ALTERNATIVE TILLAGE AND NITROGEN MANAGEMENT OPTIONS TO INCREASE CROP PRODUCTION AND REDUCE NITROUS OXIDE EMISSIONS FROM CLAYPAN SOILS

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PATRICK R. NASH

Dr. Peter Motavalli, Thesis Co-Supervisor
Dr. Kelly Nelson, Thesis Co-Supervisor
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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled:

ALTERNATIVE TILLAGE AND NITROGEN MANAGEMENT OPTIONS TO INCREASE CROP PRODUCTION AND REDUCE NITROUS OXIDE EMISSIONS FROM CLAYPAN SOILS

presented by Patrick R. Nash

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

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Peter Motavalli

Dr. Kelly Nelson

Dr. Robert Kremer

Dr. Felix Fritschi

………………………I would like to thank my family for always supporting me.

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CHAPTER 1

LITERATURE REVIEW

Agriculture's Impact on Soil Nitrous Oxide Emissions and Its Environmental Implications

Global emissions of nitrous oxide (N_2O), a major greenhouse and ozone-depleting gas, have risen 50% from 1970 to 2007, a period during which industrial emissions of N_2O decreased while agricultural emissions increased (Smith et al., 2007). Agricultural practices account for approximately 78% of the total N_2O emissions produced in the U.S., with 38% of agriculturally produced N_2O emitted from the soil (USEPA, 2007). Future global N_2O emissions are projected to increase 35 to 60% by 2030 due largely to the projected increase in global N fertilizer use and animal production (FAO, 2003). These projections are of public concern because of the negative impact N_2O has on the environment. Nitrous oxide is a chemically stable, long lived greenhouse gas that has a residence time in the atmosphere of a decade up to centuries (Fields, 2004; Solomon et al., 2007). Chemical reduction of N_2O to N_2 does not occur in the atmosphere, and N_2O is not deposited via precipitation. These properties allow for N_2O to persist in the atmosphere for long periods. Increasing atmospheric levels of N_2O have significant environmental consequences because N_2O in the atmosphere is linked with the greenhouse effect and stratospheric ozone depletion.

Nitrous oxide in the troposphere is an important greenhouse gas that absorbs infrared radiation in a spectral range not absorbed by other common greenhouse gases, such as carbon dioxide. Because of N_2O's unique spectral absorption range each molecule absorbs about 297 times as much outgoing radiation as carbon dioxide

(Venterea et al., 2005). Therefore, mitigating soil N_2O emissions from agricultural practices is an extremely important component in minimizing the greenhouse effect and climate change.

Nitrous oxide entering the stratosphere is a precursor gas to the breakdown of ozone which is commonly referred to as ozone depletion. In a process called photolysis, ultraviolet light hits N_2O producing nitric oxide (NO) which in turn acts as a catalyst in the breakdown of ozone (Fields, 2004). Reduction in ozone allows for higher levels of ultraviolet light reaching the earth’s surface which has been linked to increased skin cancer rates. A report in 1998 claimed that decreased ozone levels had increased ultra violet radiation reaching the surface by 10 to 20% which the study concluded explains the 20 to 40% rise in skin cancer since the 1970’s (Kane, 1998).

Mitigating soil N_2O emissions from agricultural practices will be difficult since it is estimated that global food production will need to double by 2050 in order to feed the exponentially growing global population (Lal, 2007). Reducing the global agricultural use of N fertilizers would be the most effective means of mitigation. However, reducing agricultural applications of N is not a practical option since this may lower crop yields and potentially lead to food shortages. A more realistic option is to minimize soil N_2O emissions from high-yielding cropping systems through improved N management. Accomplishing this will require selecting the best agricultural management practices that work with and/or manipulate soil conditions to manage soil microbial N transformations in a way which promote increased recovery of applied N fertilizers through plant uptake.

Microbial Nitrogen Transformations' Effect on Nitrogen Loss

Nitrogen has a wide range of oxidation states (+6 to -3) which makes N transformations within soil very diverse and complex. In theory, chemical transformation of N can occur in soils; however, due to extremely large activation energies and kinetics, many of these reactions cannot occur in natural soil environments without microbially-mediated N transformations. Microbes produce enzymes which lower the activation energy required for N transformations and substantially increase the rates of these transformations. The main biological N transformations related to urea-based fertilizers include urea hydrolysis, nitrification, and denitrification which all have rates of reactions directly related to soil temperature (Figure 1.1). The rates of all microbial N transformations are dependent on factors, such as soil temperature, soil water content, soil organic matter (SOM), concentrations of N species, soil redox potential, soil reaction, and microbial diversity and activity (Shi et al., 2004).

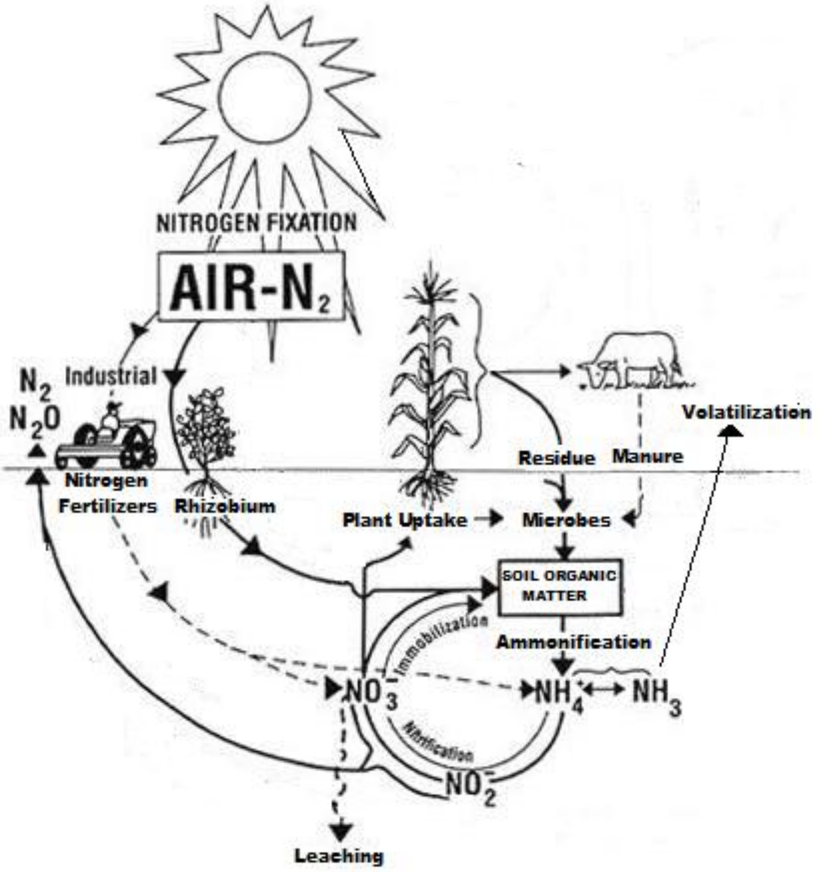

Figure 1.1. Nitrogen cycle and transformations.
Source: Adapted from Ohio State University Extension Fact Sheet.

Urea Hydrolysis

Urea hydrolysis is the conversion of synthetic organic N (urea) to ammonium (NH_4^+) or gaseous ammonia (NH_3) by heterotrophic microorganisms that require organic carbon for energy. Hydrolysis involves the release of OH^- into the soil solution (equation 2) and has the potential to raise the soil pH which would affect other microbial N transformations. However, research suggests that the buffering capacity of soils is typically large enough to neutralize the release of OH^- from the oxidation of organic N (Rodríguez et al., 2005).

$$(NH_2)_2CO + H_2O \rightarrow NH_3 + H_2NCOOH \rightarrow 2NH_{3\,(g)} \quad (1)$$

$$NH_{3\,(g)} + H_2O \rightarrow NH_4^+ + OH^- \quad (2)$$

The rate of urea hydrolysis is dependent on the soil conditions that affect microbial activity, including enzyme production. Soil conditions that promote microbial activity will have higher rates of urea hydrolysis. The highest rates of microbial activity occur in aerobic environments with increasing soil temperature, water-filled pore space between 50 – 70 %, and a neutral soil pH (Fisher and Parks, 1958). Urease enzymes produced by soil microbes allow for the oxidation of urea to ammonium in natural soil environments by lowering the activation energy of the N transformation reaction. A diverse group of soil microbes produce urease enzymes making it available in most soil environments to some extent. The rate of urease activity is highly correlated with the level of soil organic carbon (SOC), generally resulting in higher urease activity going from a sandy to clay textured soils (Zantua et al., 1977). During moderately wet growing season conditions, claypan soils have warm, organic rich topsoil which promotes high rates of urea hydrolysis that can increase the potential for ammonia volatilization and other types of N loss associated with nitrification and denitrification. However, poor drainage typical of claypan soils in combination with rainfall can result in soil conditions that limit microbial activity and the potential for urea hydrolysis.

Ammonia Volatilization

Ammonia volatilization is a natural byproduct of the hydrolysis of urea, resulting in gaseous N loss as NH_3 gas and can be a significant contributor to the loss of applied urea fertilizers. The amount of $NH_{3\,(g)}$ volatilized is directly related to the rate of urea hydrolysis, including the ratio of NH_3 / NH_4^+ end products, and total [NH_3] in the soil. Substantial amounts of applied N fertilizers can be lost as $NH_{3\,(g)}$ if agricultural practices do not take into account soil conditions (i.e., pH, moisture content, temperature) which affect microbial activity, end product ratio of NH_3 / NH_4^+, and the total [NH_3]. Since NH_3 volatilization is a microbial process, the rate will increase with temperature and decrease during extreme saturated or dry soil conditions. However, conversion of NH_3 to NH_4^+ is a hydrolysis reaction (equation 2) and low moisture conditions will result in a greater end product ratio of NH_3 / NH_4^+. Potential for ammonia volatilization will significantly increase above a soil pH of 9.3, as NH_4^+ deprotonates to form NH_3 (equation 3).

$$NH_4^+ \leftrightarrow NH_3 + H^+ \quad \text{(pKa 9.3)} \tag{3}$$

Many practical agricultural management options exist to manipulate soil pH (e.g., liming) and water content (e.g., irrigation/drainage) that can reduce the potential for ammonia volatilization. However, manipulating soil pH and water content could adversely affect other N transformations which could lead to greater loss of applied N through nitrification and denitrification.

Nitrification

Nitrification is a two step microbial oxidation-reduction reaction involving NH_4^+ (-3 oxidation state) being oxidized to NO_2^- (+3 oxidation state) and then NO_3^- (+5 oxidation state). The main microbial population responsible for nitrification is chemoautotrophic bacteria (*Nitrosomonas* and *Nitrobacter*) who obtain energy from the oxidation of N. Oxidized soil conditions and microbial enzymes are required for nitrification to occur and will have a rate directly related to soil NH_4^+ concentration. Therefore, application of NH_4^+ fertilizers or soil conditions that promote high rates of urea hydrolysis or ammonification will have the highest rates of nitrification.

$$1/6\ NH_4^+ + 1/3\ H_2O \rightarrow 1/6\ NO_2^- + 4/3\ H^+ + e^- \quad (K_R = 10^{-15.1},\ E^o_H = -.893) \qquad (4)$$

$$1/2\ NO_2^- + 1/2\ H_2O \rightarrow 1/2\ NO_3^- + H^+ + e^- \quad (K_R = 10^{-14.1},\ E^o_H = -.834) \qquad (5)$$

Because nitrification reactions (equations 4 and 5) involve H_2O and H^+ protons, in theory soil water content and pH could affect the direction and rate of the reaction. However, soil water content and pH will have a larger effect on the rate of nitrification through its impact on soil microbial activity. Soil pH between 6 to 8 is ideal for nitrifying bacteria since the availability of carbonates and a variety of nutrients including macronutrients, and micronutrients that microbes also require will be at its highest within this soil pH range (Kyveryga et al., 2004). Factors which can limit nitrification are anoxic conditions, waterlogged soil, low soil pH and temperature, and lack of nitrifying organisms or inhibition of enzyme production.

Soil conditions which promote high rates of nitrification can lead to greater potential for N loss of applied fertilizers. Ammonium and NO_3^- are both plant available forms of N, but since NO_3^- is an anion there is reduced potential for adsorption to negatively charged soil particles (i.e., clay and SOM). This lack of interaction between soil surfaces and NO_3^- makes it more susceptible to loss through surface water runoff or leaching into groundwater. However, claypan soils typically have poor drainage through the claypan layer so the potential for leaching of NO_3^- is minimal; although lateral surface and subsurface flow is possible. Poor drainage means there may be greater concentration of soil NO_3^- available for plant uptake throughout the growing season, but also N loss through denitrification may be higher resulting in greater potential for soil N_2O emissions.

Denitrification

Denitrification is a multiple step oxidation-reduction reaction involving denitrifying soil microbes that reduce NO_3^- to dinitrogen gas (N_2). Denitrification can only occur in reduced environments or soil microclimates in absence of O_2 (i.e., anoxic conditions) in which NO_3^- is used as the electron acceptor during the microbial decomposition of organic matter. The presence of multiple enzymes are required for the complete reduction of NO_3^- to $N_{2(g)}$ under natural soil conditions. Nitrate and nitrite reductase allows for the reduction of NO_3^- to $N_2O_{(g)}$, while nitrous oxide reductase (NOS) is required for the reduction of $N_2O_{(g)}$ to $N_{2(g)}$. During anoxic periods in soil, the rate of denitrification will increase with acidity, enzyme availability, and soil NO_3^- concentration.

$$4\,(CH_2O) + 4\,NO_3^- + 4\,H^+ \rightarrow 4\,CO_2 + 2\,N_2O_{(g)} + 6\,H_2O \qquad (6)$$

$$5\,(CH_2O) + 4NO_3^- + 4H^+ \rightarrow 5\,CO_2 + 2\,N_{2\,(g)} + 7\,H_2O \qquad (7)$$

End-Products Ratio of Denitrification

The molar fraction of $N_2O/[N_2O + N_2]$ emitted through microbial denitrification will vary depending on the soil water content, nitrate and nitrite concentrations, pH, and NOS activity (Bergsma et al., 2002). Nitrous oxide reductase availability is highly related to soil conditions since NOS is not stable under dry soil conditions and cannot be produced by denitrifying bacteria until saturated, anoxic soil conditions are present

(Bergsma et al., 2002; Brandt et al., 1964). As a result, the molar fraction of $N_2O/[N_2O + N_2]$ increases as a soil becomes more oxic, and will be at its greatest directly after a rainfall preceded by a dry period (Bergsma et al., 2002). Besides enzyme production and availability, soil conditions with a pH above 6.0, and high soil moisture levels promote the complete reduction of NO_3^- to N_2 which lower the molar fraction $N_2O/[N_2O + N_2]$ of denitrification end products (Bergsma et al., 2002).

Agricultural Implications

Denitrifying bacteria include a broad range of organisms that are found in most soil environments, leading to potential N loss in most agricultural soils that experience anoxic periods with NO_3^- present. Yet in most agricultural soils, N loss through denitrification is typically much lower compared to leaching and ammonia volatilization losses. However, physical properties of claypan soils limit NO_3^- leaching and promote saturated soil conditions resulting in a greater percentage of applied N to be lost as N_2 and N_2O through denitrification than most soils. Selecting management practices which can reduce the potential for denitrification N loss will be important to mitigating soil N_2O emissions from agricultural practices on claypan soils.

