure 3.2 Precipitation data from 2005 and 2006 at the Centralia site in north central Missouri. The bars represent daily rainfall events. The dashed line is cumulative rainfall from time of planting to the grain harvest date.

Initial soil characteristics

Initial soil characteristics in 2006 showed a greater amount of exchangeable Ca, Mg, and K in the sideslope landscape position over the footslope and summit positions in CS2 and CS3 (Table 3.1). This is probably due to the shallower depth to claypan in this landscape position. Extracted samples in the sideslope were probably higher in clay content than the other two landscape positions. Percent organic matter and CEC in the sideslope position of CS3 was 0.9- and 0.8% higher in organic matter, respectively, and CEC was 9 and 7 $cmol_c\ kg^{-1}$, respectively, greater than the footslope and summit positions. Neutralizable acidity in this position was significantly greater than at the footslope, but not at the summit position.

Again in 2007, exchangeable Ca and Mg were significantly higher in the sideslope position, than the summit or footslope in CS2 and CS3 (Table 3.2). Soil K was significantly higher by 44- and 41 $mg\ kg^{-1}$, respectively, in the sideslope than summit or footslope in CS2 only. Soil CEC was also significantly higher in the sideslope than the summit and footslope positions for CS2 by 5.2- and 5.0 $cmol_c\ kg^{-1}$, respectively, and for CS3 by 8.3- and 7.3 $cmol_c\ kg^{-1}$, respectively. Neutralizable acidity was 1.5 $cmol_c\ kg^{-1}$ higher in the sideslope than the footslope in only CS3. The wheat in the cropping system appears to be causing an increase in these properties at the sideslope position. Increased plant residues may attribute to these increases. Claypans layers often contain higher amounts of base cations compared to the topsoil (Bray, 1935) which would explain these differences.

Table 3.1 Initial soil characteristics in 2006 at the Centralia site from a depth of 0-20 cm due to differences in cropping system and landscape position.

Cropping System	Landscape Position	pH	Bulk Density	Org. matter	Neut. acidity	CEC	Bray I P	Exchangeable Ca	Exchangeable Mg	Soil test K	Inorganic N NO_3^--N	Inorganic N NH_4^+-N
			Mg m^{-3}	- % -	-- $cmol_c$ kg^{-1} --		mg kg^{-1}					
1 (Min.Till C/S)	Summit	6.3	1.28	1.9	1.7	15	36	4477	481	273	9.3	6.6
	Side Slope	6.3	1.22	2.1	2.2	21	65	5893	863	413	18.0	9.0
	Footslope	6.9	1.29	2.0	0.2	16	68	5423	530	312	15.9	12.8
	DMRT $_{(0.05)*}$	NS	0.02	NS	NS	NS	NS	1403	NS	NS	NS	NS
2 (No-Till C/S)	Summit	5.7	1.33	2.1	3.5	17	52	4304	564	313	3.6	7.8
	Side Slope	6.0	1.25	2.3	3.5	25	58	6424	1060	471	4.9	9.1
	Footslope	6.5	1.41	1.9	1.7	15	40	4814	470	251	4.8	7.4
	DMRT $_{(0.05)}$	0.7	0.09	NS	NS	NS	NS	1761	567	213	NS	NS
3 (No-Till C/S/W)	Summit	5.8	1.36	2.3	3.3	18	47	4595	568	299	8.8	7.5
	Side Slope	5.8	1.36	3.1	3.7	25	49	6318	1124	445	11.8	9.6
	Footslope	6.2	1.40	2.2	2.0	16	45	4794	515	301	12.1	8.4
	DMRT $_{(0.05)}$	0.3	NS	0.6	1.0	2	NS	656	191	52	NS	NS

*Duncan's Multiple Range Test (P≤ 0.05); NS = not significant

Table 3.2 Initial soil characteristics in 2007 at the Centralia site from a depth of 0 - 20 cm due to differences in cropping system and landscape position.

								Exchangeable			Inorganic N	
Cropping System	Landscape Position	pH	Bulk density	Org. matter	Neut. acidity	CEC	Bray I P	Ca	Mg	Soil test K	NO_3^--N	NH_4^+-N
			Mg m^{-3}	-%-	- $cmol_c$ kg^{-1} -		---------- mg kg^{-1} ----------					
1 (Min.Till C/S)	Summit	6.1	1.28	1.9	2.0	13.6	19	1891	433	99	2.0	16.5
	Side Slope	6.2	1.22	2.1	2.3	16.2	18	2257	559	102	2.5	9.5
	Footslope	6.6	1.29	2.0	1.0	14.4	19	2258	449	88	1.5	5.0
	DMRT $_{(0.05)*}$	NS	0.02	NS	NS	NS	NS	NS	NS	NS	NS	NS
2 (No-Till C/S)	Summit	6.1	1.33	1.9	2.3	14.7	17	2073	416	90	0.3	7.7
	Side Slope	6.2	1.25	2.3	2.5	19.9	20	2801	738	134	1.3	9.0
	Footslope	6.3	1.41	2.5	1.8	14.9	17	2189	453	93	2.7	11.0
	DMRT $_{(0.05)}$	NS	0.09	NS	NS	4.7	NS	660	247	26	NS	NS
3 (No-Till C/S/W)	Summit	6.1	1.36	1.9	2.3	14.5	16	2022	434	95	1.7	8.0
	Side Slope	6.1	1.36	2.4	3.0	22.8	16	3089	959	157	3.0	9.3
	Footslope	6.5	1.40	2.2	1.5	15.5	16	2330	507	112	5.7	6.0
	DMRT $_{(0.05)}$	NS	NS	0.4	1.2	4.9	NS	605	362	NS	NS	NS

*Duncan's Multiple Range Test ($P \leq 0.05$); NS = not significant

Gravimetric soil water content data showed the sideslope tended to be the wettest landscape position (Figure 3.3). The sideslope and summit positions of CS1 and CS2 in 2006 were significantly higher in soil water content than the footslope position by 4.7- and 4.6%, respectively in CS1 and 3.5- and 2.5%, respectively in CS2. The sideslope and summit positions of CS2 in 2007 were significantly higher in soil water content than the footslope position by 5.5- and 5.2%, respectively. The sideslope position in CS1 in 2007 was 4.5% greater than the footslope and 4.6% greater than the summit position. The sideslope position in CS3 showed 2.3 and 4.1% higher water content than the summit and footslopes positions, respectively, and the summit position was 1.8% higher water content than the footslope position in 2006. In 2007 the sideslope and summit positions of all three cropping systems were significantly higher in water content than the footslope positions.

Figure 3.4 shows a topsoil depth to claypan map, which was derived from EC_a data. This map shows the sideslope position is the shallowest position to the claypan, meaning the water content samples from this position were higher in clay content than the summit or footslope. These samples were taken two days after rainfall, or at about field capacity. The clays most likely were able to hold moisture better than the footslope and summit in some cases, resulting in the sideslope predominately being the wettest landscape position. The summit position is the next shallowest position to the claypan, which is probably why it also had significantly higher water content than the footslope.

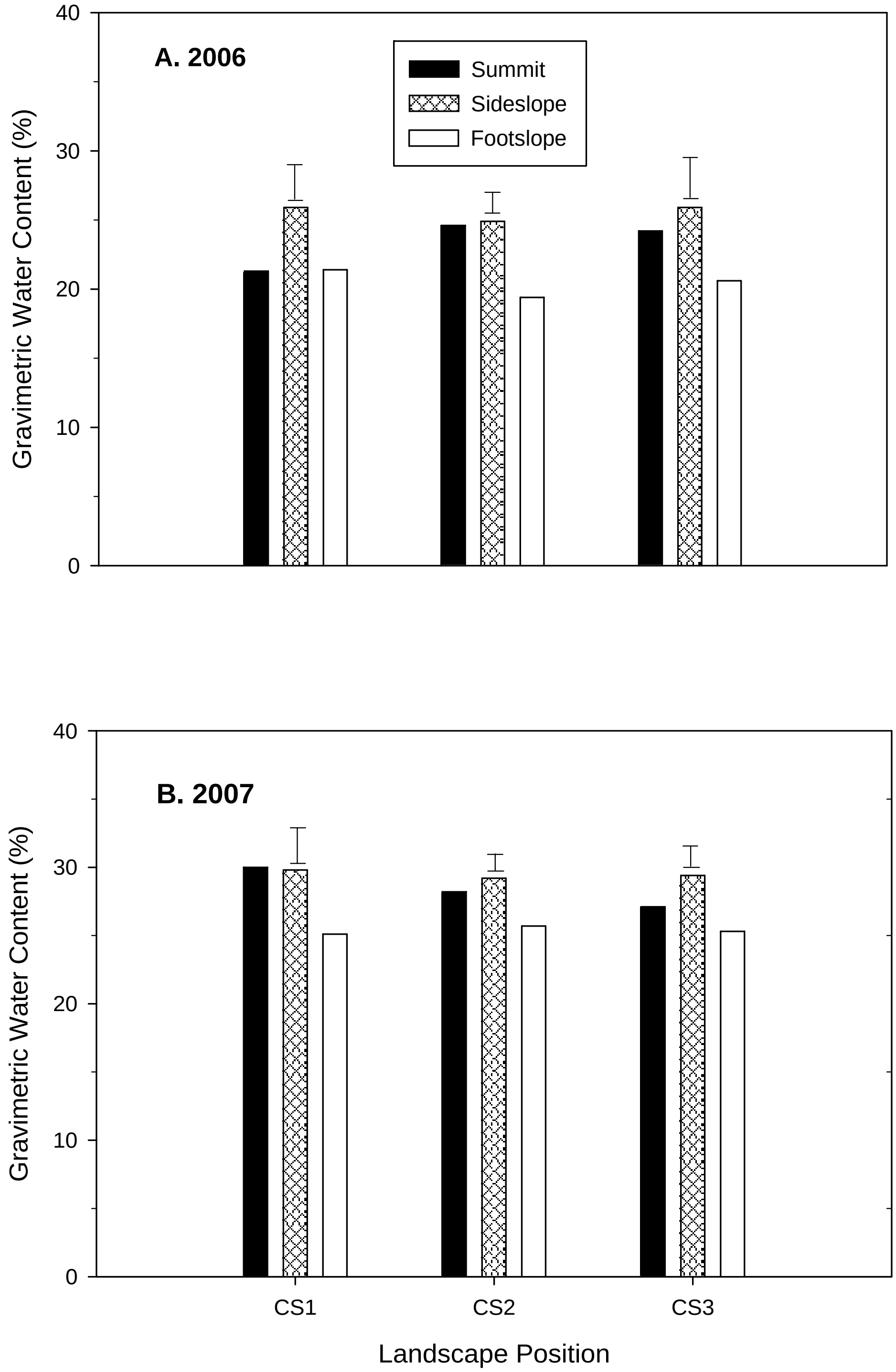

Figure 3.3 Gravimetric soil water content collected from 0 to 20 cm deep from each cropping system and landscape position in A. 2006 and B. 2007. CS1 was minimum till Maize/Soybean rotation, CS2 was no-till Maize/Soybean rotation, and CS3 was no-till Maize/Soybean/Wheat rotation.

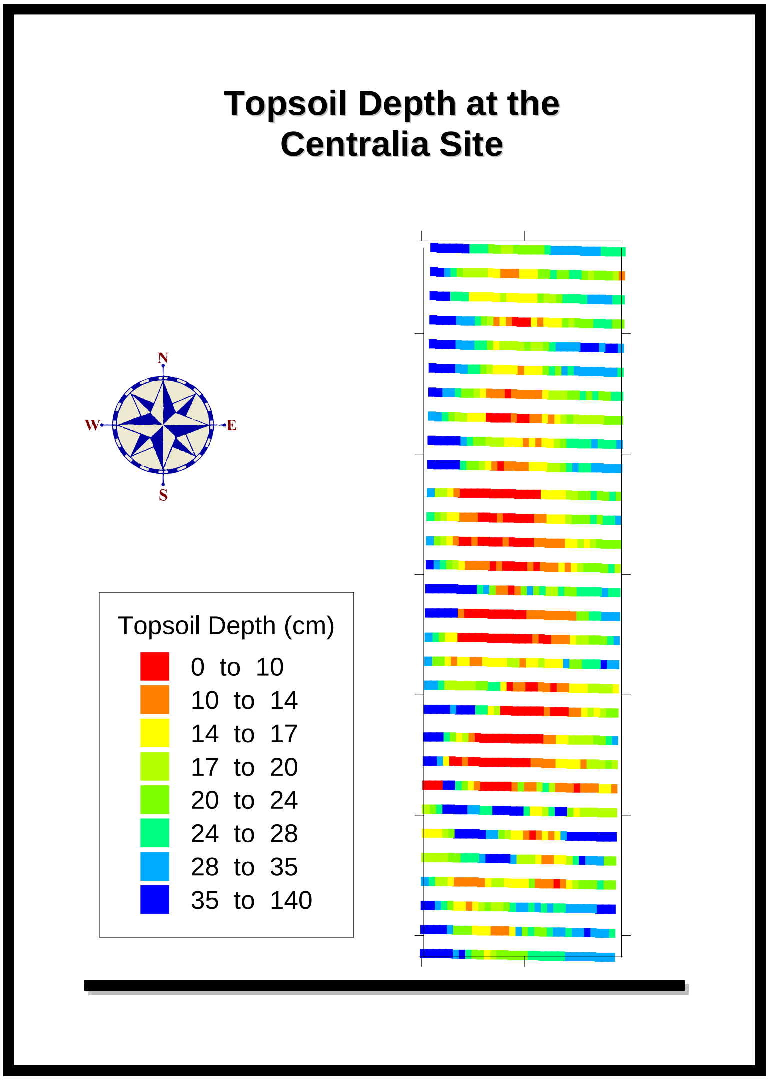

Figure 3.4 Topsoil depth as derived from apparent electrical conductivity (EC_a) measured on the experimental site near Centralia.