Properties of Claypan Soils and Rainfall Distributions Impact on the Amount and Forms of Nitrogen Loss

Properties of Claypan Soils

Claypan soils are characterized as containing a sub-soil layer that has at least 100% higher clay content than the overlying horizon and are commonly found 20-40 cm below the soil surface (Jung et al., 2006; Myers et al., 2007). The central claypan region covers an area of 4 million ha and it includes parts of Missouri, Illinois, and Kansas

(Noellsch et al., 2009). Water permeability through the claypan layer is low and typically restricts the drainage of water. As a result, claypan soils exhibit extended periods of saturation after rainfall events which promote denitrification loss of N, while the potential nitrogen (N) loss from nitrate (NO_3^-) leaching is relatively low. Due to characteristics, claypan soils can lose an abnormally high percentage of applied N through runoff and gaseous emissions of N (i.e., ammonia volatilization and denitrification) which can significantly lower N recovery, plant uptake, and crop yield. However, the amount of N loss as a result of runoff and denitrification in a claypan soil will vary considerably due to the distribution of rainfall in relation to N application and availability.

Rainfall Distribution's Impact on Nitrogen Loss

In general, greater total rainfall in a growing season results in an increased potential for denitrification leading to greater soil N_2O emissions. However, the distribution of the total rainfall in relation to microbial activity, concentrations of N species present, and level of NOS is essential to fully understanding the variability in total N loss and N_2O emissions from one season to another.

Wetting and drying cycles occur in all soils, but the number of cycles and the magnitude of each cycle will be dependent on the rainfall amount and distribution. Wetting and drying cycles can significantly affect N_2O emissions from application of urea-based fertilizers because nitrification requires moderately wet, oxic soil conditions while denitrification requires saturated, anoxic soil conditions. The magnitude and length of each wetting and drying cycle in relation to N application will, therefore, affect the concentration of NO_3^- available for denitrification when soils are saturated with water.

During drying periods the rate of denitrification dramatically decreases from 100% to 20% water-filled pore space while denitrification rates dramatically increase upon wetting up to 60% water-filled pore space (Groffman and Tiedje, 1988). When NO_3^- is not limiting, the length of time a soil remains saturated will also affect the rate and total N lost through denitrification. Due to drainage properties, fine textured soils have a longer dry down period after rainfall than sandy soils. This has been reported to cause higher potentials for denitrification and soil N_2O emissions over longer periods than well drained soils, resulting in significantly higher N_2O and N_2 emissions (Sexstone et al., 1985).

Impact of Agricultural Management on Soil Nitrous Oxide Emissions

Conventional and Conservation Tillage Practices

Different tillage practices used in agricultural management systems can impact soil N_2O emissions by altering soil physical properties which affect the rates of microbial N transformations in soil. Conservation tillage practices which include no-till (NT) require a minimum of 30% of the crop residues to remain on the soil surface which minimizes soil disturbance, soil erosion, and increases soil fertility and the amount of sequestered carbon (Triplett and Dick, 2008). A national survey conducted by the Conservation Technology Center reported NT practices on agricultural soils in the United States increased from 6 to 22.6% (62.4 million acres) from 1990 to 2004 (Conservation Technology Information Center, 2006). However, soil N_2O emissions may increase switching from conventional tillage (CT) to NT due to increased soil bulk density within the top 30 cm (Mosier et al., 2006) and slower drying periods after rainfall events due to surface residues can increase the periods of anaerobic, saturation soil conditions (Blevins and Cook, 1971), water-filled pore space (Linn and Doran, 1984), resulting in greater microbial activity involved with denitrification and subsequent N_2O emissions (Six et al., 2004). Increased soil emissions of N_2O with the adoption of NT practices could offset CO_2 mitigation resulting in a global warming impact similar to CT practices (MacKenzie et al., 1997; Six et al., 2004; Grandy et al., 2006).

Recent advancements in conservation tillage technology now allow for minimal tillage practices (MT) which maintains the stipulations set forth for conservation tillage but do include some degree of tillage. Strip-tillage (ST) is an example of minimal tillage, which tills only the seed row, leaving majority of the soil area non-disturbed. Therefore, ST can potentially to retain most of the soil conservation benefits associated with NT practice and reduce soil N_2O emissions by allowing deep placement of dry N fertilizers (i.e., urea) under soil conditions less conducive for denitrification. A two-year field study conducted in Ontario, Canada found that zone tillage (21 cm width, 15 cm depth), which in principle is the same as ST had 20% lower cumulative soil N_2O than NT (Drury et al., 2006). However, researchers examining strip till have not evaluated whether placement of N in the tilled rows is an effective alternative to NT in terms of reducing soil N_2O emissions.

Researchers investigating the differences in cumulative soil N_2O emissions between CT and NT practices have reported higher emissions with NT (MacKenzie et al., 1997; Baggs et al. 2003; Venterea et al., 2005; Almaraz et al., 2009), while other studies have reported similar to lower emissions with NT (Robertson et al., 2000; Elmi et al., 2003). These contrasting results are possibly due to differences in soil type, N management practices, and climate. Fine-textured soils have relatively poor soil structure and a lower proportion of macropores which lead to slower drainage and a greater potential for saturation conditions. Tilling of fine textured soils may increase the drainage and reduce the periods of saturated, anaerobic conditions which may have accounted for lower soil N_2O emissions from CT compared to NT (Almaraz et al., 2009). Coarser textured soils with naturally good drainage may show little difference in soil N_2O emissions between CT and NT practices (Rochette et al., 2008). In addition to site conditions and management practices, significant differences in soil N_2O emissions between CT and NT can be reversed depending on variation in weather over growing seasons (Halvorson et al., 2008; Halvorson et al., 2010).

Nitrogen Fertilizer Placement and Distribution

Placement of N fertilizer can impact soil N loss which may also affect daily and cumulative soil N_2O emissions depending on where (e.g., surface applied or at depth in soil) and how (e.g., broadcasted and banded) the N fertilizers are applied to the soil. Surface applications of N have been reported to increase soil N_2O emissions with CT practices (Halvorson et al., 2008). No-till management typically restricts N placement of dry N fertilizers (e.g., urea) to surface broadcasting and banding. Placement of N in concentrated bands within the soil profile can reduce the rates of nitrification and denitrification (Grant et al., 2010) which could reduce the total amount of applied N fertilizer lost as N_2O. Use of CT and MT expand N placement options of dry N fertilizers to allow for specific fertilizer placement at depths ranging from shallow (≈2 cm) to deep

(≈20 cm). Research suggests that the ideal placement of N to reduce soil N_2O emissions will depend on the tillage practice and how much crop residue is left on the soil surface, fertilizer source, and rainfall events after application (Halvorson et al., 2010). There are many different studies looking at crop management's effect on soil N_2O emissions, but limited research has isolated N placement as a single factor, presumably due to the confounding of placement with tillage and N fertilizer source. However, different environmental conditions associated with where and how N fertilizers are applied will affect the rate of release from urea based fertilizers and subsequent microbial N transformations leading up to soil N_2O emissions.

No-till practices do not incorporate surface residues within a soil. As a result, these practices can increase soil water content causing reduced soil temperature and microbial activity early in the growing season leading to lower rates of soil N mineralization (Kuzyakov et al., 2000) and higher soil N_2O emissions from surface broadcast applications over that period (Halvorson et al., 2010). In comparison, tilling a soil will reduce soil bulk density in the topsoil by breaking up soil aggregates, incorporating crop residues, and increase temperature that elevates soil microbial activity earlier in the spring and potentially increases soil N_2O emissions from shallow placement of N. Deep placement of N fertilizers will typically have reduced soil temperature and soil organic matter levels compared to surface placement which may further reduce microbial activity and soil N_2O emissions. A recent study found cumulative soil N_2O emissions from urea applications deceased with depth (2.5, 5.0, and 7.5 cm depth), with placement at 5.0 and 7.5 cm depth having a 35 and 77% reduction in emissions, respectively, to shallow placement of N (Khalil et al., 2009). In contrast, a study in 2006 found deep placement (10 cm) increased cumulative soil N_2O emissions by 26% over shallow placement (2 cm) of N when the results were averaged over three tillage practices (NT, MT, CT) and growing seasons (Drury et al., 2006). Overall, deep placement of N may reduce soil N_2O emissions from agricultural soils. These mixed research results reinforce the importance of site-specific factors that influence the effects of N placement and agricultural management on soil N_2O emissions.

The method of fertilizer distribution may also be an important factor affecting soil N_2O emissions. The main difference between broadcasting and banding fertilizers is the resulting surface area of the N fertilizer in contact with soil microbes. Broadcasting results in the greatest amount possible of the surface area of N fertilizer applied in contact with soil microbes, potentially resulting in higher rates of N mineralization. In contrast, banding of N fertilizers will minimize the surface area of N in contact with soil microbes which presumably reduces the rate of N mineralization and soil N_2O emissions. However, recent research found greater cumulative soil N_2O emissions from banding than broadcasting N fertilizers on the soil surface (Engel et al., 2010). More in-depth studies will be required to elucidate the impact of broadcasting and banding of applied N fertilizers on soil N_2O emissions in combination with site conditions and management.

Traditional and Enhanced Efficiency Nitrogen Fertilizers

Global increases in the application of N fertilizers are the main reason soil N_2O emissions from agricultural practices have dramatically increased over the past 30 years (Smith et al., 2007). Unfortunately, reducing the amount of N fertilizer applied in agricultural practices is not a practical option. One alternative is to select N fertilizer sources that will minimize soil N_2O emissions as much as possible. Urea is the most used N fertilizer source and accounts for 43% of the global N fertilizer sales (Bouwman et al., 2002). Urea fertilizers have been found to significantly reduce soil N_2O emissions compared to anhydrous ammonia fertilizers (Venterea et al., 2010). These results demonstrate the potential of using urea based fertilizer to minimize soil N_2O emissions from agricultural practices.

Enhanced efficiency urea fertilizer products could potentially minimize soil N_2O emissions to an even greater extent. Polymer-coated urea (PCU) is an enhanced fertilizer product which encases urea within a polymer coat of varying thickness. Addition of the polymer coat should slow or delay the rate of urea hydrolysis compared to traditional urea fertilizers. With PCU, urea must first dissolve within the prill, then at a rate dependant on soil temperature and moisture, diffuse out of the polymer coat before the urea can be transformed by soil microbes in other N forms (Fujinuma et al., 2009). Slowing or delaying the release of urea may potentially reduce the amount of available N for nitrification and denitrification throughout the growing season resulting in a lower potential for soil N_2O emissions. Limited research has evaluated whether PCU can significantly reduce soil N_2O emissions compared to traditional urea fertilizers. However, one study conducted in 2005 through 2006 found strong evidence that PCU does delay and lower soil N_2O emissions in relation to urea (Halvorson et al., 2008). Over a three year study conducted an irrigated potato field under CT reported soil N_2O emissions from surface-applied PCU ranged from 0.10 to 0.15% compared to 0.25 to 0.49% with a split surface application of traditional urea (Hyatt et al., 2010). While surface banding PCU in an irrigated, NT, and continuous corn rotation reduced soil N_2O emissions by 49% compared to traditional urea, emissions were not significantly different under CT (Halvorson et al., 2010). Differences in the effectiveness of reducing soil N_2O emissions with PCU compared to traditional urea may be related to tillage's effect on soil conditions and the soil microclimate. Limited research has already demonstrated PCU's potential to minimize soil N_2O emissions compared to traditional urea fertilizer, the same research also suggests that site specific conditions and management may have a significant effect on PCU's ability to reduce soil N_2O emissions.

Agricultural Management's Effect on Crop Yields

Leguminous Cover Crops

Crop rotations that include winter legume cover crops interseeded or planted after fall harvest have the potential to reduce N application requirements while sustaining high crop yields the next year. Leguminous cover crops have the ability to fix atmospheric N, and immobilize residual N which can be used to significantly increase soil N when incorporated with tillage or killed with a herbicide. Additional benefits of these cover crops include improved soil aggregation, structure, organic matter, and protection against soil erosion. Adopting the use of cover crops in crop rotations, such as red clover (*Trifolium pratense* L.), has great potential to sustain high crop yields while reducing the required rates of N applied, and environmental impact associated with N fertilizer loss.

Research efforts to determine the benefits of incorporating red clover into crop rotations on increasing soil N and yields have had mixed results. In a five-year field study located in New York, addition of wheat/red clover into a corn/soybean rotation increased corn grain yields by 4 and 6% for ridge and moldboard plow tillage, respectively (Katsvairo and Cox, 2000). However, it was not determined whether yield increases were due to increased soil N levels through N fixation and/or improved soil properties. A recent three-year study over two locations with red clover interseeded or planted after wheat harvest found only one site year that red clover significantly increased soil N (90 kg N ha^{-1}); however, corn yields were improved due to non-N related benefits (Henry et al., 2010). A similar study evaluating five cover crops (i.e., rye, oilseed radish, oat, red clover, no cover crop) measured soil NO_3^--N levels to be 24% higher for red clover than the other cover crops after incorporation or spring chemical kill, resulting in significantly greater corn grain yields (Vyn et al., 2000).

Timing of Nitrogen Application

Timing and frequency of N application can significantly affect plant uptake of applied N and crop yields. The optimal single application timing is typically around planting since it will minimize the period of time between application and plant N uptake. Earlier application of N will have greater potential for N loss through leaching, erosion, volatilization, denitrification and inefficient uptake of applied N (Balkcom et al., 2003), but actual N loss and plant recovery will vary depending on the weather. Dry and cold weather conditions between fall application and planting can minimize N loss and yield reductions associated with fall applications; however, warm and wet springs have been reported to reduce grain yields and N recovery by 20 and 42%, respectively, compared to preplant applications (Vetsch and Randall, 2004). Differences in yield production between fall and preplant applications will typically be magnified during growing seasons with optimal or high rainfall in the fall; poor growing season conditions can substantially increase N loss in preplant applications and delay plant growth which can minimize yield differences between fall and preplant N applications. A four year study examining the effects of fall versus spring N fertilizer applications on corn production under NT management in Texas found the greatest yield reduction (48%) of fall compared spring applied N fertilizer to have occurred in the year with the most optimal conditions for high yield production, while reductions became less significant with poorer growing conditions (Torbert et al., 2001). Although, significant yield reductions with fall N applications do not occur every season, spring applications of N will produce significantly higher yields when averaged over multiple seasons (Randall et al., 2003a).

Even with lower crop N recovery and yield production, application of N in the fall is a common agricultural practice. This preference for fall N application is often due to individual farmers managing large acreages which creates logistical issues with applying N in the same time period as planting operations, as well as lower N fertilizer costs in the fall, and wet field conditions associated with wet springs (Scharf et al., 2002). Initiating N fertilizer applications as early as March (i.e., early preplant) may minimize the potential for N loss that occur with fall applications while avoiding time conflicts and wet field conditions associated with preplant applications. Expanding current research efforts to include N applications ranging from fall to preplant will help to determine the optimal application timing resulting in the greatest overall yield production.

Conventional and Conservation Tillage Practices

The large increase in the adoption of NT practices since the 1980’s have had a positive impact on the environment and producers. Minimum soil disturbance associated with NT practices has increased soil fertility, structure, and reduced the potential for soil erosion (Triplett and Dick, 2008). Agricultural producers that have switched from CT to NT have directly benefited as well through a reduced time commitment (35.9%) and fuel cost (36%) when not tilling a soil compared to CT (Lithourgidis et al., 2005). Adoption of NT has also been reported to increase carbon storage in soils (Lal et al., 1994; Campell et al., 1995; Campell et al., 1996) which may help reduce atmospheric CO_2 concentrations. There are research studies that did not find increased carbon storage in agricultural soils converted to NT practices (Paustian et al., 1995; Angers et al., 1997; Needleman et al., 1999).