In-season soil N

Soil N sampling during the 2006 growing season revealed that the summit position of CS1 under PCU treatment contained 2.1 mg kg^{-1} greater amount of NH_4^+-N than the urea treatment in the same landscape positions and cropping system (Table 3.3). The urea treatment in CS1 was 6.0 mg kg^{-1} greater at the sideslope position than at the summit. At the footslope under PCU treatment NH_4^+-N was significantly higher by 3.7 mg kg^{-1} in CS1 over CS2. Similarly, the control treatment at the footslope position in CS1 was 2.6 mg kg^{-1} greater in NH_4^+-N than CS3. The sideslope for the control and urea treatments was 1.2- and 2.5 mg kg-1 greater than the summit for the control and urea treatments respectively for NH_4^+-N in CS3. The summit position in CS1 in both urea and PCU treatments was significantly higher in NO_3^--N than the control treatment by 26.4- and 28.2 mg kg^{-1}, respectively. The footslope position in CS1 was higher in NO_3^--N under urea treatment than the control by 27.5 mg kg^{-1}, but the PCU treatment was not. Urea and PCU treatments in the sideslope and footslope positions in CS2 were significantly higher in NO_3^--N than the control treatments. In CS3, PCU treatment at the summit position was 32.1 mg kg^{-1} higher in NO_3^--N than the control, but the urea treatment was not significantly different from the control. The PCU treatment at the sideslope and footslope positions in CS3 was higher in NO_3^--N than both the urea and control treatments by 47- and 54.5 mg kg^{-1}, respectively, at the sideslope, and by 53.9- and 57.2 mg kg$_{-1}$, respectively at the footslope. The sideslope position under urea treatment in CS2 was 27.6 mg kg^{-1} higher in NO_3^--N than the sideslope position under urea treatment in CS3. The footslope position of CS3 was 49.3- and 44.2 mg kg^{-1} higher in NO_3^--N than the footslope positions in CS1 and CS2, respectively.

Similar to 2006, the summit position under PCU treatment in CS1 contained 23.6 mg kg^{-1} greater NH_4^+-N than the urea treatment in 2007 (Table 3.4.). PCU in the summit position in CS1 was 20.5- and 24.7 mg kg^{-1} higher in NH_4^+-N than the summit positions in CS2 and CS3, respectively. The urea treatment at the summit in CS2 contained 9.9- and 21.2 mg kg^{-1} higher NO_3^--N than the PCU and control treatments, respectively. Urea was 16 mg kg^{-1} higher in NO_3^--N than the control treatment at the summit position in CS3. Urea and PCU were 19.5- and 15.6 mg kg^{-1} higher in NO_3^--N than the control treatment at the footslope in CS3, respectively. The footslope position of the control treatment in CS1 was 12.4- and 9.9 mg kg^{-1} higher in NO_3^--N than in CS2 or CS3, respectively. The footslope position under PCU treatment in CS1 was 30.0- and 13.8 mg kg^{-1} higher in NH_4^+-N than the footslope positions under PCU treatment in CS2 and CS3, respectively. The footlope position under PCU treatment in CS3 was 16.2 mg kg^{-1} higher in NO_3^--N than the footslope position under PCU treatment in CS2.

Table 3.3 Differences in soil inorganic N sampled on July 13, 2006 from a depth of 0-20 cm due to the effects of cropping system, landscape position, and N fertilizer source.

Cropping System	Landscape Position	Soil NH_4^+-N Control	Urea	PCU	DMRT $_{(0.05)}$	Soil NO_3^--N Control	Urea	PCU	DMRT $_{(0.05)}$
		mg kg^{-1}							
1	Summit	4.0	3.0	5.1	1.9	12.5	38.9	40.7	17.3
(Min.Till	Sideslope	7.1	9.0	7.4	NS	11.0	22.9	31.4	NS
C/S)	Footslope	5.2	5.4	5.5	NS	10.3	37.8	25.5	26.0
	DMRT $_{(0.05)}$*	NS	4.6	NS		NS	NS	NS	
2	Summit	2.3	2.7	3.4	NS	8.0	31.4	58.8	NS
(No-Till	Sideslope	5.7	4.8	5.2	NS	6.9	42.6	33.0	24.1
C/S)	Footslope	3.0	4.9	1.8	NS	8.5	51.6	30.6	22.0
	DMRT $_{(0.05)}$	NS	NS	NS		NS	NS	NS	
3	Summit	2.1	2.2	2.2	NS	6.5	22.2	38.6	29.2
(No-Till	Sideslope	3.3	4.7	4.7	NS	7.5	15.0	62.0	40.0
C/S/W)	Footslope	2.6	3.5	2.6	NS	17.6	20.9	74.8	48.1
	DMRT $_{(0.05)}$	0.9	2.1	NS		NS	NS	NS	
Cropping	Summit	NS	NS	NS		NS	NS	NS	
System	Sideslope	NS	3.2	NS		NS	26.8	NS	
DMRT $_{(0.05)}$	Footslope	2.4	NS	3.0		NS	NS	40.0	

*Duncan's Multiple Range Test (P≤ 0.05); NS = not significant

Table 3.4 Differences in soil inorganic N sampled on June 8, 2007 from a depth of 0-20 cm due to the effects of cropping system, landscape position, and N fertilizer source.

Cropping System	Landscape Position	Soil NH_4^+-N Control	Urea	PCU	DMRT $_{(0.05)}$	Soil NO_3^--N Control	Urea	PCU	DMRT $_{(0.05)}$
		----- mg kg^{-1} -----							
1 (Min.Till C/S)	Summit	4.0	4.2	27.8	6.3	19.4	37.4	26.2	NS
	Sideslope	2.9	6.8	11.0	NS	11.6	32.5	30.2	NS
	Footslope	4.3	4.6	12.0	NS	16.7	38.6	36.2	NS
	DMRT $_{(0.05)*}$	NS	NS	NS		NS	NS	NS	
2 (No-Till C/S)	Summit	3.3	4.3	7.3	NS	13	34.1	24	8.0
	Sideslope	4.0	5.0	37.1	NS	16.3	31.6	23.7	NS
	Footslope	4.3	8.6	6.2	NS	4.3	8.6	6.2	NS
	DMRT $_{(0.05)}$	NS	NS	NS		NS	NS	NS	
3 (No-Till C/S/W)	Summit	4.3	4.5	3.1	NS	11	27	18.9	11.0
	Sideslope	3.4	2.7	16.0	NS	12	25.5	24.4	NS
	Footslope	2.4	5.7	6.0	NS	6.8	26.3	22.4	13.0
	DMRT $_{(0.05)}$	NS	NS	NS		NS	NS	NS	
Cropping System DMRT $_{(0.05)}$	Summit	NS	NS	8.5		NS	NS	NS	
	Sideslope	NS	NS	NS		NS	NS	NS	
	Footslope	NS	NS	NS		6.1	NS	13.0	

*Duncan's Multiple Range Test ($P \leq 0.05$); NS = not significant

Silage and grain yield

The urea treatment in the footslope position of CS3 in the 2006 growing season significantly increased silage yield over PCU and the control treatments (Table 3.5). No other urea/PCU comparisons showed significantly differences in 2006. No significant differences were observed among fertilizer treatments for silage yields in CS1 in 2006. The summit and footslope positions in CS2 were significantly higher in silage yield under PCU and urea treatments than the control treatments due to the addition of N fertilizer. The summit and sideslope positions under PCU and urea treatments in CS3 were significantly higher in silage yield than the control treatments due to addition of N fertilizer. The urea treatment in the fooslope position of CS3 produced 3.3- and 5.0 Mg ha^{-1} higher silage yields than the PCU and control treatments, respectively. Furthermore, the urea treatment at the CS3 footslope was 5.0 Mg ha^{-1} higher than the control treatment. In CS2 the footslope position under PCU treatment produced higher silage yield than the sideslope. In CS3 the footslope position under control treatment produced 3.1 Mg ha^{-1} higher silage yield than the summit position, and the summit position produced 2.7 Mg ha^{-1} higher silage yield than the sideslope position under PCU treatment. The summit position in CS3 under PCU treatment was higher in silage yield than the summit positions in CS1 by 4.0 Mg ha^{-1}.

In 2007, only the PCU treatment in CS3 was higher in silage yield than the control treatment at the summit position by 3.2 Mg ha^{-1}; however, both the PCU and urea treatments were higher in silage yield at the sideslope position in CS3 than the control treatment by 4.3- and 4.2 Mg ha^{-1}, respectively. The footslope in CS2 was 2.5 Mg ha^{-1}

higher in silage yield than the sideslope under the urea treatment. The sideslope position in CS1 in the control was higher in silage yield than the sideslope position in CS2 and CS3 by 3.4- and 6.3 Mg ha^{-1}, respectively. The summit position under the urea treatment in CS1 was higher in silage yield than CS3 by 6.1 Mg ha^{-1}.

In 2006 in CS2 at the footslope position, PCU grain yield was 1520 kg ha^{-1} greater than urea grain yield (Table 3.5.). Grain yield under the urea treatment in the sideslope position of CS2 was 2186- and 4250 kg ha^{-1} greater than grain yield under PCU and control treatments, respectively. Grain yield under the urea treatment in the sideslope in CS3 was 2130 kg ha^{-1} higher than grain yield under the control treatment. The urea and PCU treatments were higher in grain yield than the control treatment in CS2 and CS3 in the summit positions by 3675- and 2732 kg ha^{-1}, respectively in CS2, and 2407- and 2196 kg ha^{-1}, respectively in CS3. In CS1 at the summit position the urea treatment was lower in grain yield than both CS2 and CS3 by 2163- and 2553 kg ha^{-1}, respectively. The control treatment in CS3 at the footslope was higher in grain yield than the control treatment at the footslope in CS2 by 2601 kg ha^{-1}. Grain yield under the PCU treatment in CS2 was 4235 kg ha^{-1} higher in the footslope than CS1 at the footslope.

In 2007, the only significant treatment differences in grain yield occurred in CS3. PCU treatment resulted in higher grain yield than the control treatment in the summit position by 2423 kg ha^{-1}, PCU and urea treatments resulted in higher grain yields than the control treatment in the sideslope position by 2211- and 1624 kg ha^{-1}, respectively, and PCU and urea treatments resulted in higher grain yields than the control treatment in the footslope position in CS3 by 2976- and 2667 kg ha^{-1}, respectively. PCU treatment at the footslope position resulted in higher grain yield than PCU treatment at the summit position in CS3 by 1301 kg ha^{-1}. In 2007 the control treatment grain yield in CS1 was higher than the control treatment grain yield in CS2 by 2739 kg ha^{-1}, and CS2 was higher than the control treatment in CS3 by 1155 kg ha^{-1}. The control treatment grain yield in CS1 was 1732 kg ha^{-1} higher than the control treatment grain yield in CS3 at the footslope position. The large amount of variability in maize silage and grain yields was probably due to the variability in soil water content throughout the plots, causing random maize N response to the treatments.

Table 3.5 Silage yields from the 2006 and 2007 growing seasons.