Research has shown that adoption of NT practices can produce similar or higher yields than CT (Mehdi et al., 1999; Torbert et al., 2001; Al-Kaisi and Licht, 2004; Al-Kaisi and Kwaw-Mensah, 2007), but lower yields have also been reported (Vetsch and Randall, 2004; Halvorson et al., 2006). Research has shown NT practices result in higher moisture contents, and lower soil temperatures in the spring due to surface residue cover (Mehdi et al., 1999), which in other research was assumed to be responsible for reduced plant emergence (Hendrix et al., 2004; Licht and Al-Kaisi, 2005a; Lithourgidis et al., 2005), and delayed plant growth (Licht and Al-Kaisi, 2005b; Halvorson et al., 2006). Lower yields reported in NT compared to CT have been attributed to slow spring development, delayed tasseling, or reduced N uptake (Halvorson et al., 2006; Vetsch and

Randall, 2004). High amounts of N loss from dry N fertilizers (i.e., urea) in NT practices can be attributed to the requirement of surface applications which typically have soil conditions more conducive to microbial activity than deep placement within the soil (Khalil et al., 2009). Humid environments and wet growing seasons promote lower plant populations, delay growth, and increased gaseous N loss which can lower yield potentials in NT systems (Drury et al., 1999; Lithourgidis et al., 2005; Drury et al. 2006).

Minimal tillage practices, such as ST, may be the best long term soil conservation tillage practice to produce high yields in humid environments and/or poorly drained soils, while also minimizing yield reductions in growing seasons with poor growing conditions. Although research is limited, one study has shown that ST can produce as high of yields as NT, while significantly improving yields during seasons with conditions favoring low yield production in NT (Al-Kaisi and Licht, 2004). However, variation in weather may also affect whether ST produces significantly higher yields than NT. A two location study with the same soil types found only one location had significantly higher yields with ST (Licht and Al-Kaisi, 2005). Other studies could only conclude that ST produced similar yields compared to NT, presumably due to limited years of evaluation, site locations, and/or climatic variation between seasons (Al-Kaisi and Kwaw-Mensah, 2007; Vetsch and Randall, 2004). Preliminary research has shown that ST practices can at least produce yields similar to NT practices. Research conducted in varying locations is needed to conclude whether ST can significantly increase overall yield production compared to NT.

Nitrogen Fertilizer Placement and Distribution

In order to minimize N loss and maximize yields through optimal N placement, microbial N transformations should convert fertilizer N into plant available N forms during the periods of highest plant needs. Placements that have higher microbial activity will typically have a greater potential for N loss (e.g., surface applied or shallow placement) and lower yield production (Riedell et al., 2000). However, placement options can be limited depending on the tillage practice and fertilizer source. In-soil banding of liquid N fertilizers (i.e., UAN) can be done in CT and NT practices, and have been found to increase yields in both systems (Halvorson et al., 2006; Vetsch and Randall, 2000). These results are most likely due to reduce microbial activity involving N transformations (i.e., urea hydrolysis, nitrification, and denitrification) leading to greater plant uptake of applied N. Use of dry N fertilizers (i.e., urea) in NT practices typically require application to the soil surface which can lower yield potentials due to an increased vulnerability to ammonia volatilization and immobilization of N within surface residues (Malhi et al., 2001). However, the overall impact of N placement on potential N loss and yield production is often not clear in agronomic research because of interactions between tillage and the N fertilizer source.

Nitrogen placement in relation to the seed row can also affect yield production due to impacts on seed damage and emergence. High rates and concentrated placement of N within the soil profile in close proximity to seed rows increase the potential for seed damage due to salt toxicity (Gerwing et al., 1996), resulting in lower plant populations and yields. However, it is still a common agricultural practice to apply N fertilizer in the seed row at the same time as planting to minimize production costs, labor, and soil disturbance (Zentner et al., 2002). Many research studies have reported increased seed damage with close N application to the seed row which paralleled reductions in yield (O'Donovan et al., 2008; Rehm and Lamb, 2009). Seed damage and reduced emergence due to placement of N in the seed row may also be magnified in sandy textured soils (Rehm and Lamb, 2009). The potential for seed damage can be minimized with deeper and/or further N placement from the seed row, but may require higher costs, labor, and soil disturbance (O'Donovan et al., 2008). Reducing seed damage and improving seed emergence could lead to greater yield production; however, applying N farther away from the seed row could also reduce the amount of fertilizer N available to plants resulting in yield reduction.

Traditional and Enhanced Efficiency Nitrogen Fertilizers

Differences in yield production between N fertilizer sources will be largely dependent on the ability to provide plant available forms of N (i.e., NH_4^+, NO_3^-) in adequate concentrations in synchrony with plant uptake needs. Yields have been found to increase with plant uptake of applied N (Al-Kaisi and Yin, 2003). The amount of plant available N present over time after N application will depend on a variety of factors, including soil physical properties, regional climate, application timing, tillage practice, and N placement. Based on these fixed factors, agricultural producers can select an N fertilizer source which favors N availability closest to plant needs resulting in the greatest yield potential. However, variation in weather will significantly affect the rates of microbial N transformations from one season to another. Therefore, even with the same fixed factors, the temporal pattern in plant available N concentrations from an applied N fertilizer can be drastically different over multiple seasons, making selection of the optimal N fertilizer source for yield production very challenging. Selecting a fertilizer source less susceptible to variations in weather conditions may be the best option to increase overall yield production by minimizing low yields in poor growing seasons.

Urea-based fertilizers are the most popular in the world and account for 43% of global N fertilizer sales (Bouwman et al., 2002). Nitrogen loss from applied urea fertilizer can be very susceptible to weather. Urea is highly soluble and has a large potential for N to be lost through leaching in sandy soils (Wilson et al., 2009) and lateral transport in poorly drained soils. Besides leaching and lateral flow, ammonia volatilization after application of urea can contribute to N loss (Rochette et al., 2009b). Contrary to ammonium and nitrate based fertilizers, urea must go through urea hydrolysis/ammonification before it is in a plant available form of N. Volatilization loss from urea fertilizers is common, but management practices, such as fall application and/or surface placement, can increase the overall potential and/or rate of volatilization loss (Sommer et al., 2004). The amount of applied urea lost as $NH_{3(g)}$ has been reported to range from 9-65% when applied on the soil surface (Sommer et al., 2004; Rochette et al., 2009a; Rochette et al., 2009b). Volatilization loss from surface applications of urea can be minimized if applied directly before rainfall or irrigation event. Typically conditions within the soil profile have lower microbial activity related to urea hydrolysis and potential for volatilization loss. Leaching of urea in claypan soils may be limited, but significant N loss and yield reductions can occur due to volatilization loss, denitrification, and possibly lateral flow.

Polymer-coated urea fertilizers are designed to have a slower release rate than traditional dry urea fertilizers (Wilson et al., 2009), which may reduce the potential for volatilization and leaching N loss (Blaylock et al., 2004, 2005; Motavalli et al., 2008). Surface applications of urea fertilizers have resulted in 60% reductions in volatilization loss with PCU (Rochette et al., 2009b). Research comparing traditional dry urea fertilizer and PCU has been reported to increase yield production in corn (Blaylock et al., 2004, 2005) and potatoes (Zvomuya et al., 2003), presumably due to slower release rates resulting in lower amounts of N loss. Coating urea with a polymer can minimize N loss associated with urea by limiting the movement and the amount of urea available throughout the growing season which can undergo microbial transformations that result in N loss. Limiting the release of urea throughout the growing season with PCU has been reported to minimize N loss in poorly drained, low lying areas (Noellsch et al., 2009) and in sandy soils during high rainfall growing seasons (Zvomuya et al., 2003). However, yields obtained using PCU could be similar or worse than traditional urea if the slower release rates do not provide adequate amounts of available N in conjunction with plant needs. Research has shown that the slower release rate from PCU can increase yield production over traditional dry urea fertilizer, but benefits in yield production will depend on the interaction of management systems, soil properties, moisture conditions, and weather.

Objectives

Primary Research Objective

To determine if alternative tillage or N management practices can increase crop production and/or reduce soil N_2O emissions in claypan soils in Northeast Missouri.

Specific Research Objectives

1. To evaluate the differences in daily and cumulative soil N_2O emissions throughout the growing season due to tillage/fertilizer placement (strip-tillage/deep banding and no-tillage/surface broadcasted) and N source (non and polymer coated urea).
2. To assess the differences in the amount of N_2O emitted per bushel of corn grain produced between treatments.
3. To determine the period of time after N application that soil N_2O emissions are above natural background emissions.
4. To determine the effects of variability in weather and soil conditions including daily/annual rainfall, soil temperature, and water content on the soil N_2O flux.
5. To evaluate differences in corn grain response due to N application timing (i.e., fall, early preplant, preplant), tillage/fertilizer placement (i.e., strip-tillage/deep banded and no-tillage/surface broadcasted), and N fertilizer source (i.e., non- and polymer-coated urea) including a fertilized check (i.e., anhydrous ammonia) and a non-fertilized control.
6. To assess the differences in NT wheat yields due to N source, application rate, and N application timing.

7. To determine the impact of winter wheat management (i.e., N source, rate, application timing) on soybean yields in a wheat-soybean double-crop production system.

Hypotheses

Specific Research Hypotheses

1. Strip-tillage with deep banding placement and/or PCU fertilizer will have lower cumulative soil N_2O emissions when compared to NT with surface broadcasting and/or NCU fertilizers due to greater uptake of applied N by the corn plants.

2. Strip-tillage with deep banding placement and/or PCU treatments will have the greatest corn grain yields and lowest cumulative soil N_2O emissions resulting in the least amount of N_2O emitted per bushel of corn grain produced compared to NT with surface broadcasting and/or NCU fertilizers treatments.

3. The period of time when significant soil N_2O emissions begins to occur after N fertilizer application will depend upon the soil temperature and rainfall events.

4. The rate of N_2O emitted will be greater under higher soil temperatures and water contents but the magnitude of these increases will be directly linked to the number of days after N application and recent rainfall activity.

5. All preplant N applications will have significantly greater corn grain yields than fall applied N applications. Strip-tillage with deep banded placement and/or PCU fertilizers will have greater grain yields than NT surface broadcasted and/or NCU fertilizer due to better plant populations and enhanced N use efficiency.

6. Potential yield benefits with blending PCU and NCU compared to NCU fertilizer will depend on the application timing, with 100% PCU and 50%PCU/50%NCU having the greatest yield benefits with fall and early spring applications, respectively.
7. Residual N from a spring applications of PCU could be utilized by double-cropped soybean as indicated by grain yield and protein concentration in soybean.

Arrangement of the Thesis

This thesis contains three chapters which have been organized in a standard research journal format. All chapters provide crop production results of field experiments conducted in Northeastern Missouri at the Greenley Memorial Research Center in Novelty. Chapter 2 also includes soil N_2O emission data collected from a portion of the corn yield production experiment described in chapter 3. A final concluding chapter is added to provide a synthesis of the thesis research.

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CHAPTER 2

NITROUS OXIDE EMISSIONS FROM CLAYPAN SOILS DUE TO NITROGEN FERTILIZER SOURCE AND TILLAGE/FERTILIZER PLACEMENT PRACTICES

ABSTRACT

Agricultural practices on poorly drained claypan can have high amounts of applied N lost through denitrification and, therefore, can be a major contributor to soil nitrous oxide (N_2O) emissions. Nitrous oxide emissions can have a large impact on global warming and ozone depletion. Nitrogen fertilizer source and placement can influence soil N_2O emissions by affecting the concentration of soil ammonium and nitrate available for nitrification and denitrification. The objectives of this research were to quantify the effect of tillage/fertilizer placement (i.e., no-till/surface broadcast and strip-till/deep banded) and N fertilizer source (i.e., non-coated urea (NCU), polymer-coated urea (PCU), non-treated control) on soil N_2O emissions from agricultural practices in claypan soils. Soil N_2O emissions were measured and analyzed using vented, static chambers and gas chromatography, following the USDA GRACEnet protocol for field measurement of trace gases. The field experiment was conducted in corn production (*Zea mays* L.) over the 2009 and 2010 growing season in a claypan soil in Northeast Missouri. The experimental design consisted of six treatments with three replications and two subsamples for gas flux measurements in each plot. All the plots were arranged in a randomized complete block design. No significant interaction was found between N fertilizer source and tillage/fertilizer placement ($P < 0.05$). Polymer-coated urea did not significantly lower cumulative growing season emissions of N_2O compared the NCU fertilizer. Averaged over 2009 and 2010, no significant differences were observed in cumulative soil N_2O emissions, due to N fertilizer source which ranged from 5.21 (NCU) to 5.48 (PCU) kg N_2O-N ha^{-1}. These N_2O-N losses represented between 2.8 to 3% of annual fertilizer N applied. Although not statistically different, cumulative soil N_2O emissions from strip-till/deep banded N placement averaged 3.66 kg N_2O-N ha^{-1} which were not significantly different than 4.34 kg N_2O-N ha^{-1} averaged with no-till/surface broadcast treatments. The alternative management options, of PCU and strip-till/deep banding, both produced significantly ($P < 0.05$) higher yields than their conventional management counterparts (i.e., NCU and no-till/surface broadcast). Combining cumulative growing season N_2O emission with grain yield revealed strip-till/deep banded N placement emitted significantly less N_2O (0.2 kg N_2O-N) per Mg grain produced compared to no-till/surface broadcasted N.

INTRODUCTION

Agricultural Emissions of Soil Nitrous Oxide and the Environmental Implications

From 1970 to 2007, global emissions of N_2O have increased 50%. During this time, emissions from industrial sources have decreased while emissions from agricultural sources have increased (Smith et al., 2007). Agricultural practices in the United States account for approximately 78% of the anthropogenic N_2O emissions, with 38% of agriculturally produced N_2O emitted from the soil (USEPA, 2007). Future global N_2O emissions are projected to increase 35 to 60% by 2030 due largely to the projected increase in global N fertilizer use and animal production (FAO, 2003). Increasing levels of N_2O in our atmosphere can have significant environmental consequences because N_2O

in the atmosphere has a residency time of a decade up to centuries, global warming potential 297 times that of CO_2, and is a precursor gas to ozone (Venterea et al., 2005; Smith et al., 2007).

Properties of Claypan Soils Related to Soil Nitrous Oxide Emissions

Claypan soils are characterized by a subsoil layer that has at least 100% higher clay content than the surface horizon immediately above it, and are commonly found 20 to 40cm below the soil surface (Jamison et al., 1968; Jung et al., 2006; Myers et al., 2007). Water permeability through the claypan layer is low and typically restricts the drainage of water. The central claypan region covers 4 million ha and is composed of parts of Missouri, Illinois, and Kansas (Noellsch et al., 2009). Mitigation of soil N_2O emissions from agricultural practices through alternative management in this region is important since the restrictive claypan layer favors saturated conditions and minimal leaching of nitrate which can result in higher than average fertilizer N loss as N_2O (Bailey, 2005) Higher percentages of applied N fertilizers being lost as N_2O from claypan soils can adversely affect the environment. Selecting management that can optimize N recovery and plant uptake of applied N fertilizers will minimize soil N_2O emissions from these agricultural practices while still insuring high agricultural yields.

With poorly drained soils, higher total rainfall in a growing season will typically increase denitrification and soil N_2O emissions (Sexstone et al., 1985). However, longer periods of saturation may actually lower N_2O emissions with conditions favoring the complete transformation of NO_3^- to N_2 gas which lowers the end product ratio of N_2O/N_2. Wetting and drying cycles can also significantly affect N_2O emissions from applied urea-based fertilizers since nitrification requires dry, oxic soil conditions while denitrification requires saturated, anoxic soil conditions. The magnitude and length of each wetting and drying cycle in relation to N application will, therefore, affect the concentration of NO_3^- available for denitrification during saturated periods.