Cropping System	Landscape Position	2006 Control	2006 Urea	2006 PCU	2006 DMRT (0.05)*	2007 Control	2007 Urea	2007 PCU	2007 DMRT (0.05)*
		Mg ha^{-1}							
1 (Min.Till C/S)	Summit	9.3	10.3	11.2	NS	9.6	14.4	7.4	NS
	Sideslope	7.9	8.8	11.6	NS	11.9	9.4	11.8	NS
	Footslope	10.7	14.3	13.6	NS	7.2	13.3	8.0	NS
	DMRT0.05)*	NS	NS	NS		NS	NS	NS	
2 (No-Till C/S)	Summit	6.5	16.3	14.9	6.7	9.5	10.5	9.5	NS
	Sideslope	6.1	10.5	9.7	NS	8.5	8.3	11.8	NS
	Footslope	9.1	16.8	17.0	4.8	8.6	10.8	9.0	NS
	DMRT (0.05)	NS	NS	3.0		NS	2.2	NS	
3 (No-Till C/S/W)	Summit	9.2	13.0	15.2	2.7	7.0	8.3	10.2	2.9
	Sideslope	10.1	14.3	12.5	3.4	5.6	9.8	9.9	3.6
	Footslope	12.3	17.3	14.0	2.3	6.7	10.5	10.6	NS
	DMRT (0.05)	2.2	NS	1.8		NS	NS	NS	
Cropping System DMRT(0.05)	Summit	NS	NS	3.8		NS	2.8	NS	
	Sideslope	NS	NS	NS		4.1	NS	NS	
	Footslope	NS	NS	NS		NS	NS	NS	

*Duncan's Multiple Range Test (P≤ 0.05); NS = not significant

Table 3.6 Grain yields from the 2006 and 2007 growing seasons.

Cropping System	N Treatment	2006 Summit	2006 Sideslope	2006 Footslope	2006 $DMRT_{(0.05)}$*	N Treatment	2007 Summit	2007 Sideslope	2007 Footslope	2007 $DMRT_{(0.05)}$
		kg ha^{-1}					kg ha^{-1}			
1 Min. Till C/S	Control	4130	2943	4178	NS	Control	6560	4146	5146	NS
	Urea	4357	3073	6081	NS	Urea	5512	6127	6609	NS
	PCU	4943	4065	6227	NS	PCU	5048	6658	5756	NS
	$DMRT_{(0.05)*}$	NS	NS	NS		$DMRT_{(0.05)}$	NS	NS	NS	
2 No-Till C/S	Control	2845	1627	3870	NS	Control	3821	3301	4016	NS
	Urea	6520	5877	8942	NS	Urea	5577	5121	5333	NS
	PCU	5577	3691	10462	NS	PCU	5333	4894	6113	NS
	$DMRT_{(0.05)}$	1295	1667	1383		$DMRT_{(0.05)}$	NS	NS	NS	
3 No-Till C/S/W	Control	4503	4731	6471	NS	Control	2666	3122	3414	NS
	Urea	6910	6861	7073	NS	Urea	4715	4764	6081	NS
	PCU	6699	6373	8276	NS	PCU	5089	5333	6390	1113
	$DMRT_{(0.05)}$	1995	1985	NS		$DMRT_{(0.05)}$	2112	1523	958	
Cropping System $DMRT_{(0.05)}$	Control	NS	NS	2475		Control	960	NS	1640	
	Urea	513	NS	NS		Urea	NS	NS	NS	
	PCU	NS	NS	2462		PCU	NS	NS	NS	

*Duncan's Multiple Range Test (P≤ 0.05); NS = not significant

N uptake and NRE

Nitrogen recovery efficiency (NRE) in 2006 with PCU treatment at the summit position in CS2 was 24% greater than urea (Table 3.7). The urea and PCU treatments at the summit position in CS1 were 45- and 38 kg ha^{-1} greater in N uptake than the control treatment, respectively. Urea and PCU treatments at the summit and footslope positions in CS2 were higher in N uptake than the control treatments by 53- and 93 kg ha^{-1}, respectively for the summit, and 87- and 71 kg ha^{-1}, respectively at the footslope. N uptake under urea treatment was 38 kg ha^{-1} greater than the control treatment in the sideslope of CS2. N uptake under PCU treatment was 30 kg ha^{-1} greater than urea in N uptake at the summit position in CS3, and urea was 28 kg ha^{-1} greater than the control in the summit in CS3. Urea was 47- and 67 kg ha^{-1} greater than the control in N uptake in the sideslope and footslope positions of CS3, respectively.

Nitrogen recovery efficiency under the PCU treatment in CS3 at the summit position in 2007 was 30% greater than urea (Table 3.8). Nitrogen uptake under the urea treatment at the summit position in CS1 was 96 kg ha^{-1} greater than the control treatment. Nitrogen uptake under the PCU treatment at the sideslope position in CS2 was 59- and 56 kg ha^{-1} greater than N uptake under the urea and control treatments, respectively. Nitrogen uptake under the PCU treatment at the summit position in CS3 was 55- and 56 kg ha^{-1} greater than N uptake under the urea and control treatments.

Table 3.7 Silage N content, N uptake, and N recovery efficiency (NRE) from 2006.

Cropping System	Landscape Position	N treatment	Tissue N Content	N uptake	NRE
			- % -	kg ha^{-1}	- % -
1 (Min. Till C/S)	Summit	Control	0.5	44	--
		Urea	0.9	89	27
		PCU	0.7	82	23
		$DMRT_{(0.05)}$*	0.1	27	NS
	Sideslope	Control	0.5	42	--
		Urea	0.5	63	18
		PCU	0.8	90	29
		$DMRT_{(0.05)}$	NS	NS	NS
	Footslope	Control	0.6	60	--
		Urea	0.7	96	21
		PCU	0.8	105	27
		$DMRT_{(0.05)}$	NS	NS	NS
2 (No-Till C/S)	Summit	Control	0.5	34	--
		Urea	0.6	87	32
		PCU	0.9	127	56
		$DMRT_{(0.05)}$	0.1	47	24
	Sideslope	Control	0.7	39	--
		Urea	0.8	77	23
		PCU	0.6	57	11
		$DMRT_{(0.05)}$	NS	36	NS
	Footslope	Control	0.5	45	--
		Urea	0.8	132	52
		PCU	0.9	116	42
		$DMRT_{(0.05)}$	0.3	62	NS
3 (No-Till C/S/W)	Summit	Control	0.5	49	--
		Urea	0.6	77	17
		PCU	0.7	107	34
		$DMRT_{(0.05)}$	NS	23	NS
	Sideslope	Control	0.4	41	--
		Urea	0.6	88	27
		PCU	0.7	85	26
		$DMRT_{(0.05)}$	0.2	35	NS
	Footslope	Control	0.5	67	--
		Urea	0.8	134	39
		PCU	0.7	96	17
		$DMRT_{(0.05)}$	NS	51	NS

*Duncan's Multiple Range Test ($P < 0.05$); NS = not significant

Table 3.8 Silage N content, N uptake and N recovery efficiency (NRE) from 2007.

Cropping System	Landscape Position	N treatment	Tissue N content	N uptake	NRE
			- % -	kg ha^{-1}	- % -
		Control	0.7	65.0	--
1	Summit	Urea	1.1	160.7	52.0
(Min. Till		PCU	0.9	68.2	14.0
C/S)		$DMRT_{(0.05)}$	NS	87.5	NS
		Control	0.6	73.0	--
	Sideslope	Urea	0.9	84.5	18.5
		PCU	1.0	111.8	37.0
		$DMRT_{(0.05)}$	NS	NS	NS
		Control	0.6	44.9	--
	Footslope	Urea	0.8	103.9	32.0
		PCU	1.1	89.2	9.5
		$DMRT_{(0.05)}$	NS	NS	NS
		Control	0.8	74.9	--
2	Summit	Urea	0.7	73.1	19.0
(No-Till		PCU	0.9	82.9	21.0
C/S)		$DMRT_{(0.05)}$	NS	NS	NS
		Control	0.6	46.7	--
	Sideslope	Urea	0.5	43.8	4.0
		PCU	0.9	102.7	28.5
		$DMRT_{(0.05)}$	NS	55.3	NS
		Control	0.5	38.1	--
	Footslope	Urea	0.7	71.6	8.5
		PCU	0.8	73.0	18.3
		$DMRT_{(0.05)}$	0.4	NS	NS
		Control	0.6	43.4	--
3	Summit	Urea	0.6	44.2	5.0
(No-Till		PCU	1.0	99.2	35.0
C/S/W)		$DMRT_{(0.05)}$	0.1	15.8	6.5
		Control	0.6	36.5	--
	Sideslope	Urea	0.6	62.2	10.7
		PCU	0.7	69.9	18.7
		$DMRT_{(0.05)}$)	NS	NS	NS
		Control	0.6	36.9	--
	Footslope	Urea	0.7	70.0	17.0
		PCU	0.7	79.1	23.2
		$DMRT_{(0.05)}$	NS	NS	NS

*Duncan's Multiple Range Test ($P < 0.05$); NS = not significant

Grain yield differences among treatments and landscape positions were minimal and did not show a consistent higher yield response for the PCU treatment compared to the urea treatment at the low-lying position as was observed in a field experiment at the Greenley Research Center in Northeast Missouri (see Chapter 2 in this thesis). This is probably because the footslope position at the Centralia site of this study was not a true footslope. The lowest portion of the landscape in the experimental area continues its gradual incline past the plot border and eventually to the Goodwater Creek. The designated footslope position may behave more like a sideslope, meaning water drainage may continue laterally from the plot area. If water is able to drain from this area, then it is not frequently wet during the growing season as was observed at the Greenley site, and would not cause a PCU fertilizer effect of increased grain yields, similar to that seen at the Greenley site.

Grain yield among cropping systems in 2006 tended to show higher grain yields in CS2 and CS3, which were the tilled plots. This may have been due to the heavy rainfall that eroded topsoil during the early part of the growing season. In a two-year study, Medeiros et al. (2006) observed no average grain yield increase when using polymer- or gel-coated urea, compared to conventional urea in a no-till maize study. They did not take into account landscape position. Observations of broadcast compared to injected or incorporated urea showed no significant differences.

CONCLUSIONS

Differences in spatial variation across the study site, along with misapplication of N fertilizer in 2007 caused crop N response variability in this study. The footslope position relatively held less soil gravimetric water content at the 0 to 20 cm depth than the other landscape positions, which possibly contributed to the lack of crop N response differences between the treatments.

Increases in silage yield, grain yield, or N uptake at the sideslope position were due to this landscape position being shallower to the claypan, which caused increased Ca, Mg, K, and CEC. This landscape position also had the highest gravimetric soil water content, which also contributed to increased crop yield in 2006. The lack of excessive water in this cropped landscape caused minimal crop response to N fertilizer treatments, unlike results from the Greenley experiment.

Further research into the relationships between landscape elevation variability, topsoil depth to the claypan, and soil infiltration and drainage variability, and silage and grain yield, and NRE is needed to successfully delineate field areas that may be more suitable for enhanced efficiency fertilizers than conventional fertilizers.

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CHAPTER 4

GIS-BASED ASSESSMENT OF SPATIAL ENVIRONMENTAL VARIABILITY POTENTIALLY AFFECTING MAIZE N FERTILIZER USE EFFICIENCY AND GRAIN YIELD ACROSS CROPPED LANDSCAPES

ABSTRACT

Cropped landscapes can exhibit a great deal of environmental variability in topography and soil characteristics. This spatial variability can cause decreased nitrogen (N) fertilizer use efficiency and reduce grain yields in maize (*Zea mays L.*). The objective of this study was to use geographic information systems (GIS) to gather, compile, and assess spatial environmental variability that leads to reduction in maize N fertilizer use efficiency and grain yield. A two-year maize N fertilizer response study was established in 2005 at the Greenley Memorial Research Center in northeast Missouri (i.e., Greenley). Elevation, soil apparent electrical conductivity (EC_a) and gravimetric soil water content data were collected and mapped using a GIS. The study contained five treatments, including anhydrous ammonia, polymer-coated urea (PCU), urea, 50%PCU/50%urea mix, and a control, which were applied in strips across a summit, sideslope, and low-lying landscape position. A second two-year maize N fertilizer response study was established in 2006 at the USDA Agricultural Research Service Cropping Systems and Water Quality Research Unit (USDA-ARS-CSWQRU) experiment station in north central Missouri (i.e., Centralia). The study contained three N fertilizer treatments, including PCU, urea, and a control. The fertilizer treatments were within three different cropping systems that were randomly organized into three replications. Elevation, gravimetric soil water content, EC_a, and grain yield data were

collected and mapped to assess possible interactions between these variables. The Greenley site showed increased water content and increased depth to the claypan in the low-lying landscape position, along with a grain yield increase under PCU and anhydrous ammonia treatments. The Centralia site showed no clear pattern in maize N fertilizer response due to a lack of water collection at the footslope landscape position.

INTRODUCTION

Nitrogen (N) is the primary limiting nutrient for maize (*Zea mays* L.) production. Excessive N loss into the environment and increasing N fertilizer prices have stimulated interest in improving maize N recovery efficiency (NRE). Observed variation in NRE, crop yields, and environmental N loss across agricultural landscapes may warrant the implementation of fertilizer application strategies that take this variation into account. The strategic use of enhanced efficiency fertilizers (EEF) may be one method to increase NRE. Enhanced efficiency fertilizers, such as slow- or controlled-release fertilizers, which are intended to improve the efficient use of nutrients by synchronizing the release of plant nutrients with changes in crop requirements over the growing season and reducing environmental N loss (Shaviv, 2001).

The variable source N (VSN) fertilizer strategy, which is being examined in this research, includes application of EEFs to sections of fields which may pose a greater risk for N loss and application of conventional N fertilizer sources in lower risk areas of that same field. Areas deemed suitable for EEFs may be delineated through use of topographical maps, topsoil depth maps, or any other method, which may prove successful in identifying areas susceptible to N loss. Digitalization of these suitability maps would allow for use in a fertilizer applicator equipped with multiple bins for an EEF and conventional fertilizer, and a global positioning system (GPS), which would allow for on-the-go N fertilizer application.

Delineation of suitable areas for EEFs requires identification of factors that affect agronomic performance and environmental N loss. These factors may include a variety of soil and landscape characteristics, but generally the most important are those which affect soil water (Timlin et al., 1998). Claypan soils tend to be poorly drained which may cause temporary perched water tables (Blanco-Canqui et al., 2002). Interflow may be a large part of total erosion and runoff during heavy spring rains (Minshall and Jameson, 1965; Ghidey and Alberts, 1998). This erosion and runoff due to lateral or interflow may subsequently cause leaching and denitrification of applied N fertilizer. In addition, the depth to the claypan layer often varies across agricultural fields leading to spatial variability in N response and crop yields (Wang et al., 2003). Sudduth et al. (2003) showed a strong correlation between apparent electrical conductivity (EC_a) measurements and topsoil depth to the claypan layer. A device for measuring EC_a may aid in identifying and mapping areas that may be suitable for EEFs due to the possible effect of variable topsoil depth on NRE.

Schmidt et al. (2007) showed that the economically optimal N rate (EONR) may be affected by within-field soil water content variability during a growing season. Additionally, Timlin et al. (1998) concluded that topography and soil depth and drainage strongly relate to maize yields, and that water-holding capacity and drainage primarily impact grain yields. Gravimetric soil water content data collected at the Greenley

Research Center in the claypan region of northeast Missouri has shown that soil water content can increase by as much as 22% after a rainfall event from a summit to footslope position with only 1 m difference in elevation (unpublished data). Use of EEF in low-lying landscape positions or other areas of a field which may have higher environmental N loss may be an effective way of improving NRE and also make the use of EEF more economically viable since these forms of N fertilizer (e.g., PCU) are usually more expensive than conventional N fertilizer (e.g., urea).

Topography and soil properties affect crop yield on hillslopes (Timlin et al., 1998). Several spatially variable factors that affect crop yield have been studied, including surface thickness and sand content relationships with wheat yield (Miller et al., 1988), pH and biomass production on a hillslope (Boyer et al., 1991), and erosion causing patterns in organic matter distribution, and the subsequent effect wheat yields (Bhatti et al., 1991). The most important topographical characteristics are landscape position (Changere and Lal, 1997; McConkey et al., 1997), total land surface area from which inflow water is supplied (Simmons et al., 1989), and curvature (Sinai et al., 1981; Simmons et al., 1989; Timlin et al., 1998) that affect soil water distribution. Kravchenko and Bullock, (2000) concluded that topographical characteristics and soil properties could successfully be used to delineate site-specific field areas that would be more susceptible to climatic extremes, such as drought and flooding. However, results may be variable based on different field locations and annual climatic variability. Timlin et al. (1998) concluded that spatially variable factors including topography, depth of soil, and drainage have a large effect on maize grain yield variability. They determined that landscape curvature, as derived from elevation maps, strongly related to maize yields. Site-specific research to better understand these characteristics and their relationships with yield may lead to improved crop management.

Interpretation of crop yield maps may be difficult because many permanent and temporary factors may cause variability in yield maps (Kaspar et al., 2003). Breaking a field up into management units, or areas of similar landscape patterns and soil properties usually about 50 to 100 ha in size (Mahmood et al., 1998), may allow for successful yield predictions. Another example of management zones, although at a smaller scale, is presented in a study conducted by Priya and Shibasaki (1999). This study separated the country of India into 50 km (national scale) and 10 km (regional scale) cell sizes to evaluate the effects of soil and weather conditions, and agricultural practices on crop yield. Both resolutions varied as functions of these three variables and the researchers were able to demonstrate that this type of modeling could be applicable at the national level.

Use of sensors to obtain highly resolute spatial variability in soil properties has recently been researched (Sudduth et al., 2003; Corwin and Lesch, 2005). Ritter et al. (2008) observed that spatial correlation of soil characteristics, weed competition, and herbicide treatment with yield, explained yield variation and how these factors affected yield. When combined with yield and topographical variability data, factors that affect crop yield can be identified and new management practices, such as VSN can be implemented to improve crop NUE.

The objective of this research was to use GIS mapping, statistical software, data for crop N response, soil properties, and landscape variability to identify field areas more suitable for EEFs than conventional fertilizer sources.

MATERIALS AND METHODS

A two-year field trial investigating topography and topsoil depth to the claypan layer effects on N fertilizer use in maize was established at the Greenley Research Center in northeast Missouri (40° 1' 17" N 92° 11' 24.9" W) in 2005 (Figure 4.1). The soils in the Greenley experiment were a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs) and a Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiqualfs) (Figure 4.2). Treatments at Greenley were arranged in a split-plot design with five 457 m long treatment strips crossing three landscape positions (i.e., summit, sideslope, and low-lying), and included four replications. The treatments consisted of 168 kg N ha^{-1} of anhydrous ammonia, polymer-coated urea (PCU), urea, 50% urea/50% PCU, and a control treatment of no N. Anhydrous ammonia was knifed into the soil, whereas the other treatments were broadcast and incorporated using a field cultivator to a depth of approximately 15 cm.

A second study was initiated in north central Missouri (39°38’N, 92°20’W) near the town of Centralia in 2006 on a long-term USDA-ARS-Cropping Systems and Water Quality Research Unit (USDA-ARS-CSWQRU) experiment with claypan soils (Figure 4.1). This site consisted of bulk field areas and thirty plots consisting of five different cropping management systems, and is arranged into three replications. In October of 1990, the site was chosen to be a part of the Management Systems Evaluation Area (MSEA) project (Ward et al., 1994). The Centralia site soils consisted of Adco silt loam (fine, smectitic, mesic Aeric Vertic Albaqualfs) and Mexico silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs) (Figure 4.3). Treatments at Centralia were arranged in a split-split-plot with 3 replications and consisted of a control and post-plant application of 168 kg N ha^{-1} of either urea or PCU applied across 3 landscape positions (i.e., summit, sideslope, and footslope) and 3 cropping systems : (CS 1) minimum till, corn/soybean rotation, (CS 2) no-till corn/soybean, and (CS 3) no-till corn/soybean/wheat. Fertilizer was hand-spread shortly after planting and treatments in the tilled plots were immediately incorporated. Silage and grain yields were taken after crop physiological maturity and silage was used to determine maize N recovery efficiency.

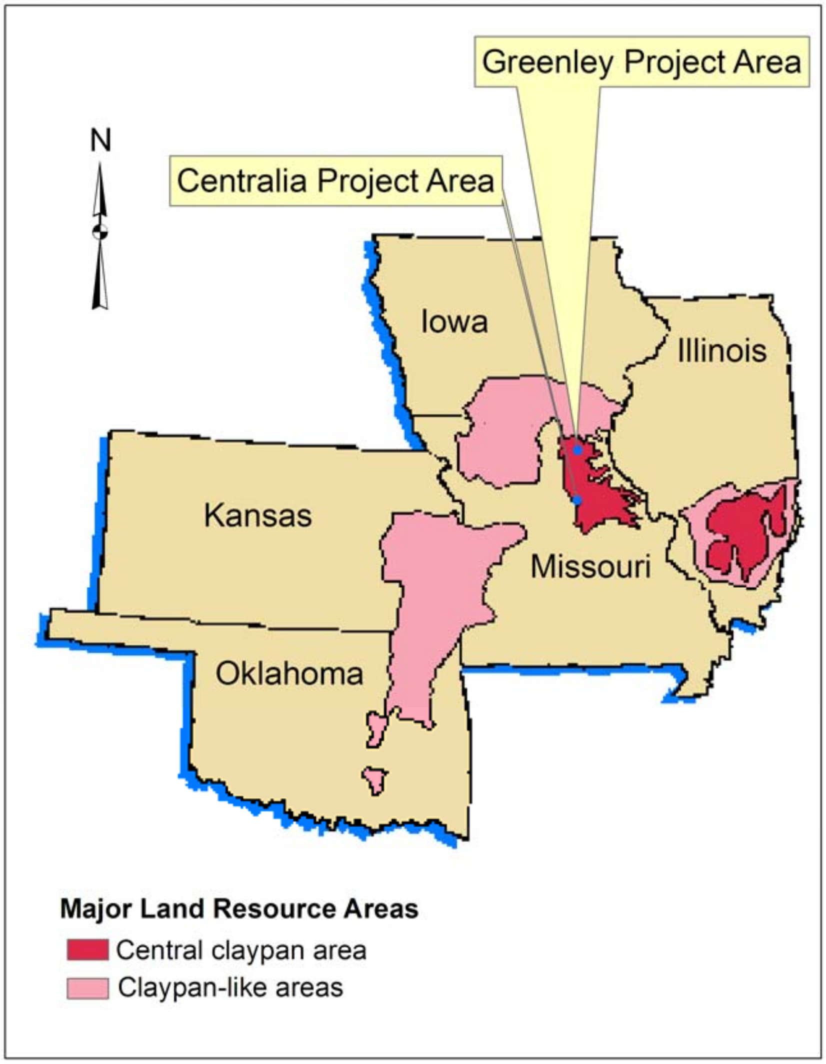

Figure 4.1 Locations of the experiments at the Greenley Research Center near Novelty, -MO, and the USDA-ARS-CSWQRU Research Station near Centralia, MO.

Soils data and a National Agricultural Imagery Program (NAIP, 2007) aerial photograph were used to produce the following maps (Figures 4.2 and 4.3) in ArcMap Version 9.2 (ESRI, Redlands, CA) showing soils in and around the study area. The imagery and soils data layers were taken from the Center for Applied Research and Environmental Systems (CARES) website. The county insets were taken from the Missouri Spatial Data Information Service (MSDIS).

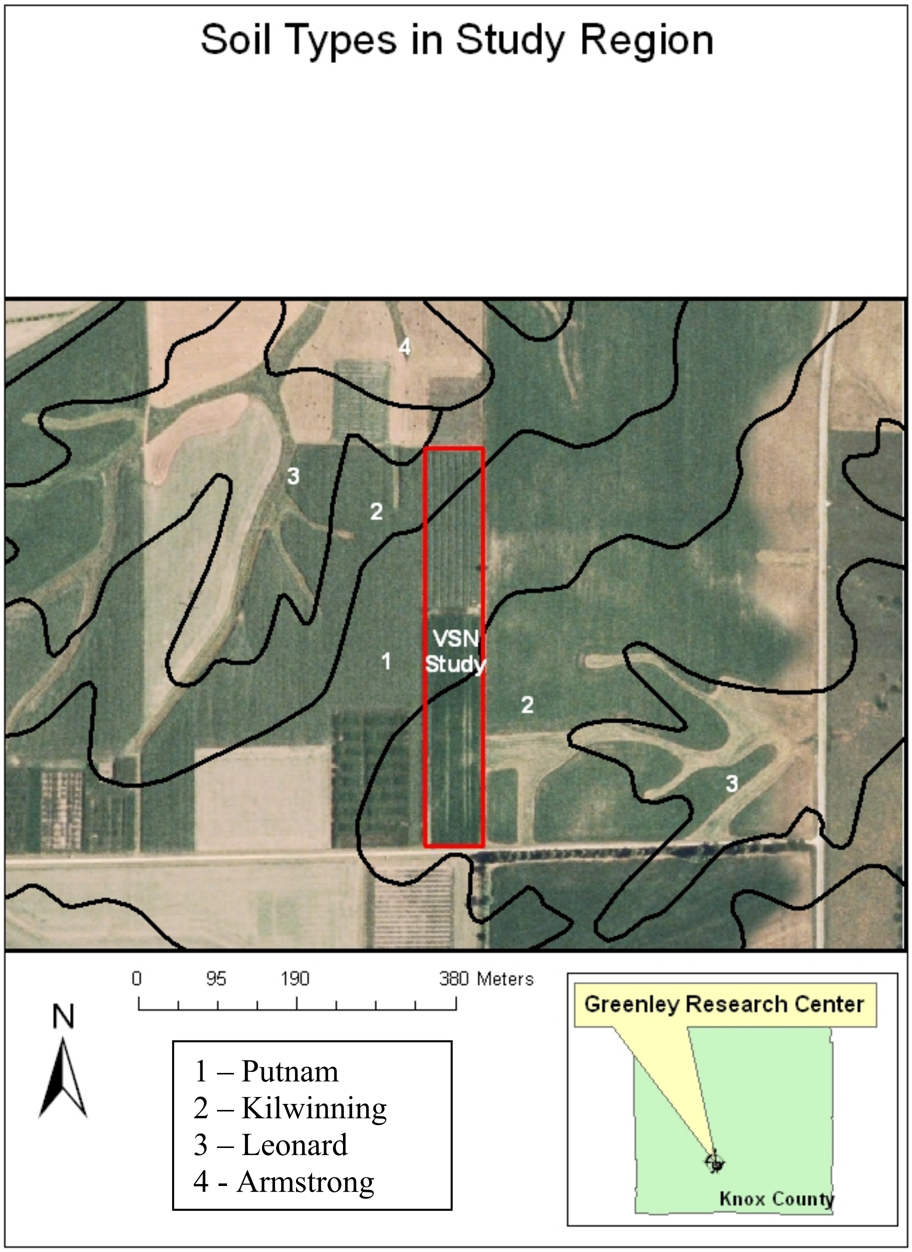

Figure 4.2 Soil survey map showing the soil types in and around the study area. The site is in Knox County, near Novelty, MO. The primary soils in the study are Putnam silt loam (fine, smectitic, mesic Aeric Vertic Albaqualfs), and Kilwinning silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs).