Mitigation of Nitrous Oxide Emissions from Agricultural Soils

Mitigation of soil N_2O emissions from agricultural practices will be difficult since it is estimated that global food production will need to double by 2050 in order to feed the exponentially growing global population (Lal, 2007). Minimizing soil N_2O emissions from high yielding cropping systems is a practical option to reduce total emissions of N_2O from agricultural soils. Accomplishing this will require selecting the best agricultural management practices that work with and/or manipulate soil conditions to manage soil microbial N transformations in a way which promote increased recovery of applied N fertilizers through plant uptake.

Tillage Practices

Tillage practices used in agricultural management systems can impact soil N_2O emissions by altering soil physical properties, and soil conditions which affect the rates of microbial N transformations in soil. No-till (NT) is a conservation tillage practice has many benefits including reduced potential for soil erosion, increased soil fertility, and a greater potential to sequester carbon (Triplett and Dick, 2008). A national survey conducted by the Conservation Technology Information Center reported that the amount of agricultural land on which NT was practiced in the United States increased from 6 to 23 % (25.3 million ha^{-1}) from 1990 to 2004 (Conservation Technology Information

Center, 2006). However, potential disadvantages of switching from conventional tillage (CT) to NT may include an increased bulk density within the top 30 cm (Mosier et al., 2006) and slower drying periods after rainfall events due to surface residues which can increase the periods of anaerobic, saturation soil conditions (Blevins and Cook, 1971), resulting in greater microbial activity involved with denitrification and subsequent N_2O emissions (Six et al., 2004). Increased emissions of N_2O have been reported in NT practices (Almaraz et al., 2009) and could offset CO_2 mitigation resulting in a global warming impact similar to CT practices (MacKenzie et al., 1997; Six et al., 2004; Grandy et al., 2006). However, no significant difference in soil N_2O emissions between CT and NT practices were found in a study conducted on coarser textured soils, presumably due to naturally good drainage (Rochette et al., 2008). Variation in these results could be caused by differences in soil type, fertilizer source, and regional climate. Besides site conditions and management practices, significant differences in soil N_2O emissions between CT and NT can vary depending on changes in weather over growing seasons (Halvorson et al., 2008; Halvorson et al., 2010).

Nitrogen Placement and Distribution

The N fertilizer application method can impact N losses including daily and cumulative soil N_2O emissions. The fertilizer application methods include how (e.g., broadcast or banded) and where (e.g., surface-applied and shallow or deep placement) the fertilizer is applied. No-till management typically restricts N placement of dry N fertilizers (i.e., urea) to surface broadcasting and banding. Broadcasting N fertilizers results in a more uniform spreading of N fertilizer over the soil surface potentially causing greater soil contact with the fertilizer granule and higher rates of several N processes including ammonia volatilization, nitrification and denitrification. In contrast, banding of N fertilizers may minimize N fertilizer granule contact with soil microbes which presumably reduces the rate of ammonia volatilization and soil N_2O and N_2 emissions (Grant et al., 2010).

Soil tillage expands N placement options of dry N fertilizers to allow for broadcasting and banding at depths ranging from shallow (≈2 cm) to deep (≈15 cm), respectively. Deep placement of N fertilizers will typically place fertilizer at soil depths which have relatively lower soil temperature and total organic carbon levels compared to the soil surface and shallow depths. Resulting from these conditions at deeper soil depths, deep placement of N fertilizers may expose fertilizer to reduced soil microbial activity and lower soil N_2O emissions. A recent study found cumulative soil N_2O emissions from urea decreased with application depth (i.e., 2.5, 5.0, and 7.5 cm depth), with placement at 5.0 and 7.5 cm depth having a 35 and 77% reduction in emissions, respectively, compared to shallow placement of N (Khalil et al., 2009). However, a study in 2006 averaged over three tillage practices [NT, minimal tillage (MT), CT] and multiple growing seasons found deep placement (10 cm) increased cumulative soil N_2O emissions by 26% over shallow placement (2 cm) of N (Drury et al., 2006).

Strip-tillage

Recent advancements in conservation tillage technology now allow for MT which maintains the stipulations set forth for conservation tillage but do include some degree of tillage. Strip-tillage (ST) is an example of minimal tillage, which tills only the seed row, leaving majority of the soil area non-disturbed. Therefore, ST can potentially to retain most of the soil conservation benefits associated with NT practice and reduce soil N_2O emissions by allowing deep placement of dry N fertilizers (i.e., urea) into soil conditions less conducive for denitrification. However, researchers examining ST have not evaluated whether placement of N in the tilled rows is an effective alternative to NT in terms of reducing soil N_2O emissions. No-till has been reported to reduce yields in some situations which was attributed to slow spring period development, delayed tasseling, or reduced N uptake compared to CT (Halvorson et al., 2006; Vetsch and Randall, 2004). Improved seedbed conditions with ST in poorly drained soils may increase grain yields over NT by promoting higher plant populations which can reduce the amount of N_2O lost through higher overall plant uptake of applied N. Although research is limited, one study has shown that ST can produce yields as high as NT, while significantly improving yields during seasons with conditions favoring low yield production in NT (Al-Kaisi and Licht, 2004). However, variation in weather may also affect whether ST produces significantly higher yields than NT. A two location study on the same soil found only one location had significantly higher yields with ST (Licht and Al-Kaisi, 2005). Other studies could only conclude that ST produced similar yields compared to NT, presumably due to limited years of evaluation, site locations, and/or climatic variation between seasons (Al-Kaisi and Kwaw-Mensah, 2007; Vetsch and Randall, 2004).

Polymer and Non-coated Urea Fertilizer

Global increases in the application of N fertilizers are the main reason soil N_2O emissions from agricultural practices have dramatically risen over the past 30 years

(Smith et al., 2007). Enhanced efficiency urea fertilizer products may potentially lower soil N_2O emissions from application of urea fertilizer. Polymer-coated urea (e.g., ESN from Agrium, Inc, Calgary, Canada) is a enhanced efficiency fertilizer product which encases urea within a polymer coat and once urea dissolves within the prill it will diffuse out at a rate dependant on soil temperature (Fujinuma et al., 2009). Addition of the polymer coat should slow or delay the rate of urea hydrolysis compared to traditional urea fertilizers, which may increase N recovery through plant uptake and also reduce the amount of N susceptible to denitrification throughout the growing season. The overall effectiveness of reducing soil N_2O emissions with PCU compared to NCU may be related to tillage's effect on soil conditions, regional climate, and soil type. Although research is limited, results have already demonstrated PCU's potential to minimize soil N_2O emissions compared to traditional urea fertilizer (Halvorson et al., 2008). However, site specific conditions and management may have a significant effect on PCU's ability to reduce soil N_2O emissions. The overall objective of this study was to determine whether alternative fertilizer and tillage management can reduce soil N_2O emissions and/or increase corn grain yield production compared to traditional management practices used in claypan soils characterized by poor drainage.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted in 2009 and 2010 (approximately April through September) in Northeast Missouri's claypan region at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N 92° 11' 24.9" W) in Novelty, MO

(Figure 2.1) on a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs). Soil properties (Table 2.1) were determined from analysis of samples from bulk density cores taken at two depths (0-10 and 10-20 cm) from non-treated control plots. Depth to the claypan at this research station has been observed to range from 31 to 46 cm (data not presented). Daily weather conditions including air temperature, soil temperature at a depth of 5 cm with soybean residue, and precipitation were recorded on-site using an automated Campbell weather station.

Two different field locations at the Greenley Memorial Research Center were used for the 2009 and 2010 experimental plots and both were planted with a glyphosate resistant corn (*Zea mays L.*), 'DeKalb 63-42 VT3', following soybean (*Glycine max L.*). Plots were approximately 3 by 21 meters and contained four rows of corn. Seeding was done with a John Deere 7000 planter (Deere and Co., Moline, IL) on 76 cm row spacing at 74,131 seeds ha^{-1}. Planting and harvest dates, as well as burndown applications of herbicide, and pest control applications of insecticide are listed in Table 2.2. The experimental design was a 2 x 2 factorial in a randomized complete block design with three replications and non-treated controls. Treatments consisted of tillage/N fertilizer placement (NT/surface broadcast and ST/deep banded) in combination with NCU and PCU (ESN, Agrium, Inc., Calgary, Canada) applied at 140 kg N ha^{-1}. Nitrogen application took place directly before planting, with hand spreaders used for the surface broadcasting application. Strip-tillage (30.5 cm width, 20 cm depth, 76.2 cm spacing) was conducted with a 2984 Maverick (Yetter Manufacturing, Inc., Colchester, IL) unit and N fertilizers were banded 15 cm deep below the planted row. Corn grain yields were determined with a small-plot combine (Wintersteiger Inc., Salt Lake City, Utah) and adjusted to 130 g kg^{-1} prior to statistical analysis.

Nitrous Oxide Gas Sampling

In-field measurements of soil N_2O flux were conducted following the USDA-ARS GRACEnet Chamber-based Trace Gas Flux Measurement Protocol (Parkin et al., 2003). The suggested static ring chamber design was implemented and chambers were constructed out of PVC pipe sections with removable rubber PVC pipe caps. The PVC pipe sections had a diameter of 20 cm and a height of 14 cm. Caps were adapted with a gas sampling port (Swaglok, bulkhead connector with Shimadzu septa plug) and a vent port connected to a 10 cm long, 0.64 cm diameter aluminum tube contained within the chamber when capped.

The chambers were centered in the planted row and placed in the center two rows of each plot. Chambers were inserted 10 cm into the soil with 4 cm of the chamber remaining above the soil surface. Static chambers were installed within a day after application of the N fertilizer treatments and remained in place throughout the growing season. For each plot, two static chambers were installed approximately 7 meters in from each end of the plot, (6 treatments x 2 subsamples x 3 replications) equaling a total of 36 static chambers.

Upon capping of static chambers, an ambient air sample was taken for each replication representing t0, while t1 and t2 were taken from each chamber 30 and 60 minutes after capping, respectively. Gas samples removed from the chambers were approximately 10 ml and injected into 5 ml evacuated glass serum vials (Wheaton

Science Products, Millville, NJ) which over pressured the vials as prescribed in the GRACEnet protocol (Parkin et al., 2003). Gas samples were analyzed for N_2O concentration using a gas chromatograph (Model 910, Buck Scientific, Inc., Norwalk, CT) equipped with a steel, packed column (solid stationary phase), electron capture detector (ECD), helium carrier gas, and oven temperature set at 300^oC. Three calibration curves were determined during the analysis of each sampling date using analytical grade N_2O standards (Scotts Specialty Gases, Plumsteadville, PA). Nitrous oxide flux calculations representing each chamber were made using N_2O concentration obtained from the t0, t1 and t2 samples and the algorithm provided by the GRACEnet Protocol (Hutchinson and Mosier, 1981; Parkin et al, 2003). During the 2009 season (Apr. 23 to Aug. 28), gas sampling occurred 3 or 4 times a week up to 77 days after N fertilization, and approximately once every week after that point for a total of 39 sampling dates. During the 2010 growing season (Apr. 15 to Sept. 22), 42 days were sampled and sampling intensity was similar as in 2009.

Gas flux values calculated from the gas samples collected from the ST treatments were not representative of the flux over the entire area of the treatment plots since the chambers were placed directly over the banded N fertilizer in the tilled, planting row. Adjustments were made to account for fertilizer distribution in relation to static chambers location, in order to calculate a value more accurately represented the entire ST plot. Nitrous oxide flux calculation for the entire area of ST plots were done by taking the flux value from the chambers in the tilled rows directly over the banded fertilizer representing

40% area of the ST plot, and combining it with the flux value obtained from the untreated NT plot representing the 60% area of soil not tilled in a ST plot.

Additional Measurements

For each individual gas sampling date and static chamber, additional measurements were taken to determine the effects of other soil factors on soil N_2O flux. These measurements included soil temperature and gravimetric water content taken at a depth of 10 cm in the planting row, ambient air temperature, and soil NO_3-N concentration analyzed from soil samples taken at 10 cm depth. Soil samples were collected around each static chamber with a push probe, and four samples were combined to make a composite sample representing the soil conditions of each static chamber. Soil samples were analyzed for gravimetric water content using a forced air oven set at 105ºC and soil NO_3^- content was determined using a 2M KCL soil extraction and flow injection analysis (QuikChem Method 12-107-04-1-B) with the Lachat Quik Chem 8000 automated ion analyzer. Air and soil temperatures were measured using a handheld thermocouple equipped with a 10 cm long probe.

Statistical Analysis

Analysis of variance was performed on cumulative growing season soil emission of N_2O, corn grain yields, and N_2O emitted per corn grain production use the SAS v9.2 statistical program and proc GLM to determine if there were significant treatment effects. Fischer's Protected LSD was used to separate means and determine significant treatment effects. Multiple regression analysis was conducted to determine if variability in soil N_2O flux could be accounted for due to days after N fertilization, air temperature, and soil temperature, gravimetric water content, and NO_3^- concentration at 10 cm depth observed next to static chambers at gas sampling dates.

RESULTS AND DISCUSSION

Precipitation

From 2000 to 2010, the long-term average temperature and precipitation over the growing season from Apr. through Sept. was 19.7°C and 66 cm, respectively (University of Missouri Extension, 2010). Precipitation events during the 2009 and 2010 growing seasons were well distributed and totaled 80 and 108 cm, respectively (Figure 2.2). Both seasons exceeded the ten year average by 14 cm (21.7%) in 2009 and 43 cm (65.2%) in 2010. Growing seasons with higher than average precipitation may have increased amounts of N fertilizer loss and soil N_2O emissions compared to seasons with lower or average total precipitation since both these processes are affected by the amount and timing of changes in soil water content and water movement.

Soil Properties

Differences in soil temperature and gravimetric water content at a depth of 10 cm in the planting row between NT and ST management during field measurements of N_2O flux were minimal (Figure 2.3). This implies that tillage did not directly impact soil conditions which may affect the rate of microbial denitrification and soil N_2O emissions. Air and soil temperature over the 2009 and 2010 growing seasons were similar, significant increases in soil temperature occurred in early June, approximately 50 days after N fertilization.

Higher total precipitation in 2010 resulted in generally higher soil water content throughout the growing season and less defined wetting and drying cycles compared to 2009 (Figure 2.3). Soil nitrate levels analyzed from samples taken at a depth of 10 cm were considerably higher throughout the 2009 growing season compared to 2010, presumably due to drier conditions (Figure 2.4). Soil nitrate levels peaked approximately 30 days and 45 days after N fertilization for the 2009 and 2010 growing seasons, respectively. This typically corresponds to the beginning of peak uptake by the corn plant. In both seasons, no-till with surface broadcasted fertilizers generally had greater soil NO_3 concentrations than ST deep banded N (15 cm), possibly due to shallow soil sampling (0 to 10 cm) and/or minimal vertical movement of N from deep banded N fertilizer.

Soil Nitrous Oxide Flux over the Growing Season

In both 2009 and 2010, soil N_2O emissions did not consistently exceed pre N application levels until 35 days after application and returned to background levels after approximately 60 days (Figure 2.5). During the period of elevated soil N_2O flux, variation in flux was higher for all fertilized treatments. Flux increases corresponded with the period of time in which air temperature was above 20 ^{o}C (Figure 2.3A and 2.3B). This suggested that air temperature through its influence on soil temperature and microbial activity is a major factor in determining when N fertilizer is susceptible to loss as N_2O. In 2009, temporal patterns in N_2O flux varied among N fertilizer sources, with NCU treatments having earlier and higher soil N_2O flux compared to that of PCU treatments (Figure 2.4A). Temporal variation between PCU and NCU was not observed in 2010 (Figure 2.4C) and may have been affected by the 43% greater total rainfall in 2010. Temporal differences in N_2O flux between NT/surface broadcasted and ST/deep banded placement was generally not observed for either season; however, NT treatments typically had fluxes of greater magnitude than ST treatments (Figure 2.4B and 2.4D).

Multiple Regression

Other variables, such as days after N fertilization, air and soil temperatures, soil nitrate concentration, and soil water content may account for a portion of the variability observed in soil N_2O flux. Multiple regression analysis of these variables obtained at each N_2O sampling time were all found to be significant components of the rate of soil N_2O flux measured in our study, excluding soil NO_3 concentration (Table 2.3). One possible reason why soil NO_3 concentration was not found to impact soil N_2O flux was that NO_3-N in the soil may have rarely been limiting since the highest N_2O fluxes emitted an amount of N that was only a small fraction of the average NO_3-N available in the untreated control plots throughout the growing season (Figure 2.4). Of the remaining significant factors, air temperature, soil water content, days after N fertilization, and soil temperature accounted for 0.0096, 0.0049, 0.0038, and 0.0035 of the overall model R^2 value (0.0218), respectively (Table 2.3). The best model for prediction of N_2O flux based on these variables was selected using the stepwise method and is presented in Table 2.3. The partial R^2 values and parameter estimates indicate that the rate of soil N_2O flux increased with the air temperature and had the greatest influence on variability in N_2O fluxes measured.

Cumulative Growing Seasons Soil Nitrous Oxide Emissions

Due to poor drainage, claypan soils may have greater potential fertilizer N loss through denitrification than most well-drained agricultural soils. However, the naturally high variability of soil N_2O flux made finding statistical differences in cumulative emissions between N fertilizer source and tillage/N placement difficult. Significant differences in cumulative emissions over the growing seasons as a result of year, N fertilizer source, and tillage/N placement were not observed for any interactions or main effect of year and tillage/N placement (Table 2.4). The only difference ($P < 0.05$) was the main effect of N fertilizer source, in which non-treated plots had lower emissions than PCU and NCU treatments (Table 2.4). However, trends based on average cumulative growing season emissions were observed in both 2009 and 2010.

Early season emissions of N_2O from PCU applications were of a lower magnitude than NCU treatments in 2009, presumably due to the impact of soil temperature on the release of urea available for microbial activity. Although not statistically significant, cumulative emissions from PCU treamtents eventually surpassed total emissions from NCU treatments by 45 days after N application and emissions totaled 6.12 kg N_2O-N ha^{-1} at season's end which accounted for 3.6% N fertilizer loss (Table 2.3 and Figure 2.6A). In 2010, the opposite trend was observed, with average cumulative N_2O emissions from PCU was 14% lower (4.84 kg N_2O-N ha^{-1}) than NCU treatments and accounted for only 2.4 % N fertilizer loss (Figure 2.6B). A recent study found surface banding PCU in an irrigated, NT, and continuous corn rotation reduced soil N_2O emissions by 49% compared to NCU (Halvorson et al., 2010). Cumulative emissions from NCU fertilizers had less variation between seasons, but did increase from 4.77 in 2009 to 5.63 kg N_2O-N ha^{-1} in 2010 and represented 2.6% and 2.9% N fertilizer loss, respectively. Average emissions from PCU applications decreased over the wetter season while emissions with NCU increased, which indicates PCU may be an effective soil N_2O mitigation option in wet growing seasons. Total growing season emissions for fertilized treatments were higher than the total emissions of 2 to 3 kg N_2O-N ha^{-1} commonly reported in a semi-arid climate with controlled irrigation or humid continental climate (Halvorson et al., 2010; Venterea et al., 2010) which further indicates the added importance of mitigating soil N_2O emissions from agricultural claypan soils. Differences in cumulative N_2O emissions between tillage/N placement practices varied by 0.41 to 0.43 kg N_2O-N ha^{-1} between the 2009 and 2010 growing seasons (Table 2.5). However, total average emissions with ST/deep banding management was highest in the wetter 2010 season (3.46 to 3.87 kg N_2O-N ha^{-1}), while total emissions from NT/surface broadcasting management decreased (4.55 to 4.12 kg N_2O-N ha^{-1}). Higher average N_2O emissions are generally expected with increased rainfall, but lower emissions in NT/surface broadcast management may have been the result of surface soil conditions which favored the complete transformation of NO_3^- to N_2 or limited nitrification. No-till/surface broadcasting treatments did not significantly increase cumulative growing season emissions of N_2O compared to ST/deep banded management, but averaged 24% and 6% higher emissions in 2009 and 2010, respectively. These results are counter to a study which found surface applications of N have been reported to increase soil N_2O emissions using CT practices (Halvorson et al., 2008). Results from 2009 were similar to a two-year field study conducted in Ontario, Canada that found zone that tillage (21 cm width, 15 cm depth), which in principle is the same as ST, had 20% lower cumulative soil N_2O emissions than NT (Drury et al., 2006). Based on cumulative emissions and non-fertilized control plots, it was estimated that 2.4% of N fertilizer was lost as N_2O in both seasons for ST/deep banded N, while NT/surface broadcast had 3.8% and 2.8% N fertilizer loss in 2009 and 2010, respectively (Figure 2.6C and 2.6D). Results did not confirm this but trends observed in this study imply that NT/surface broadcasted N may have a greater overall potential for loss as N_2O, which may be magnified under drier growing season due to varying soil conditions in proximity to N fertilizer between surface and deep placement of N fertilizer.

Corn Grain Yields

The main effects of N fertilizer source, tillage/N placement, and year resulted in significant differences ($P < 0.05$) in corn grain yields (Table 2.4). In 2009, grain yields averaged 8.61 Mg ha^{-1} which was significantly greater than the 4.85 Mg ha^{-1} in 2010 (Table 2.5). Lower yield production in 2010 likely was the result of abnormally high rainfall, creating poor growing conditions, which resulted in fewer harvested plants, and delayed plant growth. Averaged over growing seasons, PCU, NCU, and non-treated applications all had significantly different grain yields which were 8.51, 7.28, and 4.40 Mg ha^{-1}, respectively. Yield production with ST/deep band N placement (15 cm) averaged 7.54 Mg ha^{-1} which was significantly greater (1.62 Mg ha^{-1}) than no-till/surface broadcasted N management. As indicated by previous research that found PCU increased yield in wetter, low lying areas compared to NCU (Noellsch et al., 2009). However, previous research conducted at a nearby field site in a drier conditions did not find corn grain yield differences between PCU and NCU which indicated that rainfall and soil water content were significant factors that affected yield response to PCU (Nelson et al., 2009). Further research is required to confirm whether yield benefits from ST with deep banding will be observed over varying soil and climatic conditions.

Nitrous Oxide Emitted Per Grain Yield

Strip till with deep band placement averaged 0.52 kg of N emitted as N_2O per Mg of grain produced, which was significantly lower than 0.72 kg N_2O-N Mg grain^{-1} emitted with a NT/surface broadcast application (Table 2.5). Averaged across treatments by year, the wetter 2010 season had significantly higher amounts of N_2O emitted per Mg of grain produced than 2009, further illustrating the importance of N recovery on soil N_2O emissions and yields. These results suggest that PCU and ST with deep band placement increased N recovery and plant uptake compared to a traditional, NT/surface broadcast application because of lower average N_2O emissions and significantly greater grain yields during seasons of high rainfall. However, no research is available which evaluates cumulative soil N_2O emissions in relation to corn grain yields and therefore comparisons are not possible.

CONCLUSIONS

Significant reductions in soil N_2O emissions through N management may not only require new alternative management options, but also an improved ability to identify the period of time when N is most susceptible to loss as N_2O. Conditions including, air temperature, soil temperature, soil water content, and days after N fertilization all significantly impacted soil N_2O flux. This highlights the complex relationships involved in the production and emission of N_2O in a soil environment; while, these conditions accounted for a small portion of the variation in N_2O flux. The growing seasons in 2009 and 2010 were both considerably wetter than average which may have led to higher soil water contents and greater cumulative soil N_2O emissions than seasons with average to lower precipitation. Greater precipitation in 2010 as compared to 2009 did not lead to differences in cumulative growing season N_2O emissions.

Average cumulative growing season emissions of N_2O due to the interaction of year with tillage/N placement or N fertilizer source ranged from 3.46 to 6.12 kg N_2O-N ha^{-1} over 2009 and 2010. In studies in soil with moderately well to good drainage, cumulative emissions typically did not exceed 3 kg N_2O-N ha^{-1}. Poor internal drainage in claypan soils promoted conditions for denitrification N loss which presumably accounts for the higher cumulative growing season emissions of N_2O found in this study. However, N_2O emissions did not significantly differ between tillage/N placement or N source and represented a small fraction of fertilizer N loss. Although not statistically significant, ST/deep banded N treatments did average lower cumulative emissions than NT/surface broadcasted N treatments in both seasons. Naturally high variability in soil N_2O flux made statistically proving that ST/deep banding reduced cumulative emissions difficult. Applications of PCU did not significantly lower cumulative N_2O emissions compared to NCU; however, emissions from PCU treatments decreased over the wetter season which indicates that PCU may have lower N_2O emissions with wetter conditions.

Strip-till with deep banding of N produced significantly greater corn grain yields than NT/surface broadcasting in moderately wet to very wet growing seasons. Including yield, ST/deep banded N significantly lowered the amount of N_2O emitted per Mg of grain produced compared to NT/surface broadcasting. These findings support our hypothesis that increasing corn yields by improving N management will lower the environmental impacts associated with corn grain production related to N_2O emissions. Nitrous oxide and grain yield data were not obtained in a growing season with lower than average rainfall; however, these results demonstrate that ST with deep banding placement is a promising management practice in poorly drained, claypan soils to produce higher yields with lower environmental impacts that NT/surface broadcasted N systems in moderately wet to very wet growing seasons. Results from this study also demonstrate that evaluation of alternative management practices impact on soil N_2O losses may also need to consider changes in yield production to allow producers to decide which practices are best suited for their production and environmental goals.

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Table 2.1. Soil properties from non-treated plots the 2009 and 2010 fields at two depths (0-20 cm).

								Exchangeable (1M NH_4AO_c)			
Year	Depth	Bulk Density	pH (0.01M $CaCl_2$)	Organic matter	Neut. acidity	CEC	Bray I P	Ca	K	Mg	NO_3-N
	- cm -	g cm^{-3}		g kg^{-1}	---- $cmol_c$ kg^{-1} ---		mg kg^{-1}	------------ kg ha^{-1} ------------			kg ha^{-1}
2009	0-10	1.37	6.2	26	1.5	15.3	41.9	5238	384	446	10.5
	10-20	1.41	6.2	19	1.8	16.4	11.2	5640	248	452	4.7
2010	0-10	1.43	6.4	29	1.5	14.7	38.7	4955	501	429	2.9
	10-20	1.50	6.4	24	1.7	14.6	21.9	4903	307	447	1.1

Table 2.2. Dates of planting, harvesting, and applications of herbicides and insecticide from the 2009 and 2010 growing seasons.

Year	Field Information and Management	Date and Rate
2009	N application	23 Apr.
	Planting date	23 Apr.
	Burndown	
	Glyphosate (N-(phosphonomethyl)glycine)	1.06 kg ha^{-1}
	Dicamba (3,6-dichloro-o-anisic acid)	0.28 kg ha^{-1}
	Application date	28 Apr.
	Harvest date	19 Oct.
2010	N application	15 Apr.
	Planting date	15 Apr.
	Burndown	
	S-metolachlor†	2.25 kg ha^{-1}
	Atrazine ‡	0.84 kg ha^{-1}
	Mesotrione §	0.23 kg ha^{-1}
	Dicamba (3,6-dichloro-o-anisic acid)	0.56 kg ha^{-1}
	Application date	16 Apr.
	Pest control	
	Lambda-cyhalothrin¶	0.01 kg ha^{-1}
	Application date	16 Apr.
	Harvest date	28 Sept.

† (2-Chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide).

‡ (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine).

§ (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione).

¶ ([1α(S*),3α(Z)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-Dimethylcyclopropanecarboxylate).

Table 2.3. Summary of multiple regression analysis of the relationship of several ancillary variables related to soil N_2O flux including the stepwise model selection and final model.

Step	Variable Entered	Variables In	Partial R^2	Model R^2	C(p)	F Value	Pr > F
1	Soil water content	1	0.0049	0.0049	47.99	13.90	0.0002
2	Air temperature	2	0.0096	0.0145	22.16	27.64	<.0001
3	Days after N fertilization	3	0.0038	0.0183	13.11	11.01	0.0009
4	Soil temperature	4	0.0035	0.0218	5.00	10.11	0.0015

Final Model

Variable	Parameter Est.	Std. Error	F Value	Pr > F
Model			15.78	<.0001
Intercept	-15.36	4.76	10.43	0.0013
Days after N fertilization	-0.12	0.03	20.98	<.0001
Air temperature	0.24	0.15	2.42	0.1196
Soil temperature	0.63	0.20	10.11	0.0015
Soil water content	58.10	17.59	10.91	0.0010

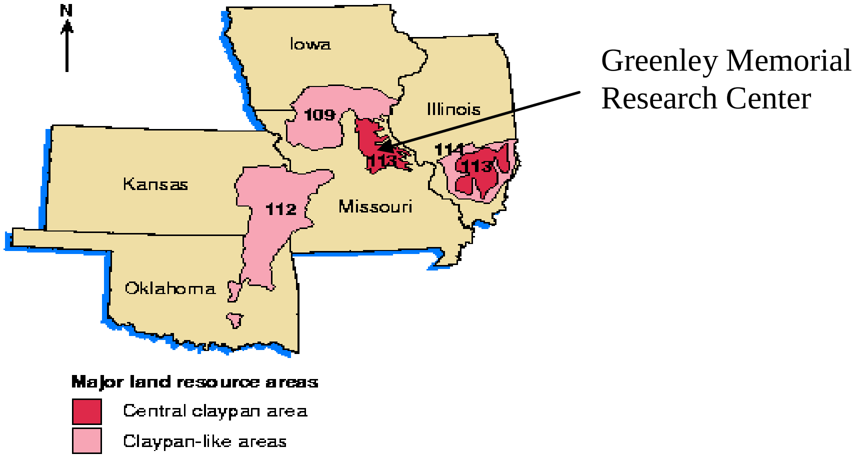
Table 2.4. ANOVA table of the analysis of cumulative growing season soil N_2O emissions, corn grain yields, and N_2O-N emitted per grain yield produced.

		Cumulative N_2O Emissions		Corn Grain Yield		N_2O / Yield	
Source	df	F value	Pr > F	F value	Pr > F	F value	Pr > F
Rep	2	1.09	0.3437	4.04	0.0321	1.62	0.2206
Year	1	0.00	0.9916	68.51	<.0001	15.11	0.0008
N fertilizer source	2	20.21	<.0001	28.92	<.0001	10.61	0.0006
Tillage / N placement	1	1.29	0.2602	12.65	0.0018	5.50	0.0284
N fertilizer source x tillage / N placement	2	0.70	0.4992	3.36	0.0534	2.17	0.1377
Year x N fertilizer source	1	1.19	0.3119	2.33	0.1213	0.68	0.5181
Year x tillage / N placement	1	0.50	0.4836	1.35	0.2585	0.03	0.8563
Year x N fertilizer source x tillage / N placement	2	0.35	0.7070	0.29	0.7530	0.16	0.8533

Table 2.5. Cumulative growing season soil N_2O emissions, corn grain yields, and N_2O-N emitted per yield produced, analyzed by the main effect of N fertilizer source, tillage/placement, and year.