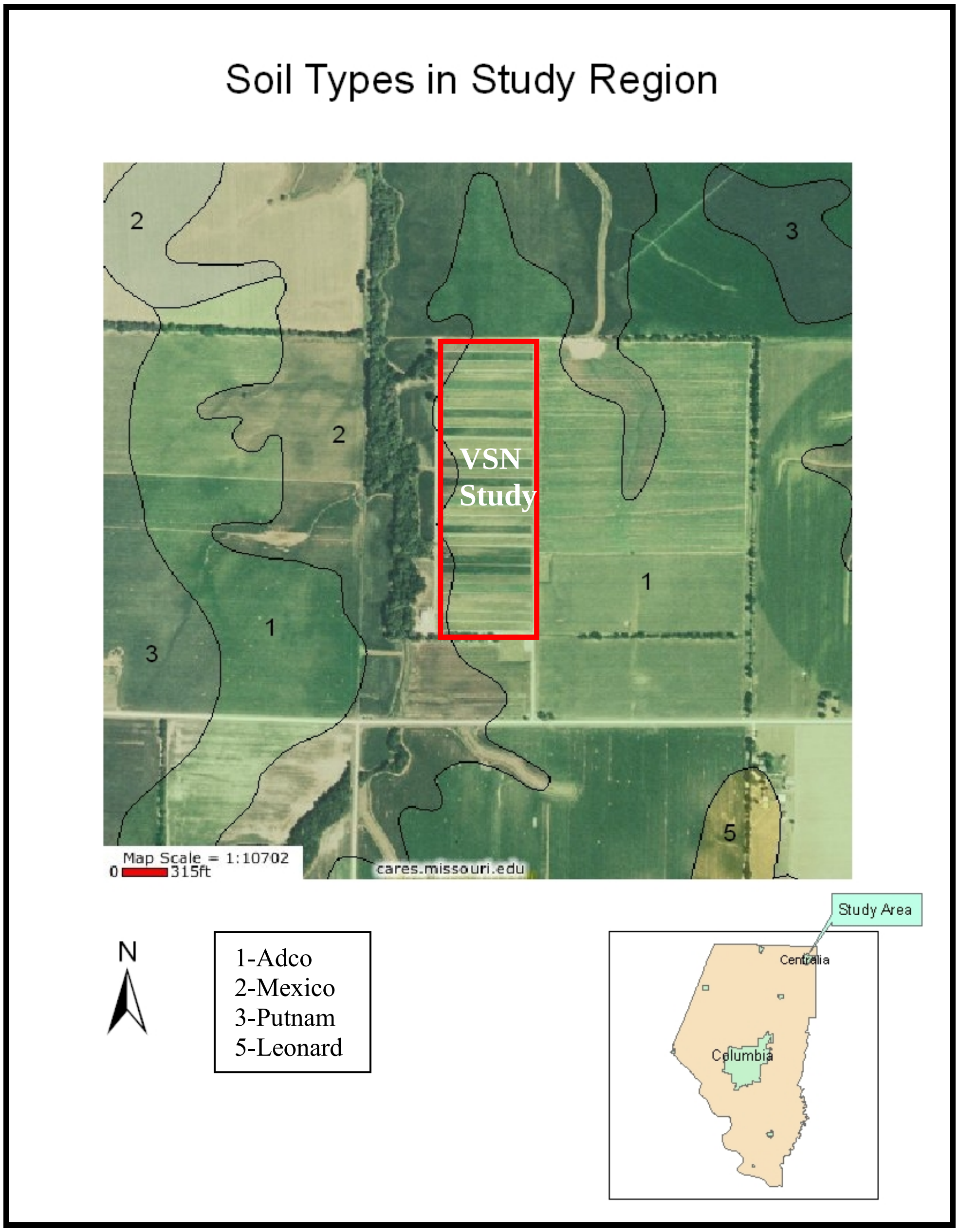

Figure 4.3 Soil survey map showing the soil types in and around the study area. The site is about 1.5 miles northeast of Centralia, MO. The main soil type in the area is Adco silt loam (fine, smectitic, mesic Aeric Vertic Albaqualfs), and Mexico silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs).

Greenley GIS data collection

Prior to planting in 2005, apparent electrical conductivity (EC_a) was measured on the Greenley field using an all-terrain vehicle (ATV) and an EM-38 (Geonics) sensor oriented in the vertical mode, which allows for 1.5 m depth measurement. Measurement of soil EC_a has been shown to correlate with subsoil claypan depth (Sudduth et al., 2003) and may influence spatial variation in soil water content. In addition, the field was surveyed using a total station survey instrument with GPS to map changes in elevation over the field.

In order to compare the effects of spatial distribution of elevation and EC_a on the distribution of soil water content, soil gravimetric water content was determined at 0 - 15 cm depth soil samples collected in a 3.0 by 7.6 m grid at the Greenley site on March 31, 2005 approximately two days after a rainfall. The results of the grid sampling were mapped using ArcMap Version 9.2 and the data was interpolated between data points using the Spatial Analyst extension.

Soil gravimetric water content sampling points were established using information gathered from the EC_a data, along with a differential global positioning system (DGPS) and Farm Works Site Mate software. These points were sampled ten times throughout the 2005 and 2006 crop seasons for soil gravimetric water content to show in-season landscape differences in soil water.

Centralia GIS data collection

At the Centralia site, elevation data determined by real time kinematic (RTK) GPS was previously collected by the USDA-ARS. Soil EC_a was collected using an EM-

38 conductivity meter attached to a wooden cart and pulled by an all-terrain vehicle (ATV) and operated in the vertical mode. Gravimetric soil water content was collected from the 0 to 20 cm depth. The soil samples were collected and composited every 18.2 m starting from the summit position, then eight more were taken from the approximate start of the footslope position every 9.1 m Locations of the soil water content data collection points were recorded using Differential GPS (DGPS) and the Farm Works Site Mate software (CTN Data Service LLC, Hamilton, IN). Plot boundaries were recorded using DGPS.

Soil gravimetric water content samples from a depth of 0-20 cm were collected in transects each year from cropping systems which contained the treatment plots.

Greenley GIS processing

The EC_a data collected by the USDA-ARS with an EM-38 device was interpolated to show spatial variability of EC_a over the study area. The EC_a data including its geographic reference data was entered into ArcMap. ArcMap Toolbox tool Spatial Analyst was used to interpolate the data using kriging. The kriging method used was ordinary, and the semivariogram used was spherical with a variable search radius of 12 points. The water content point data were also kriged using Spatial Analyst in ArcMap. First, the excel spreadsheet with the sample ID numbers was joined in ArcMap with the water content point shapefile. The kriging method used was ordinary and the semivariogram used was spherical with a variable search radius of 12 points.

Centralia GIS processing

Collected EC_a data from Centralia was mapped using ArcMap. A linear transformation, which is the inverse of the collected EC_a data, was used to change the EC_a data into topsoil depth to claypan data, which was then interpolated to show spatial variability in topsoil depth to the claypan. Grain yield from each urea plot was subtracted from the grain yield of the corresponding landscape position PCU plot. A field was added to the attribute table of each year's plot locations layers. This field was named "Yield" and it was populated using the Editor Toolbar. The field was then mapped showing grain yield in PCU fertilized plots minus grain yield in the corresponding nested urea fertilized plots, meaning the PCU and urea plots that were compared shared the same cropping system and landscape position.

Grain yield, gravimetric soil water content, and topsoil depth were combined in a layout to help interpret spatial variability. A topsoil depth map was produced using topsoil depth to the claypan layer and elevation data. Elevation data was converted from meters to centimeters and the topsoil depth was subtracted from the elevation data using Raster Calculator. The 20 cm depth gravimetric soil samples collected in transects through the cropping systems in 2006 and 2007 were added to the attribute table of their point data file in a GIS. Each cropping system consisted of 14 water content points. These groups of 14 points were each interpolated to give linear gravimetric soil water content gradient from the summit to the footslope positions. A field was added to the plot locations layer. This field was equal to the PCU treated grain yield minus urea treated grain yield at each nested plot location. This data was split into 14 breaks to show which plots had higher grain yield under PCU treatment and which had higher grain yield under urea treatment. This layer was combined in a layout with the soil water content gradient and both were overlain on the topsoil depth map.

The gravimetric soil water content data was analyzed in SAS using PROC GLM and the multiple comparison test used was Duncan's Multiple Range Test (DMRT) to test for statistical differences among cropping system means at $p \leq 0.05$.

To better understand the general soil hydrology of the study and surrounding area, a Flow Accumulation map was produced using Spatial Analyst in ArcMap. Elevation contour lines were overlain on the flow accumulation map, along with plot locations.

RESULTS AND DISCUSSION

Greenley

Figure 4.4 shows the soil EC_a map. The summit position had the shallowest topsoil depth to the claypan layer, the sideslope had the deepest, and the low-lying landscape position had an intermediate topsoil depth to the claypan. The sampling points on the map represent the locations of the in-season soil gravimetric water content sample points.

Figure 4.5 shows the gravimetric water content map. The summit landscape position had less gravimetric soil water content than the sideslope, which had less than the low-lying area. The sampling points represent the in-season gravimetric soil water content sample points. PCU and anhydrous ammonia treatments in the low-lying landscape position resulted in higher grain yields than urea in 2005 and 2006 (refer to Chapter 2). Additionally, silage yield, N uptake, and nitrogen recovery efficiency were higher in PCU and anhydrous ammonia treatments than urea treatments in the low-lying landscape position in 2005 only (refer to Chapter 2).

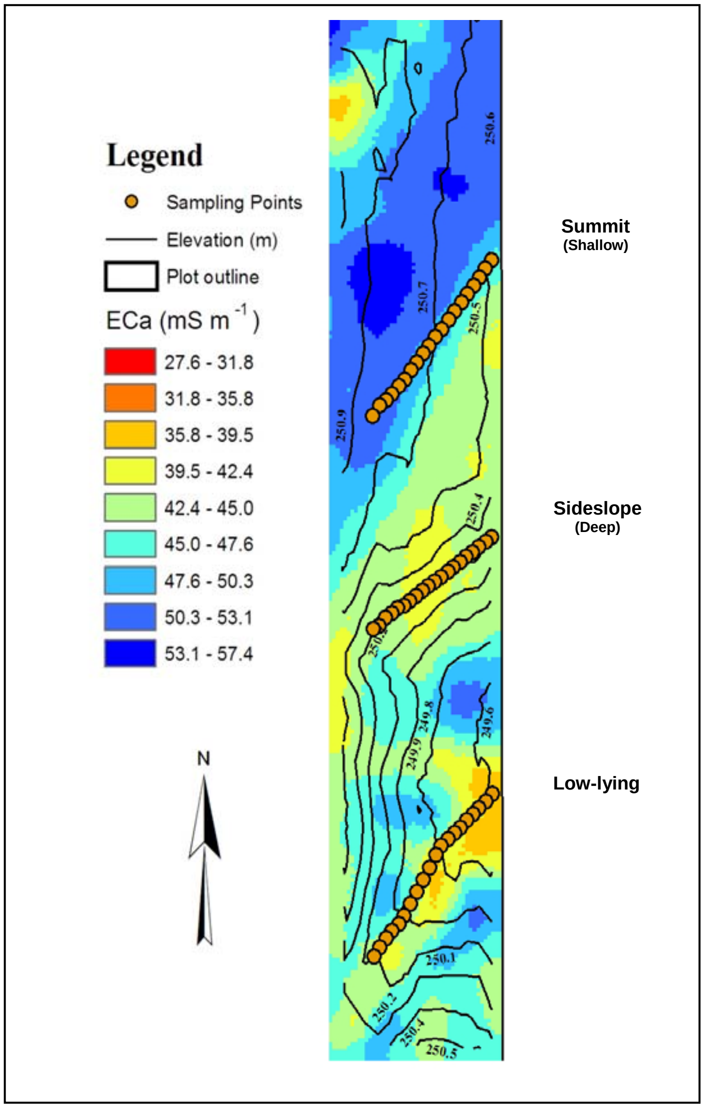

Figure 4.4 Apparent soil electrical conductivity (EC_a) of the Greenley site. EC_a data was collected using an EM-38 sensor. Blue colors indicate shallow topsoil depth to claypan and yellow or red colors indicate deeper topsoil depth to claypan. Contour lines give an idea of the topography of the site. Yellow points indicate soil water content sampling sites, which were collected throughout the 2005 and 2006 growing seasons.

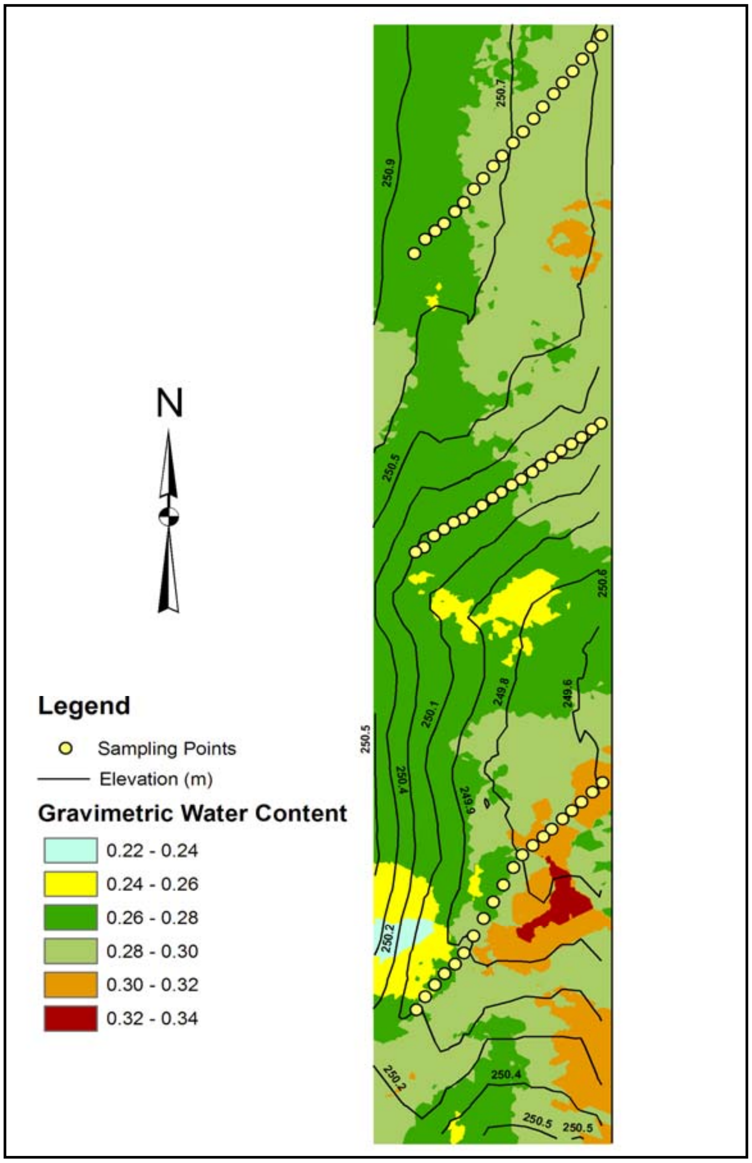

Figure 4.5 Spatial distribution of in-season soil gravimetric water content at the Greenley site on March 31, 2005. The rings represent within season shallow soil sampling points for water content at 0- to 10-cm deep.

Centralia

Figure 4.6 is an elevation map of the study site and surrounding area. The points are RTK data, which were used to interpolate the map. The maximum difference in elevation from the summit to the footslope position is 3.1 m, meaning the site has little relief (< 2%). However, lateral water movement may be significant on this soil type (Minshall and Jameson, 1965; Ghidey and Alberts, 1998) and erosion can occur.

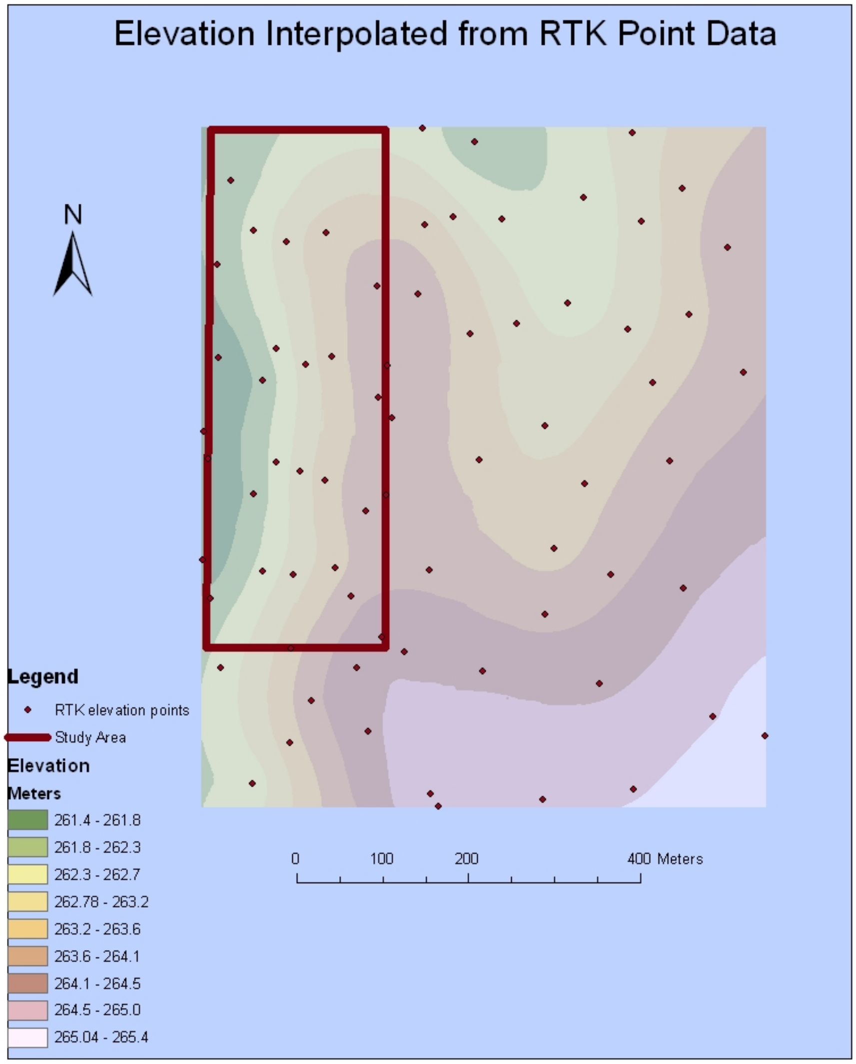

Figure 4.6 Study site (rectangle area) and point data collected by real-time kinematic (RTK) GPS. This point data was kriged to interpolate elevation data.

Topsoil depth at the Centralia site showed the sideslope landscape position was generally the shallowest to the claypan layer (Figure 4.7). Unlike the Greenley site, the footslope, or low-lying landscape position, was the deepest topsoil depth and the summit was intermediate. The shallower topsoil depth to the claypan in the sideslope position may give crops in this area an advantage by providing access to base cations found within the clay (Bray, 1935).

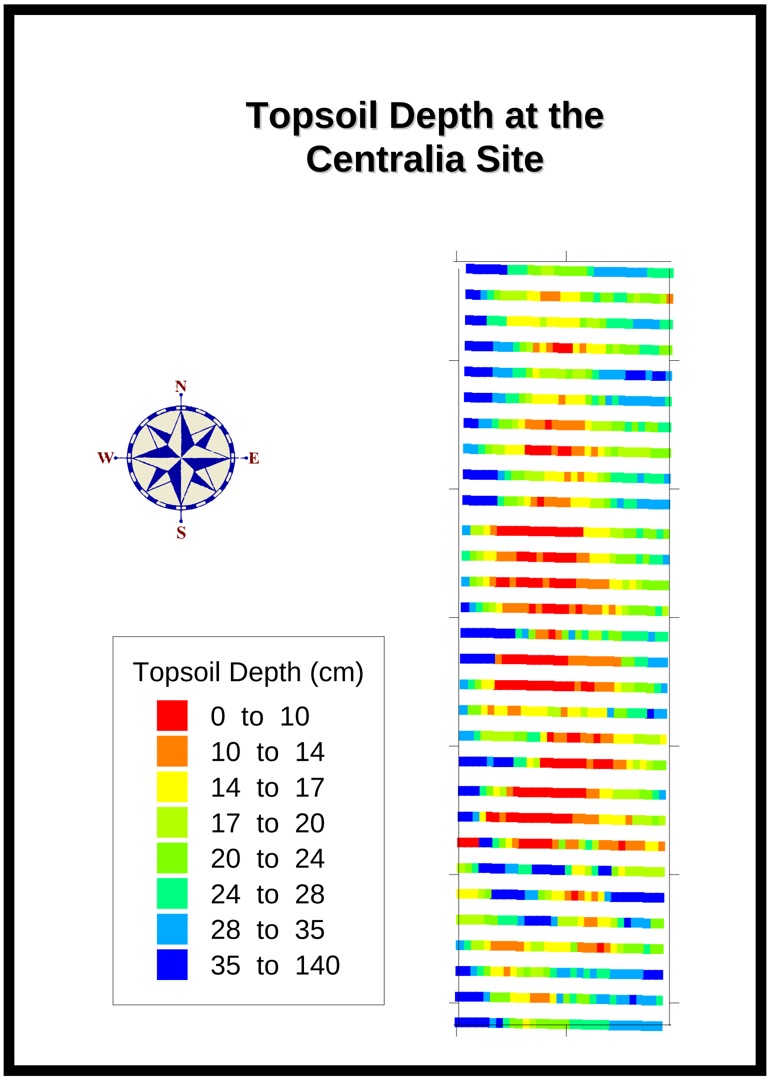

Figure 4.7 Topsoil depth to claypan at the Centralia site.

Figure 4.8 shows a NAIP image of the site overlain by elevation and plot locations. The landscape positions are not an exact representation of the summit, sideslope, and footslope, but are meant to provide an idea of the landscape.

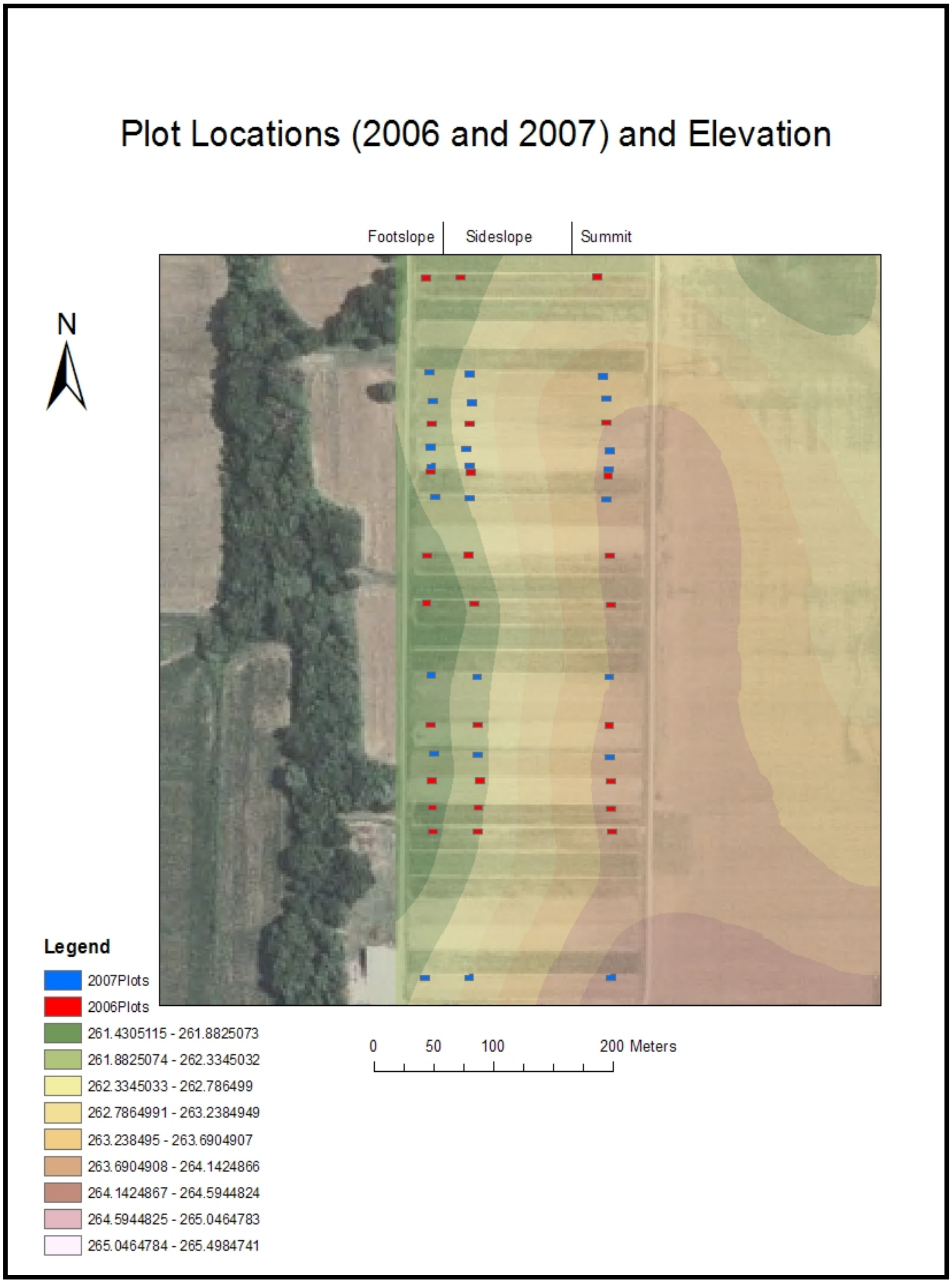

Figure 4.8 Experimental plot locations in relation to landscape position and elevation (in meters) at Centralia for 2006 and 2007.