				Tillage / Placement		
	N Fertilizer Source			No-till	Strip-till	Year
Year	PCU	NCU	Non-Treated	Surface Broadcast	Deep Banding	Average
	kg N_2O-N ha^{-1}					
2009	6.12	4.77	1.12	4.55	3.46	4.01a
2010	4.84	5.63	1.53	4.12	3.87	4.00a
Average	5.48a	5.21a	1.32b	4.34a	3.66a	
	Mg-corn grain ha^{-1}					
2009	11.04	9.03	5.75	7.54	9.68	8.61a
2010	5.98	5.54	3.05	4.31	5.40	4.85b
Average	8.51a	7.28b	4.40c	5.92a	7.54b	
	kg N_2O-N Mg-corn $grain^{-1}$					
2009	0.58	0.59	0.20	0.55	0.36	0.46b
2010	0.80	1.04	0.51	0.89	0.68	0.78a
Average	0.69a	0.81a	0.36b	0.72a	0.52b	

† Letters following averages of N fertilizer source, tillage / placement, and year for cumulative growing season N_2O emissions, corn grain yield, and N_2O / yield indicate least significant differences $P < 0.05$ among treatments.



Greenley Memorial
Research Center

Figure 2.1. Location of study site in relation to areas of regions classified as having claypan or claypan-like soils (Source: USDA Agricultural Handbook 296, 1981. Map prepared by CARES, 1998).

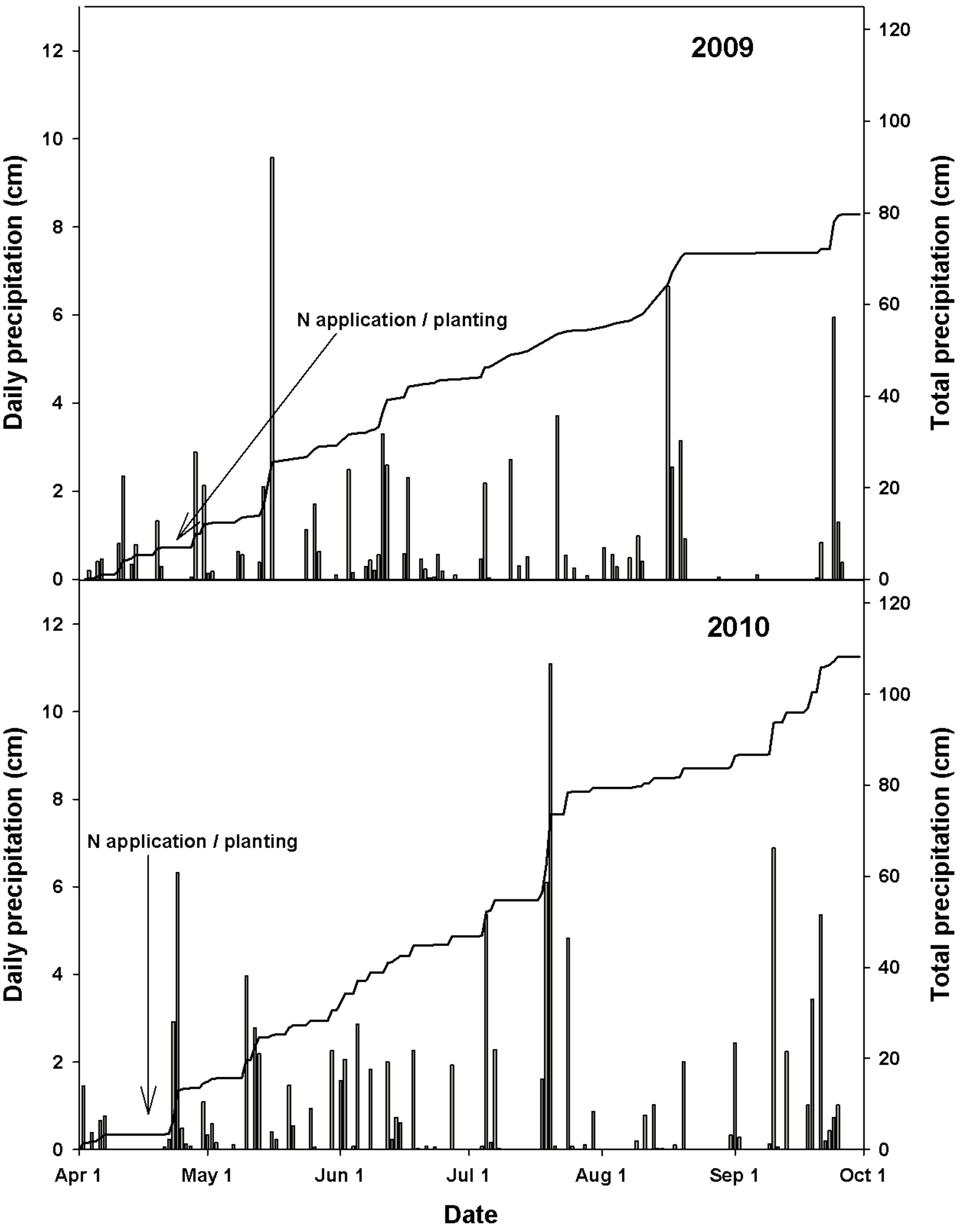


Figure 2.2. Daily (bars) and cumulative (line) precipitation at the Greenley Memorial Research Center over the 2009 and 2010 growing seasons.

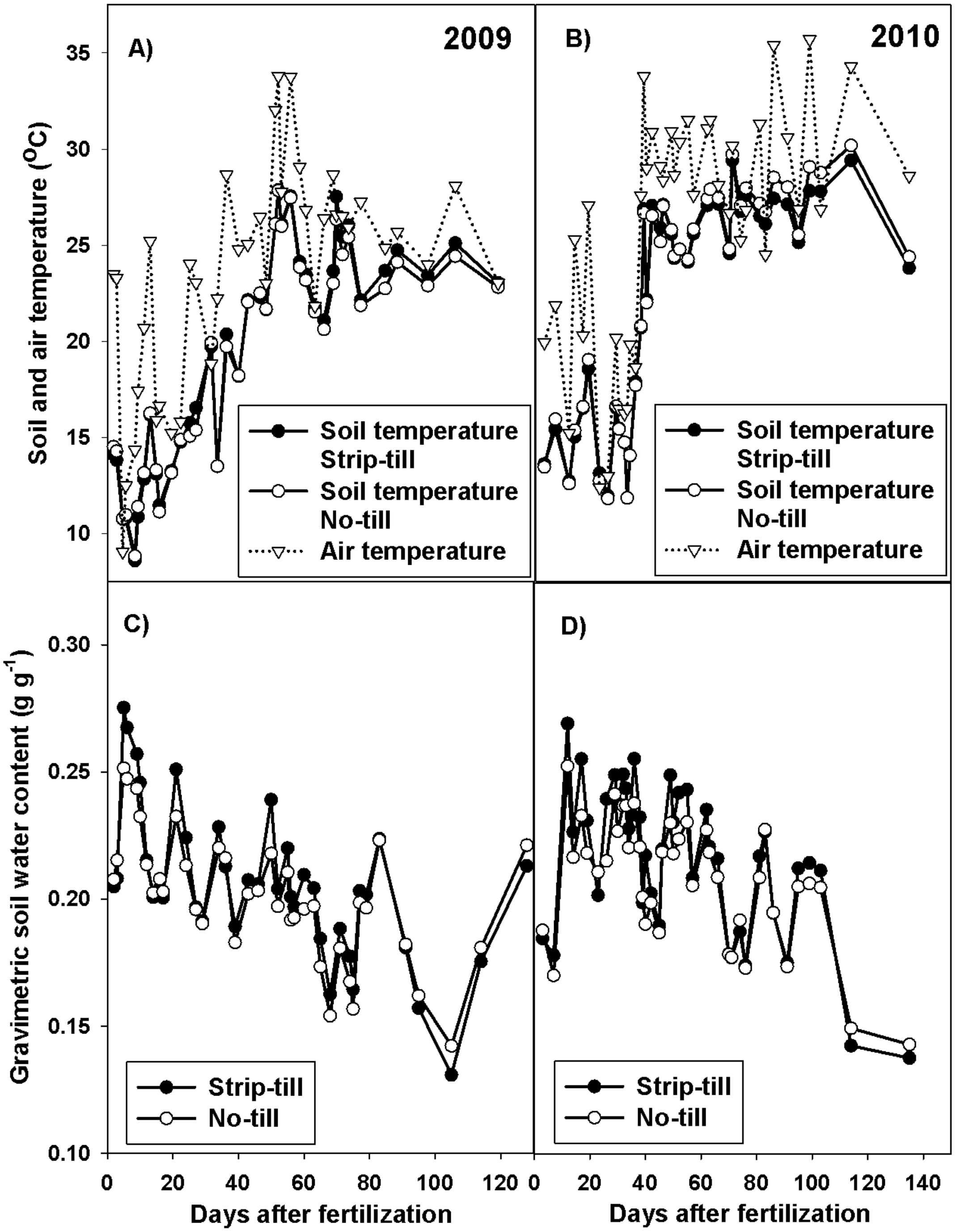


Figure 2.3. Soil temperature and gravimetric water content at a depth of 10 cm in the planting row with no-till and strip-till management over the growing season. Air temperature was recorded during the collection of soil measurements. A) Soil and air temperature (2009). B) Soil and air temperature (2010). C) Gravimetric soil water content (2009). D) Gravimetric soil water content (2010).

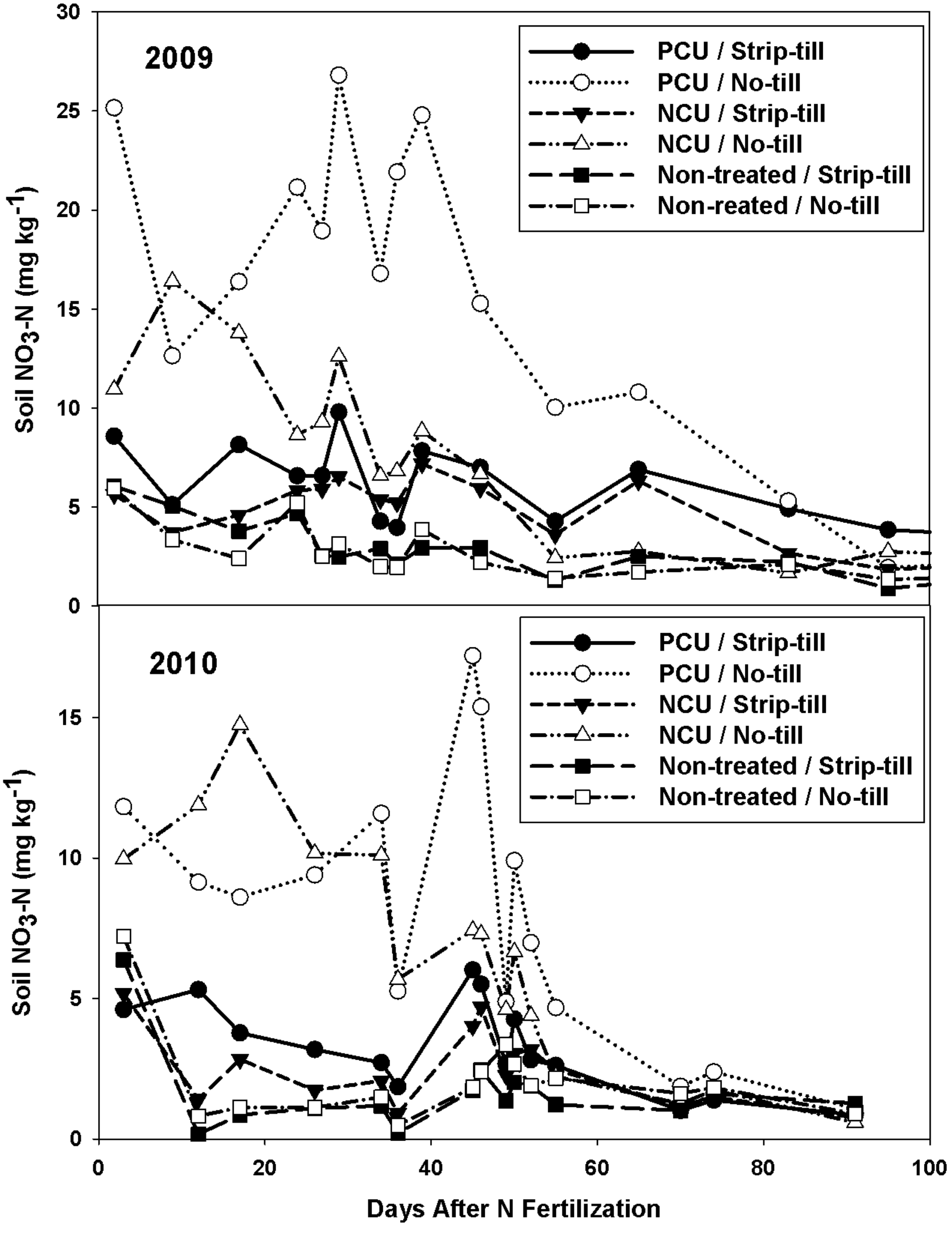


Figure 2.4. Soil nitrate-N analyzed from soil samples taken during soil N_2O flux measurements for both 2009 and 2010. Note differences in scales used for the y-axis in 2009 and 2010 (n = 6).

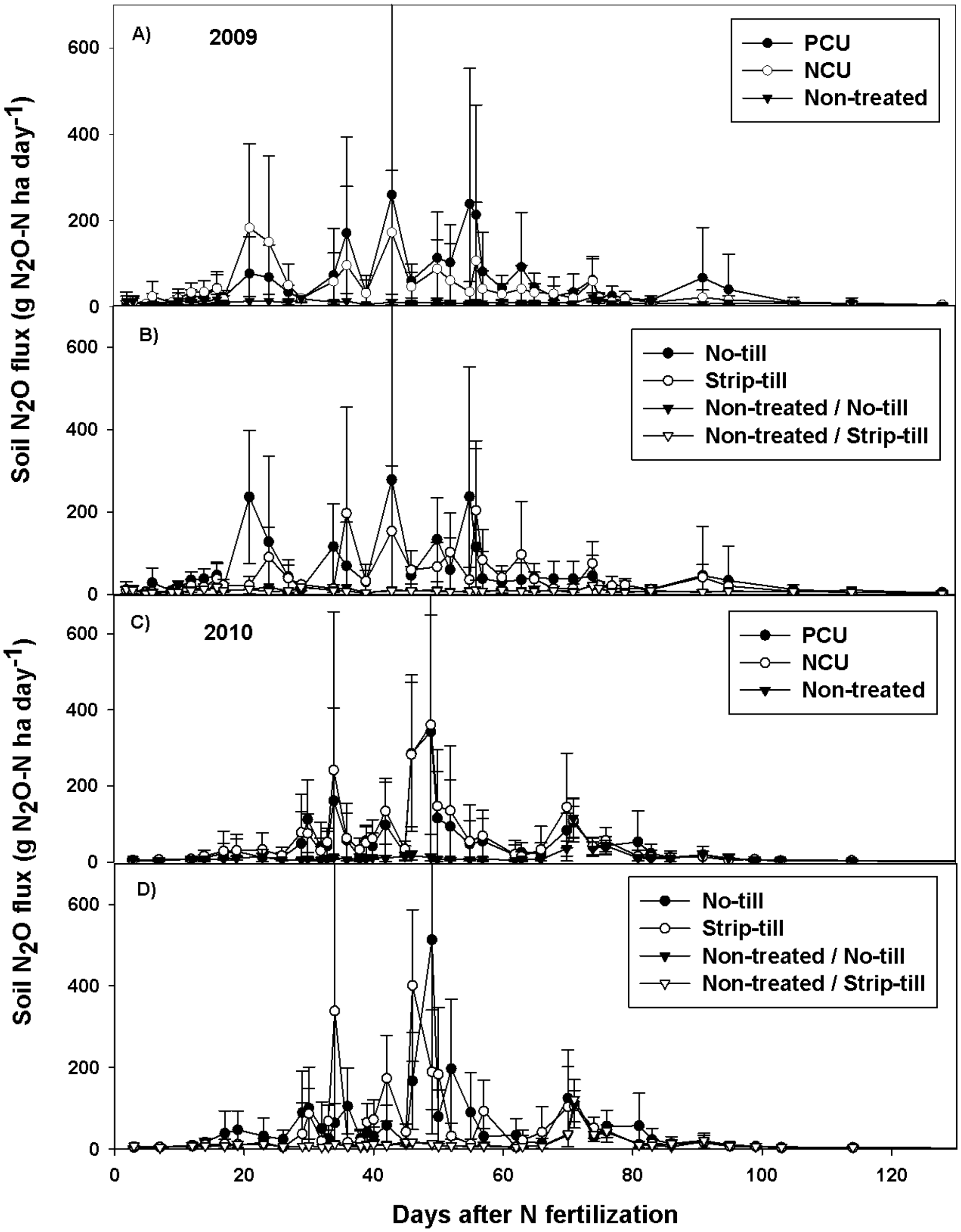


Figure 2.5. Nitrogen fertilizer source and tillage managements effect on soil N_2O flux over the 2009 and 2010 growing season (n = 12). Symbols are means with standard deviations. A) N fertilizer source (2009). B) Tillage / N placement (2009). C) N fertilizer source (2010). D) Tillage / N placement (2010).