The Centralia site showed a large amount of grain yield and soil water content variation in both 2006 and 2007 (Figures 4.9 and 4.10). However, grain yield under PCU treatment in the footslope position of CS2 in one replication was significantly greater than grain yield under urea treatment in the same plot. A large amount of soil water content variation from each sampling date in 2006 and 2007, along with a large amount of grain yield variation in both seasons made for difficulty in interpreting the results.

Based on this analysis in 2006, all but three PCU plots in the footslope position showed increased grain yield over the corresponding urea-treated plots. Two of the three plots were CS2 (no-till maize/soybean rotation), and the third was CS3 (no-till maize/soybean/wheat rotation). Five of the nine side slope positions under PCU treatment had higher grain yield than corresponding urea treatments in 2006. Two of these four were CS3, one was CS2, and the other was CS1 (min-till maize/soybean rotation). At the summit position, two urea-treated CS2 plots had higher grain yields than the corresponding PCU-treated plots, and two CS1 plots under PCU treatment were higher in grain yield than the corresponding urea-treated plots.

In 2007, five of the eight footslope PCU-treated plots had higher grain yield than corresponding urea-treated plots. At the sideslope position, all PCU-treated plots, except one, were higher in grain yield than the corresponding urea-treated plots. This out-lying treatment was on CS3. At the summit position, five of the eight urea treatments had higher grain yields than corresponding PCU-treated plots.

The 2006 gravimetric soil water content data showed a general trend of less soil water content in the footslope position. Two of the three tilled cropping systems had less soil water content than the no-till cropping systems. CS1 in rep 2 showed a large difference in gravimetric soil water content between the summit position (drier) and the sideslope and footslope (wetter) positions.

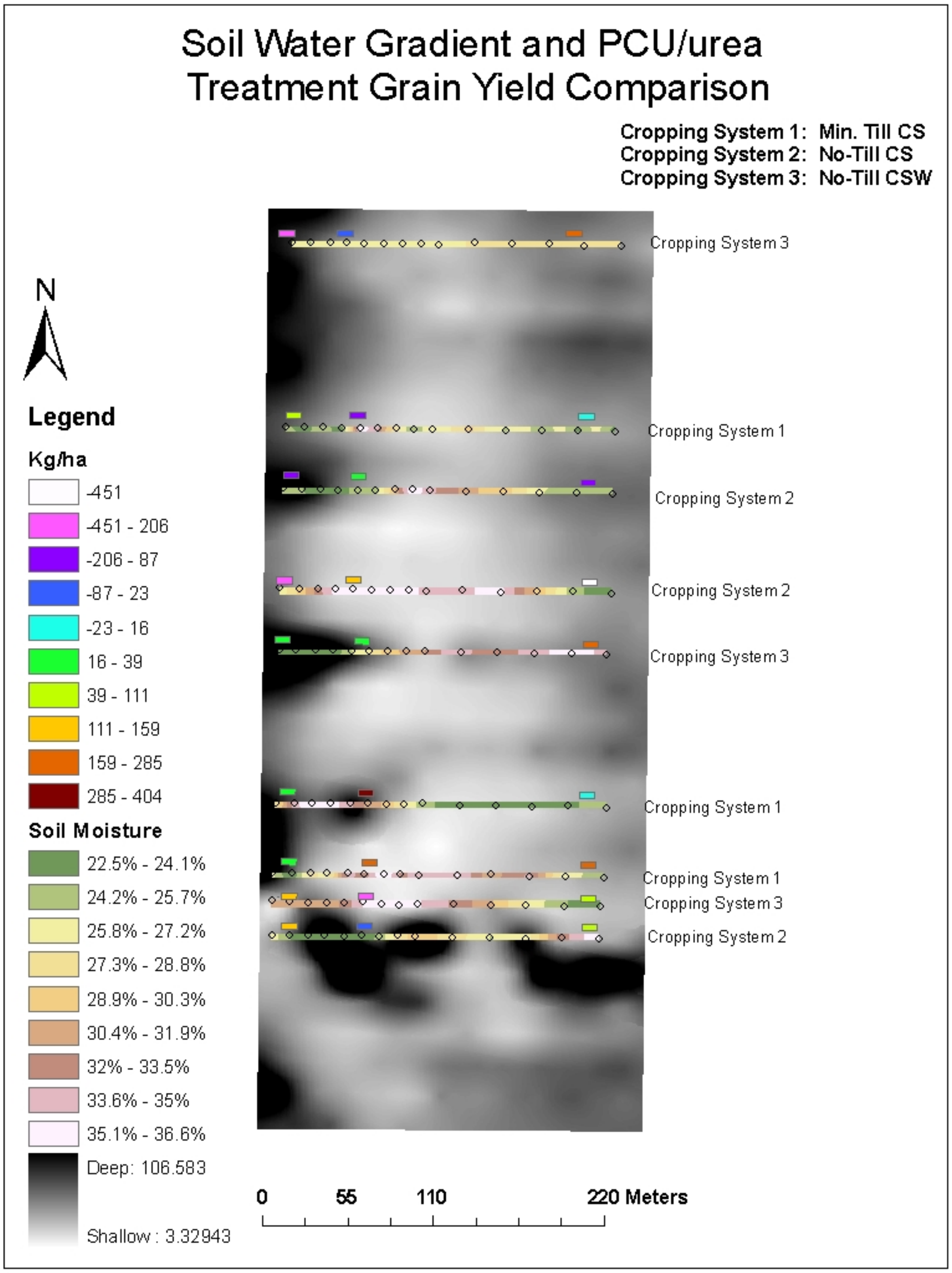

Figure 4.9 Data from 2006 showing a background of topsoil depth as derived from EC_a data. The sample points were where gravimetric soil water content data was taken and used to interpolate the lines representing a linear soil moisture content gradient. The rectangular patches are plot locations and indicate PCU and urea grain yield performance. When PCU treatment grain yield was greater than urea, the corresponding grain yield number was positive. If grain yield is negative, this means urea treatment out-performed PCU.

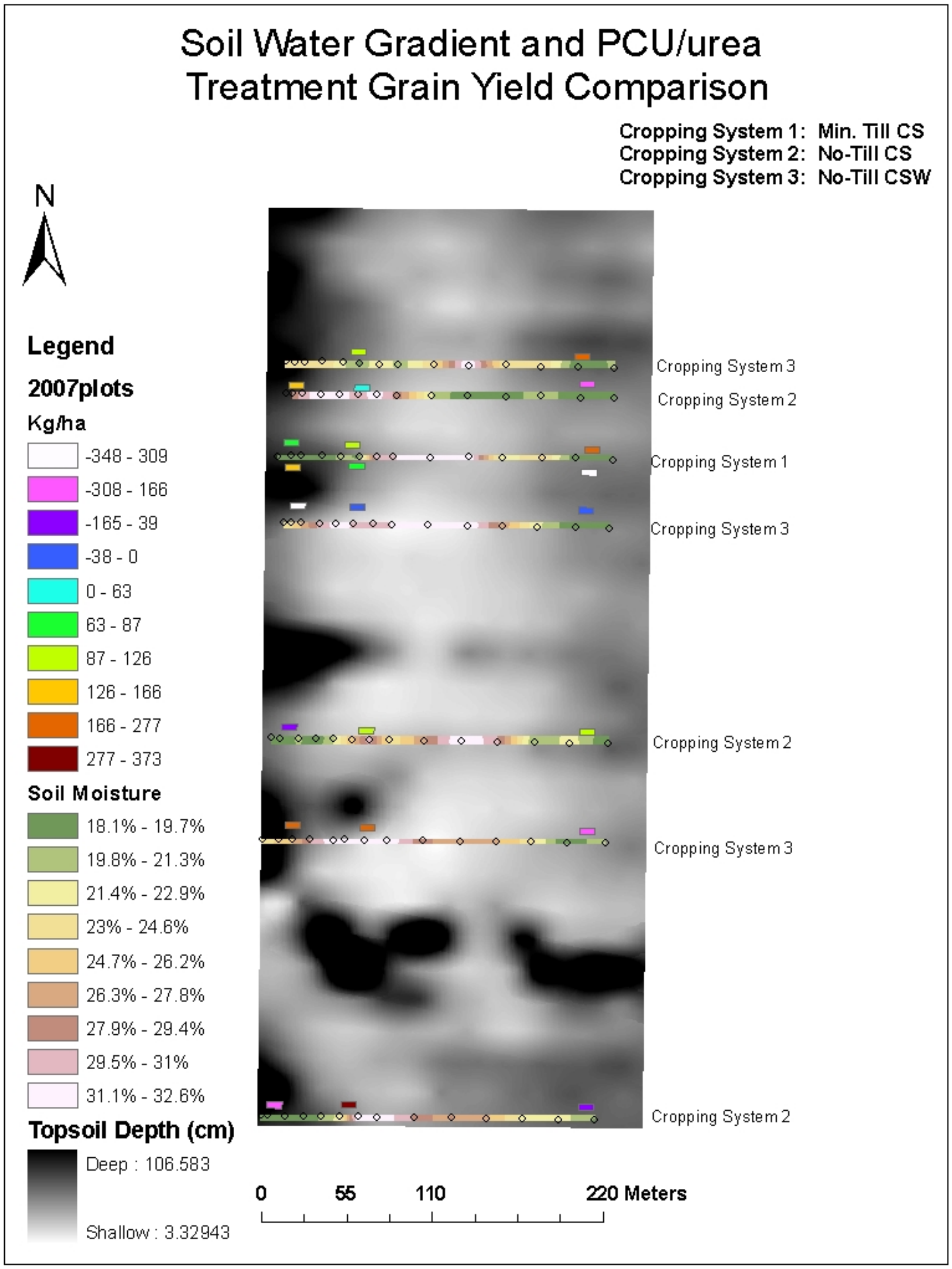

Figure 4.10 Data from 2007 showing a background of topsoil depth as derived from EC_a data. The sample points were where gravimetric soil water content data was taken and used to interpolate the lines representing a linear soil moisture content gradient. The rectangular patches are plot locations and indicate PCU and urea grain yield performance. When PCU treatment grain yield was greater than urea, the corresponding grain yield number was positive. If grain yield is negative, this means urea treatment out-performed PCU.

The footslope position in CS1 in 2006 at 0 – 20 cm deep was significantly drier than the sideslope and summit positions (Figure 4.11). Similarly, the footslope position in CS2 was significantly drier than the sideslope or summit positions. The sideslope position in CS3 was significantly drier than the summit position, and the footslope was significantly drier than both the sideslope and summit positions.

In 2007, the footslope and summit positions were significantly drier than the sideslope position (Figure 4.11). In CS2 and CS3, the footslope positions were significantly drier than the respective sideslope and summit positions.

The lower soil water content observed at the footslope position may have been due to the deeper topsoil in the footslope position than the sideslope or summit, causing it to be better drained.

The flow accumulation map shows some moderate flows increasing with decrease in elevation from the summit to the footslope position. However, the USDA Field 1 area shows heavier flow in an area with slightly more or no more relief than the plot area, meaning that water flow does not accumulate much in the plot area. Kravchenko and Bullock, 2000, observed curvature, slope, and flow accumulation explain yield variation only in areas of intense landscape locations and in years of either severe amounts of precipitation or severe lack or precipitation. Landscape curvature may be a good factor to include in the development of VSN applications, in order to more effectively predict soil moisture variability.

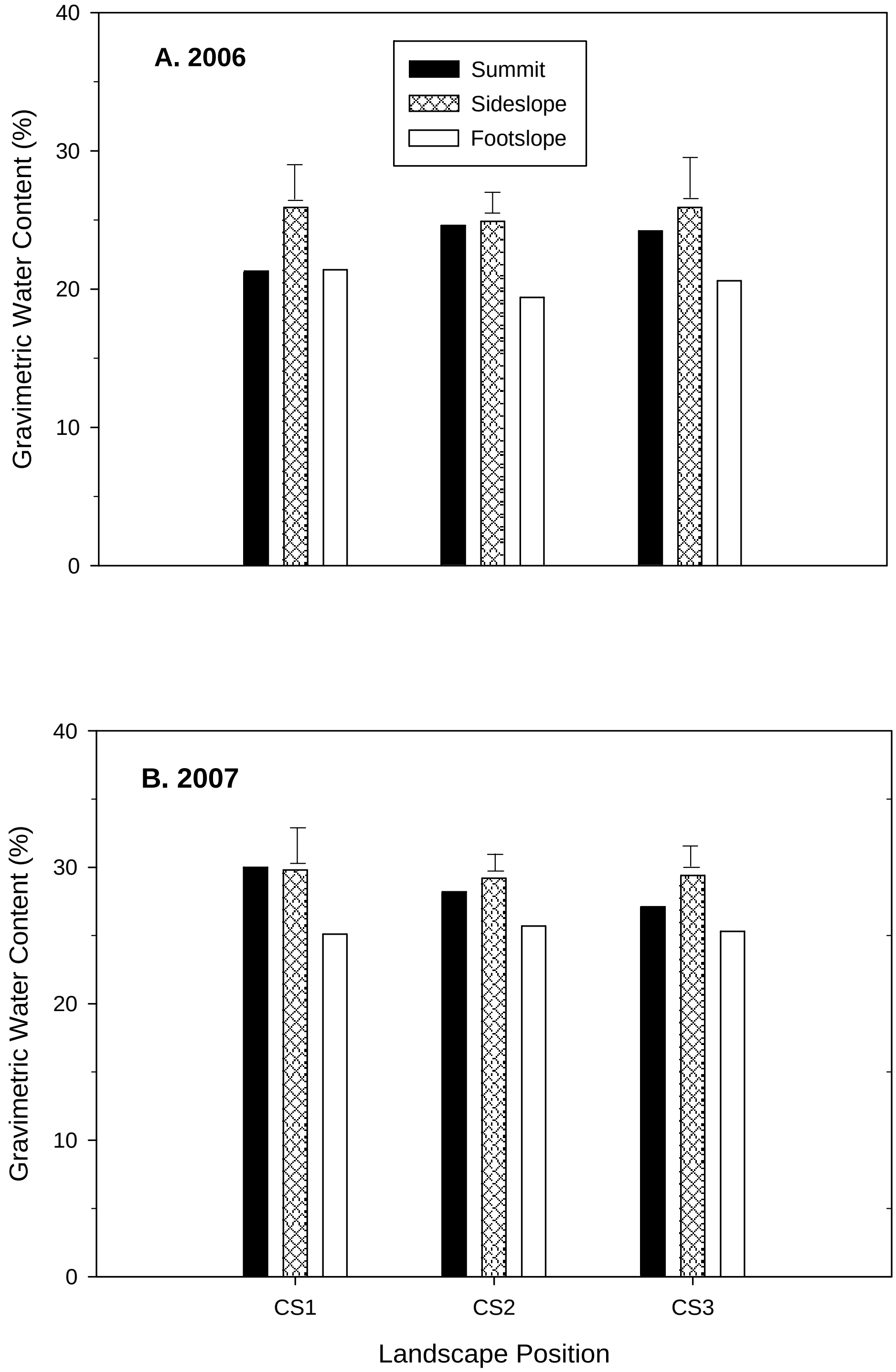

Figure 4.11 Gravimetric soil water content collected from 0 to 20 cm deep from each cropping system and landscape position in A. 2006 and B. 2007. CS1 was minimum till Maize/Soybean rotation, CS2 was no-till Maize/Soybean rotation, and CS3 was no-till Maize/Soybean/Wheat rotation.

Figure 4.12 shows that surface water flow does not accumulate much at the designated footslope landscape position. In order to compare flow accumulation, the USDA Field 1 was included. The north end of Field 1 has an area of lower elevation where water can sometimes flow several cm deep. This area can be very wet, yet it still shows roughly the same flow accumulation as the footslope position in the plot study area. This means the peak of flow accumulation is further down the landscape. Furthermore, the designated landscape position is in actuality more of a continuation of the sideslope position because it does not accumulate water flow, as was seen at the Greenley site in the low-lying area, which is likely why maize grain yield did not respond to PCU and urea fertilizer treatments similar to the Greenley experiment.

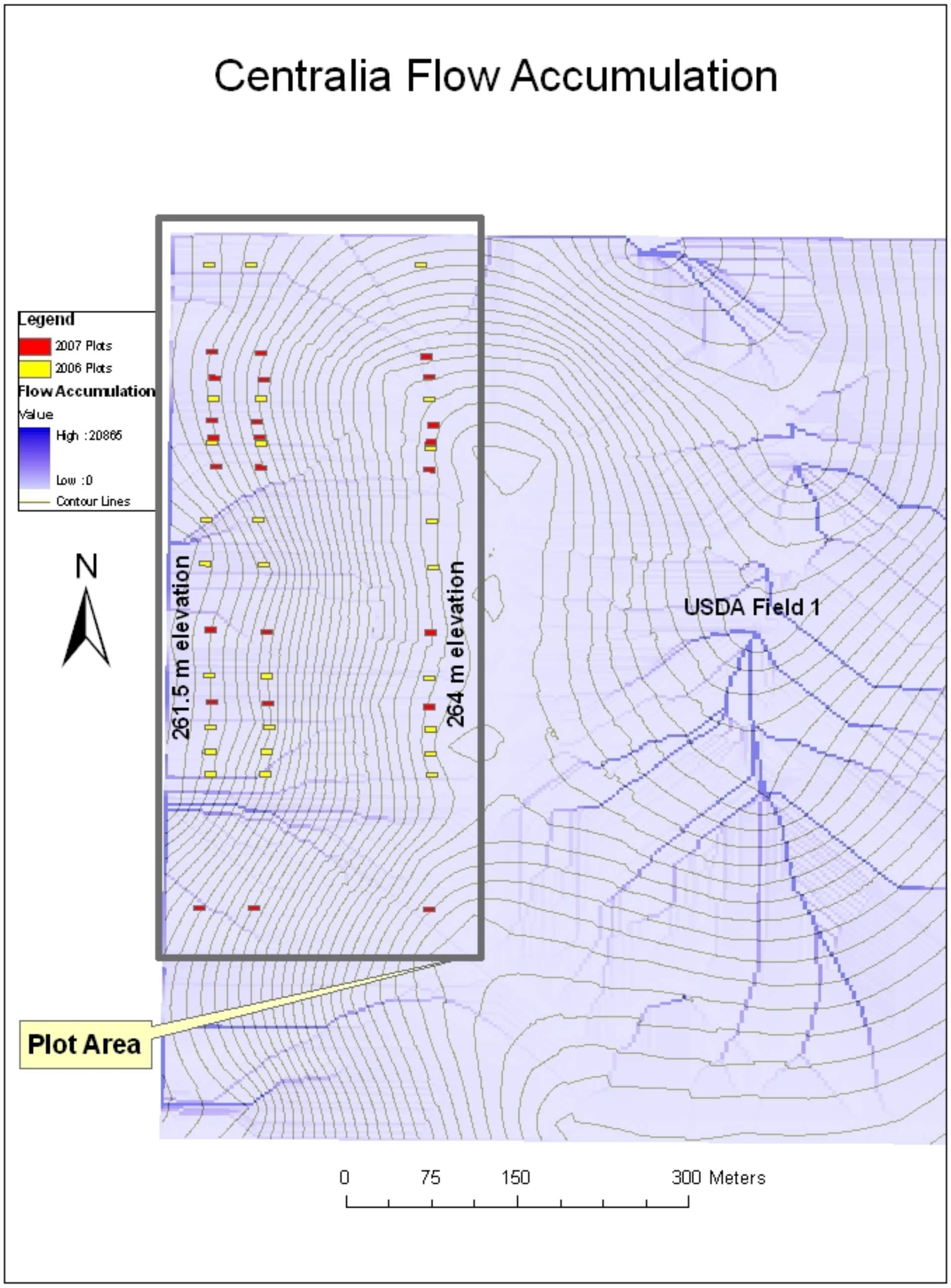

Figure 4.12 Map showing flow accumulation, plot locations, and contour lines for the plot and USDA Field 1 areas. The plot area is within the rectangular boundary. Blue lines increase with size as flow accumulation increases with decreasing elevation.

CONCLUSIONS

Development of software tools, possibly in the GIS format, is necessary to delineate areas of agricultural fields which may have differential yield response and N loss to N fertilizer applications. Based on the results of this study, GIS and associated statistical tools facilitated the collection and analysis of spatially-based information that may impact N response in claypan soils. Use of GIS allowed for a prediction of water flow in the field which can indicate where in a field periodic saturation and associated N loss may occur. Based on this analysis, we concluded that saturated areas in the field at the Centralia site occurred more frequently in lower field positions outside of the research field area. This factor, and experimental error, may account for the lack of differences in N fertilizer response observed at Centralia compared to the Greenley site.

These results emphasize the need for further research at different sites with a range of cropping systems and environmental conditions to test the VSN approach

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CHAPTER 5

GENERAL CONCLUSIONS

The main goals of this study were to identify areas within a cropped landscape that might have certain characteristics (e.g., topsoil depth to the claypan and lower elevation), which would affect N fertilizer response and NRE and to assess which N fertilizers sources may be more effective at different landscape positions. This study was conducted at two sites in northern Missouri which contained claypan soils and had differences in elevation and depth to the claypan layer across the experimental field. Several tools in GIS software were used to be able to assess the effects of topsoil depth, and elevation on observed response across the fields.

Results from the Greenley site showed improved grain yield, silage yield, N uptake, and NRE in PCU and anhydrous ammonia treatments over urea in the low-lying landscape position in 2005, and improved grain yield in PCU and anhydrous ammonia treatments over urea in the low-lying position in 2006. Results from the Centralia site showed a large amount of grain yield variation under PCU and urea treatments which was attributed to experimental error (e.g., replanting of some plots in 2006, misapplication of fertilizer in 2007) and differences in the pattern of spatial variation in soil water content across the field compared to the Greenley site. The footslope landscape position at Centralia generally had significantly lower gravimetric soil water content than that of the sideslope and summit. In comparison, at Greenley, the low-lying landscape position generally had higher gravimetric soil water content than the other two landscape positions.

This difference in the pattern of soil water content across the landscape positions in the field is probably the result of several factors including differences in drainage, water-holding capacity and plant water use. However, a primary difference between the Centralia and Greenley sites was that the Centralia site did not include a large area of the landscape in which water periodically saturated the soil, especially in the early growing season shortly after N fertilizer was applied. Identifying these areas of periodic saturation in a field may be the primary characteristic that allowed for observed differences in urea, PCU and anhydrous ammonia response.

An important first step in determining the possible significance of the better performance of the PCU and anhydrous ammonia compared to urea at the low-lying position at Greenley is to assess the magnitude of field areas which may have similar characteristics of periodic saturation and to compare the use of these N fertilizer sources to use of urea under different environmental conditions and cropping systems. However, results from the Centralia site suggest that differences in management practices represented in several established cropping systems, including differences in surface fertilizer application in no-till and incorporated fertilizer application in a tilled system, were not a major factor affecting crop response to applied N fertilizers. This effect of cropping system may need to be re-tested due to the experimental error that occurred in the Centralia study.

In general, the results from the Greenley site suggest that use of different pre-plant incorporated or injected N fertilizer sources in a field which contains periodically saturated areas, possibly at lower elevation, may improve NRE and economic returns for maize production. Delineation of the periodically wet areas in a field prior to N fertilizer application based on simulation models or prior observations (e.g., relative soil water content, ponded water) and production of maps containing those delineations may facilitate development of a variable source N practice. However, a limitation of this research for this needed development of a method for delineating these areas was that grain and silage yield and NRE data were collected over each landscape position and not in sufficient spatial detail to see the gradient of response over the field. Further study of various soil properties including topsoil depth to claypan, landscape topography, infiltration and drainage, and their relationships with grain and silage yield, and NRE is necessary and should be conducted in multiple locations to better understand and develop a strategy for variable source N fertilizer applications in maize. Finally, current GIS software tools are effective in allowing for evaluating the effects of several spatially-based parameters, including topsoil depth and elevation, on agronomic crop response and NRE. These tools will also be useful for delineating the areas of the field which would be potentially most responsive to enhanced efficiency fertilizers or conventional N fertilizer sources.