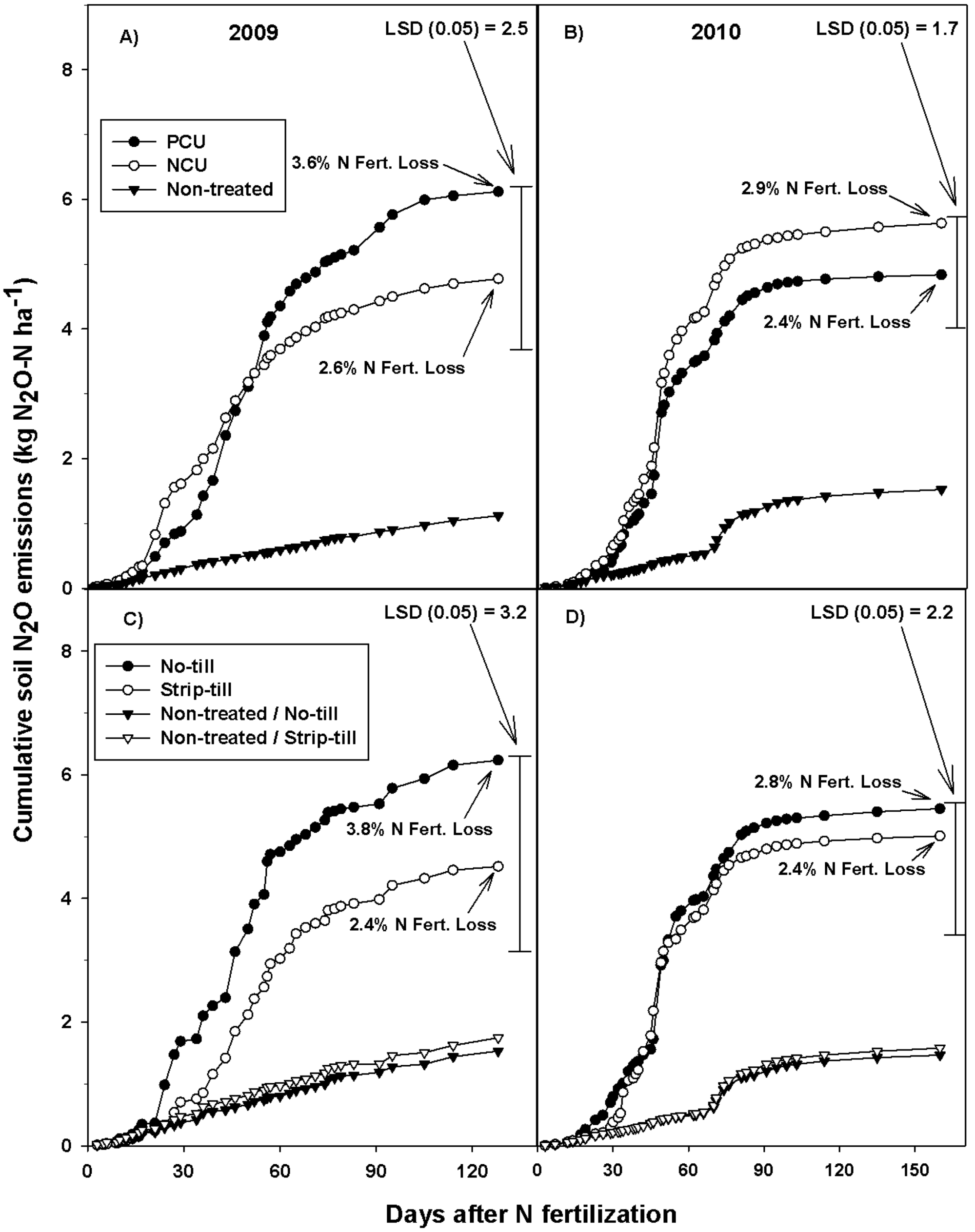


Figure 2.6. Nitrogen fertilizer source and tillage management effects on the cumulative soil N_2O emissions over the 2009 and 2010 growing season, including the % N fertilizer loss and LSD (0.05) for the last sampling date. A) Nitrogen fertilizer source (2009). B) Nitrogen fertilizer source (2010). C) Tillage / N placement (2009). D) Tillage / N placement (2010).

CHAPTER 3

ALTERNATIVE MANAGEMENT OPTIONS IN NORTHEAST MISSOURI CLAYPAN SOILS FOR INCREASING CORN PRODUCTION

ABSTRACT

Poorly drained, claypan soils can intensify the importance of tillage and N management on high yielding corn production. During wet growing seasons, poorly drained soils can have conditions conducive for environmental N loss and poor plant growth which can lower grain yield potential. Over three years, this study evaluated whether slow release, polymer-coated urea or strip-till/deep banding of N could maintain or increase yields in wet growing seasons over three N application timings (fall, early preplant, and preplant), no-till/surface broadcasting of N, non-coated urea application, and regional high yield systems which utilize anhydrous ammonia injection into the soil (with and with nitrapyrin). During the extremely wet growing seasons (2008 and 2010), low plant populations were commonly observed in no-till/surface broadcast systems. In 2010 following soybean, plant population with no-till/surface broadcasting of N was 20,860 plants ha^{-1} lower than strip-till/deep band placement. These results were similar when corn followed red clover, except high plant populations were usually not maintained in strip-till/deep banding systems with fall N application/tillage. Over the entirety of the study, N application timing and fertilizer source (polymer and non-coated urea) were found to have minimal benefits on grain yield, regardless of tillage/N placement management. In fields following soybean, strip-till/deep banding had 1560 to 5380 kg ha^{-1} greater yields than no-till/surface broadcast system in combination with N application timing and fertilizer source. When red clover was planted as a cover crop,

strip-till maintained high yield production with N applications as early as Mar. (early preplant) which coincided with the higher plant populations compared to no-till. In a comparison to high yielding management using anhydrous ammonia with and without a nitrification inhibitor (nitrapyrin), strip-till had similar yields, excluding strip-till/deep banding of non-coated urea, which had 1450 kg ha^{-1} lower yields compared to anhydrous ammonia with nitrapyrin when red clover was used as a cover crop. Yield benefits from slow release polymer-coated urea were minimal. Higher yields with strip-till/deep band placement compared to no-till/surface broadcast application in wet growing seasons was presumably a function of improved seedbed conditions, plant populations, and improved N management through deep banding placement of N. In conclusion, strip-till/deep band placement of N was a consistent, high corn grain yielding system that was a viable management option in moderately wet to wet growing seasons in poorly drained soils that can allow farmers more flexibility in N management options.

INTRODUCTION

The Central Claypan Region includes 4 million ha of soil and covers part of North-Central Missouri, Southern Illinois, and Southeast Kansas (Noellsch et al., 2009). Claypan soils contain a subsoil layer located between 20 to 40 cm below the surface and have at least 100% higher clay content than the overlying horizon (Jamison et al., 1968; Jung et al., 2006; Myers et al., 2007). Agricultural practices on claypan soils can be challenging due to poor internal drainage through the claypan layer. Poor drainage in claypan soils results in saturated soil conditions after rainfall events which can affect management decisions and reduce grain yields.

Nitrogen efficiency in corn may be improved by selecting management practices which minimize N loss and maximize plant uptake. Agricultural producers can profit from improved nitrogen management systems by increasing yields and/or lowering N fertilizer requirements by increasing nitrogen uptake efficiency. In Minnesota, a single, fall application of N fertilizers did not promote efficient N management and high yields since there was a greater period of time between N application and plant uptake, increasing the potential for N loss (Randall et al, 2003). The use of the nitrification inhibitor, nitrapyrin, with anhydrous ammonia (AA) applied in the fall to a heavy clay soil with tile drainage reduced drainage loss of nitrate by 10% compared to fall applications of AA without nitrapyrin (Randall and Vetsch, 2005). Farmers have limited time, funds, and ability to apply N fertilizers at spring planting due to a high work load, large acreages in production, higher N fertilizer costs, and wet field conditions, requiring producers to apply N before planting (Scharf et al., 2002). In these situations, some farmers apply N in the fall on a portion of their fields to reduce time conflicts in the spring, while other farmers may opt to apply N to all of their fields since lower fertilizer costs can negate yield reductions and lower returns associated with fall applied N.

Within the claypan region of Missouri, AA is typically used as an N source for corn production. However, AA requires specialized equipment for storage, handling, and application causing many producers to apply other N fertilizer sources. Urea-based fertilizers are the most popular sources in the world and account for 43% of global N fertilizer sales (Bouwman et al., 2002). Urea is highly soluble and has a large potential for N loss through leaching in sandy soils (Wilson et al., 2009) or sub-surface tile drainage in poorly drained soils (Drury et al., 2009). Lateral transport of urea derived N in poorly drained soils, without tile drainage, may be an important loss mechanism. Research in a claypan soil in has found minimal lateral transport of N from urea, while gaseous emissions accounted for approximately 35% of N fertilizer loss (Blevins et al., 1996). Besides leaching and lateral flow, in drier conditions with fall application or surface placement in NT, ammonia volatilization of urea can contribute to N loss (Sommer et al., 2004; Rochette et al., 2009b). The amount of applied urea lost as $NH_{3(g)}$ has been reported from 9-65% when applied to the soil surface (Sommer et al., 2004; Rochette et al., 2009a, 2009b). Typically, conditions within the soil profile have lower microbial activity than on the soil surface, which lowers the rate of urea hydrolysis and the potential for volatilization loss.

No-till (NT) systems can be more appealing to agricultural producers than conventional tillage (CT) because of higher yield potential (Al-Kaisi and Licht, 2004; Al-Kaisi and Kwaw-Mensah, 2007; Mehdi et al., 1999; Torbert et al., 2001) due to improved soil conservation, soil fertility, and lower production time and costs (Lithourgidis et al., 2005). However, yield benefits with NT systems will ultimately depend on specific locations which include soil type, seedbed conditions, climate, N application timing, placement, N fertilizer source, and seasonal variation in weather (Mehdi et al., 1999; Hendrix et al., 2004; Licht and Al-Kaisi, 2005a).

No-till has been reported to reduce yields in some situations. Contrary to management utilizing tillage, NT typically requires surface application of dry fertilizers (i.e., urea) which can have an adverse effect on N management. Nitrogen applied to the soil surface is placed in an environment more conducive for microbial activity, than deep within the soil profile, and may increase the potential for gaseous N loss, resulting in 400 kg ha^{-1} lower yield production than CT (Riedell et al., 2000). Higher potential for reduced plant emergence (Hendrix et al., 2004; Licht and Al-Kaisi, 2005; Lithourgidis et al., 2005), slower spring period development, and delayed tasseling (Licht and Al-Kaisi, 2005b; Halvorson et al., 2006) with increased bulk density, moisture content, and lower soil temperature in the spring with NT due to surface residues cover (Mehdi et al., 1999) may also contribute to lower yields compared to CT (Vetsch and Randall, 2004; Halvorson et al., 2006). Issues with plant emergence, delayed plant growth, and high potential N loss with surface or fall application of N may increase with poorly drained, claypan soils and abnormally dry or wet growing seasons. Potential alternative management options to minimize these potential issues and increase corn yields include winter legume cover crops, minimal tillage, and selection of urea fertilizer for enhanced N-use efficiency.

Crop rotations that include winter legume cover crops interseeded into a prior crop such as wheat or planted after fall harvest have the potential to increase soil fertility and reduce N application requirements, while sustaining high crop yields the following year. Winter legume cover crops can improve soil fertility when incorporated into the soil or after a burndown application of herbicide due to N contained in the biomass from atmospheric N fixation, uptake of residual N. Additional benefits of cover crops to yield production include improved soil aggregation, structure, organic matter, and protection against soil erosion. Adopting the use of cover crops such as red clover (*Trifolium* *pratense* L.) in crop rotations has great potential to sustain high crop yields and possibly reduce the fertilizer N requirements.

Researchers efforts to elucidate the benefits of incorporating red clover into crop rotations have had mixed results when quantifying the ability of red clover to increase soil N and grain yields. Averaged over a 5 year field study, incorporating wheat/red clover into a corn/soybean rotation increased corn grain yields 4 and 6% for ridge and moldboard plow tillage, respectively (Katsvairo and Cox, 2000). It was not determined whether yield increases were due to increased soil N levels through fixation or improved soil properties. Vyn et al. (2000), reported that red clover supplied 70% more organic N than rye, resulting in 2.16 to 3.34 Mg ha^{-1} greater corn grain yields ($P < 0.05$) when fertilizer N was not applied. Another study found inconsistencies in red clover's ability to increase soil N; however, corn yields were increased due to non-N related benefits such as rotation, increased water infiltration, and moisture conservation (Henry et al., 2010). Further research under different site conditions will be required to quantify whether the use of red clover can significantly increase soil N through fixation to allow lower rates of N application.

Strip-till (ST) is a new alternative minimal tillage practice which allows for deep, banded placement of dry, liquid, or gas-based N fertilizers within tilled, planted rows without requiring tillage of the entire field. Because only the corn rows are tilled, ST allows for many of the soil conservation and fertility benefits associated with NT practices to be maintained while lowering the potential for N loss through deep band placement. An additional benefit from tilling the soil in the seeded row breaks up soil aggregates and incorporates surface residues that lower bulk density, increase drainage and drying within the seedbed, and ultimately allow for earlier warming of the soil in the spring, which has been reported to increase plant emergence and growth (Randall and Hill, 2000). Results of previous limited studies were only been able to conclude that ST produced similar yields compared to NT (Vetsch and Randall, 2004; Al-Kaisi and Licht, 2004; Al-Kaisi and Kwaw-Mensah, 2007).

Polymer-coated urea fertilizer (PCU) was designed to slowly release urea into the soil environment over time (Wilson et al., 2009). Limiting the amount of urea available for microbial N transformations after application may reduce potential volatilization and N leaching losses compared to traditional dry urea fertilizer (Blaylock et al., 2004, 2005; Motavalli et al., 2008); which is counter to nitrification inhibitor products such as nitrapyrin which can lower N loss by restricting microbial activity involved with nitrification (Walters and Malzer, 1990). Rochette et al. (2009b), reported that surface applications of Environmental Smart Nitrogen (ESN), a common PCU fertilizer, resulted in 60% reduction in volatilization loss as compared to traditional dry urea fertilizer (NCU). Grain yield benefits from PCU applications depend on a variety of factors such as thickness and integrity of the polymer-coat, soil properties, landscape position, soil moisture, climate, management systems, and weather. Research has shown that applications of ESN can increase grain yields over NCU in corn (Blaylock et al., 2004, 2005) and potatoes (Zvomuya et al., 2003). Corn grain yields on a claypan soil in Northeast Missouri increased by 1530 to 1810 kg ha^{-1} in poorly drained, low lying areas when ESN was applied compared to NCU. However, yields were similar or less than

NCU fertilizer during a drier growing season and other landscape positions (Noellsch et al., 2009).

Nitrogen, tillage, and water management are important factors in corn production; however, the inherent properties of claypan soils increase the impact of management decisions due to a greater potential for gaseous N loss and poor seedbed conditions. Minimal tillage practices such as ST may greatly benefit this region, but related agronomic research is limited. The objectives of this study were to determine the effect of PCU placement and application timing on corn response compared to NCU, and to evaluate corn response to ST with deep banding placement of PCU and NCU compared to AA with and without nitrapyrin when applied at different times.

MATERIALS AND METHODS

General Procedures

The study was conducted from 2008 to 2010 at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N 92° 11' 24.9" W) near Novelty, MO (Figure 3.1). in a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs) with properties (Table 3.1) analyzed from bulk density cores taken from a single depth (0-10 cm) in 2008, and at two depths (0-10 and 10-20 cm) in 2009 and 2010. Depth to the claypan at this research station ranged from 46 to 60-cm (data not presented).

Separate experiments were conducted with corn (*Zea mays L.*) following red clover (*Trifolium pretense L.*) and soybean (*Glycine max L.*) residue each year. Since the experiments were independent, each experiment will be discussed separately. The experimental design was a split-plot design with 3 replications. The main plot was N fertilizer application timing (fall, early preplant, and preplant), which was blocked and randomized within each replication. Within these application timing blocks, N fertilizer source PCU (ESN, Agrium Advanced Technology, Denver, CO), NCU, and non-treated control) were in a factorial arrangement with tillage/placement (NT/surface broadcast and ST/deep band placement). Anhydrous ammonia (AA), injected into a NT soil with and without nitrapyrin (N-Serve, Dow AgroSciences, Indianapolis, IN), was included in the randomization for each application timing as a local control treatment, but was not included in the overall statistical analysis since it did not match up with the tillage/N placement factorial arrangement. All fertilized treatments were applied at 140 kg ha^{-1} to detect the enhanced efficiency properties of these fertilizer sources. Nitrogen applications in NT treatments were surface broadcasted with hand spreaders. Strip-tillage (30.5 cm width, 20 cm depth, and 76.2 cm spacing) was conducted with a 2984 Maverick unit (Yetter Manufacturing, Inc., Colchester, IL). Nitrogen fertilizers were banded to a depth of 15 cm below the planted row, and fertilizer delivered using a Gandy Orbit-Air (Gandy Company, Owatonna, MN) ground-driven metering system.

Different fields were used for each experiment, and plots were 3 by 21 m. Corn was planted (John Deere 7000, Deere and Co., Moline, IL) in 76-cm rows at 74,131 seeds ha^{-1}. The soybean residue experiment was planted to ‘DK 63-42 VT3’. Red clover was frost, inter-seeded into wheat (*Triticum aestivum L.*) the year prior to the initiation of the clover residue experiment. ‘DK 61-69 VT3’ was planted into the clover residue experiment. Planting and harvest dates, crop protection, and fertilizer application dates from the clover and soybean residue experiment are reported separately in Table 3.2.

Burndown, preemergence, and early postemergence applications of herbicides were applied from a month before and up to five days after planting. Red clover was 15 to 20 cm tall at the time of the burndown herbicide application. In order to evaluate differences in plant residue among treatments, aboveground biomass was collected from two 30 by 76 cm quadrats prior to the burndown herbicide application from each treatment plot for the fall and early preplant treatments, oven dried at 65^{o}C, and weighed. Corn grain yields were determined with a small-plot combine (Wintersteiger Inc., Salt Lake City, Utah) and adjusted to 130 g kg^{-1} prior to statistical analysis. Grain samples were analyzed for test weight (GAC 2100, DICKEY-john Corporation, Auburn, IL). Additional measurements included harvested plant population, and corn height and chlorophyll meter readings (SPAD units) recorded between the V18 and R3 growth stage (leaf collar method), and ear leaf samples (10 plot^{-1}) were collected between the R3 and R5 growth stage (Ritchie et al., 1993). Corn ear leaf samples were dried at 65^{o}C, ground (Issac and Jones, 1972), and analyzed for total C and N using a total carbon nitrogen analyzer (LECO, TruSpec CN Analyzer, St. Joseph, MI). Weather data collected on site at the Greenley Memorial Research Center weather station included daily rainfall, air, and soil temperature taken at a depth of 5 cm with soybean residue on the soil surface.

Statistical Analysis

Analysis of variance was performed on corn grain yields, test weights, plant population, corn height, and ear leaf N content using the SAS v9.2 statistical program to determine if there were significant treatment effects. Because of confounding factors in the split-plot design, proc MIXED was used for the overall ANOVA, and Fischer’s

Protected LSD was used to separate means and determine significant treatment effects. Separate analysis was conducted to compare grain yields between of ST/deep banding N (NCU, PCU, non-treated) management system and high yielding NT injected AA with and without nitrapyrin. Correlation analysis was used to determine the correlation of corn height, plant population, chlorophyll meter readings (SPAD units), and ear leaf N concentration with corn grain yields.

RESULTS AND DISCUSSION

Weather Conditions

From 2000 to 2007, average rainfall, air temperature, and soil temperature (at 5 cm depth with soybean residue) was 59 cm, 20.0 ^{o}C, and 20.2 ^{o}C, respectively, over the growing season (University of Missouri Extension, 2010). Average air and soil temperature during the 2008 and 2009 growing season were approximately 1 to 1.6 ^{o}C lower than the prior 8 year average, while the 2010 growing season was approximately 0.7 to 1 ^{o}C higher. Total rainfall during the 2008, 2009, and 2010 growing season was 107, 80, and 108 cm, respectively, which represented 36 to 85% greater rainfall than average (Figure 3.2a, 3.2b, and 3.2c). Although total rainfall was above average for all three seasons, 2008 and 2010 seasons had over 27 cm more rainfall (37%) than 2009. This may account for the greatest corn production differences among the three growing seasons. Rainfall during the growing season was evenly distributed and similar in 2008, 2009, and 2010 with majority of the rainfall occurring between Apr. and July; however, 2009-2010 had an abnormally wet fall which could account for the greater N loss and lower yield production with fall application of N (Figure 3.2A).

Plant Population

Analysis of variance of plant populations found only the interaction of tillage/N placement by year was significant ($P < 0.05$) in the experiment following soybean residue (ANOVA table not presented). When red clover was added as a cover crop, the interaction of tillage/N placement, N application timing, and year significantly ($P < 0.05$) affected plant populations. The N fertilizer source did not impact plant population in soybean residue, and or clover residue.

Corn plant populations following soybean did not significantly differ ($P < 0.05$) among NT/surface broadcasting and ST/deep banding of N in the 2008 and 2009 (Figure 3.3), and presumably did not account for yield differences among management practices. However, in 2010, plant population with NT/surface broadcasting of N was 20,860 plants ha^{-1} lower (32%) than ST/deep banding management. The 2008 and 2010 growing seasons had 25% more rainfall than in 2009 which may account for the reduced plant population in 2010 with NT/surface broadcast treatments. These results were similar to a study conducted on a silt loam soil where plant populations under NT were 26,000 plant ha^{-1} (37%) lower than ST, which may have been attributed to significantly ($P < 0.05$) higher soil moisture observed in the planting row of NT compared to ST (Hendrix et al., 2004). Strip-till with deep banded N fertilizer maintained high plant populations over moderately wet to very wet growing conditions. Improved seedbed conditions with tilled plant rows over NT is commonly stated in literature and may explain why ST maintained high plant populations in poor growing conditions in our study (Randall and Hill, 2000).

When red clover was present, N application timing (tillage event with ST) effected plant population found among tillage/N placement (Figure 3.4). In 2008, ST/deep banded at early preplant and preplant timings had 3330 to 7330 more plants ha^{-1} ($P < 0.05$) than NT surface broadcasted N in the fall or preplant. In 2009, significant differences were only found among fall, ST/deep banded N and preplant, NT/surface broadcasted N. In 2010, results were similar to 2008, except fall, ST/deep banded was 13478 to 13810 plants ha^{-1} lower than early preplant and preplant, ST/deep banding management. Since N application timing also corresponded with tillage in ST, the abnormally wet fall in 2009 (Figure 3.2) may have settled the tilled soil down over the fall and winter period which could have minimized the potential seedbed condition benefits over NT in the 2010 growing season.

Ear Leaf N Content

Analysis of variance of ear leaf N content taken between the R3 and R5 growth stage found significant interactions in the soybean and clover residue experiment due to tillage and N management (Table 3.3). The three-way interaction of tillage/N placement, N fertilizer source, and year was significant at $P < 0.10$ and $P < 0.05$ for the soybean and clover residue experiments, respectively. With clover residue, the interaction of tillage/N placement and N application timing by year was a significant ($P < 0.05$). In the soybean residue experiment, the significant ($P < 0.05$) interaction of application timing of N and fertilizer source could be averaged over the three year study.

Following soybean production, ST/deep banding of N had 5.1 to 10.3 g kg^{-1} greater ear leaf N content ($P < 0.10$) than NT/surface broadcasting in 2008 and 2009 (Figure 3.5). In 2010, ear leaf N content was similar between ST/deep banding and NT/surface broadcasting management when N fertilizer was applied (PCU and NCU).

These results imply that deep banding and surface broadcasting of N in 2010 had similar levels of N loss, limiting plant grain yield. Yield differences between these two tillage/N placement systems presumably were not related to plant uptake of N. When averaged over application timing, PCU only increased yield over NCU with NT/surface broadcasting in 2009. When taking into account application timing and averaging over tillage/N placement and the three year study we found minimal yield differences due to application timing. Polymer-coated urea applications at early preplant and preplant, and NCU applications in the fall and early preplant had significantly ($P < 0.05$) greater ear leaf N content than treatments without N applied (Figure 3.6) No difference in ear leaf N content was found between fall, early preplant, and preplant applications and may indicate that PCU can effectively minimize N loss and allow for fall application. When applying NCU, preplant application had 4.0 g kg^{-1} lower ear leaf N content compared to early preplant application.

In the clover residue experiment, averaged over N application timing, ST/deep placement of N fertilizer (PCU and NCU) had 6.2 to 7.7 g kg^{-1} greater ($P < 0.05$) ear leaf N content than NT/surface broadcasting management in 2008 (Figure 3.7). In 2009, ST/deep banding of N fertilizer had 4.3 to 5.8 g kg^{-1} greater ear leaf N content compared to NT/surface broadcast applications of NCU. However, surface broadcast application of PCU with NT management had similar ear leaf N content, possibly due to reduced N loss with the slow release of urea into the soil environment over time. No differences in ear leaf N content were found in 2010 due to the interaction of tillage/N placement and N fertilizer source, which implies N availability and plant uptake were not significantly altered by between these management practices. When averaging over N fertilizer source, differences ($P < 0.05$) in ear leaf N content due to N application timing were minimal and showed no consistent pattern over the three year study (Figure 3.8). When evaluating application timing of N within ST/deep banding and NT/surface broadcasting management, ear leaf N content was not impacted with ST/deep banding in 2008, and NT/surface broadcasting in all three years. In 2009, preplant N application with ST had 4.8 to 4.9 g kg^{-1} greater ear leaf N content than fall and early preplant applications which supports research indicating greater N loss with earlier N applications (Randall et al., 2003). However, in 2010, fall N application with ST had 4.6 to 5.4 g kg^{-1} greater ear leaf N content than early preplant and preplant applications. This demonstrates the potentially greater flexibility in N management when using ST/deep banding compared to NT/surface broadcasting management.

Corn Plant Height

Analysis of corn plant height found two significant ($P < 0.05$), two way interactions (N fertilizer source x tillage/N placement, and N fertilizer source x year) with soybean residue (ANOVA not presented). Clover residue had a significant ($P < 0.05$) interaction with all management variables, which included tillage/N placement, N application timing, fertilizer source, and year. Due to the high order interaction, clear significant differences and trends in corn plant height were difficult to conclude.

In soybean residue, differences ($P < 0.05$) in corn plant height due to N fertilizer source were only found between fertilized (PCU and NCU) and non-fertilized treatments, excluding PCU application compared to NCU in 2010 (Figure 3.9). Minimal differences in corn plant height ($P < 0.05$) were found when averaging over the three year study for the interaction of tillage/N placement and fertilizer source (Figure 3.10). Strip-till/deep banding N (PCU and NCU) and NT/surface broadcast of PCU had 33 to 50 cm greater height than tillage treatments (ST and NT) without N applied. No-till/surface broadcast of NCU was only greater than non-treated, ST management.

With red clover residue, most corn plant heights were similar ($P < 0.05$) between fertilized treatments, regardless of tillage/N placement, N application timing, fertilizer source, and year (Table 3.4). In 2008, only preplant, deep banding application of NCU with ST had 29 to 45 cm greater corn plant height than treatments without N applied, and fall, surface broadcast application of NCU with NT. Low corn plant height found with NT/surface broadcast of NCU may have been due to a variety of factors, such as high rainfall promoting greater N loss, greater potential for N loss with NCU and surface broadcast application compared to PCU and deep banding application , and delayed plant growth with NT due to surface residue cover. In 2009, early preplant and preplant, deep banding application with ST and early preplant, surface broadcast application of PCU with NT had 22 to 40 cm greater plant height than treatments without N application. However, greater plant heights with PCU compared to NCU applications were only found between early preplant and preplant, deep banding application of PCU with ST compared to early preplant, surface broadcast application with NT. In 2010, most fertilized treatments had greater plant height than non-fertilized treatments. However, NT/surface broadcasting with fall (PCU and NCU), early preplant (PCU), preplant (NCU) applications , and preplant, deep banding of PCU with ST had similar corn plant height compared to treatments without N application. These finding seem to support research with has reported delayed plant growth with NT compared to management utilizing tillage (Halvorson et al., 2006).

Aboveground Biomass Prior to Burndown Herbicide

Separate analysis of aboveground winter annual weeds and clover biomass (dry matter) was conducted for the soybean and clover residue experiments, respectively. There was a significant interaction of tillage/N placement and N fertilizer source; however, year was also significant with clover cover crop (ANOVA not presented). Without clover, NT/surface broadcasted N (PCU and NCU) had 5560 to 7020 kg ha^{-1} greater ($P < 0.10$) dry aboveground biomass than ST/deep banded N, while ST/deep banded N was similar to that of non-treated tillage practices (Figure 3.11). These results imply that ST/deep banded N into soybean residue had lower aboveground biomass due to deep placement which reduced the uptake of N from winter annual weeds. Past research indicated that deep placement of N in bands lowered the rate of microbial N transformations over surface application which may account for lower volatilization and denitrification N loss (Sommer et al., 2004; Drury et al., 2006; Rochette et al., 2008; Rochette et al., 2009; Grant et al., 2010). With red clover, aboveground biomass varied considerably between growing seasons, with 2009 having the lowest biomass production (Figure 3.12). Differences among aboveground biomass due to the interaction of tillage/N placement and N fertilizer source were similar to the soybean residue experiment. No-till/surface broadcasting of N as PCU or NCU had greater aboveground biomass averages than ST/deep banding of N, in most instances ($P < 0.10$) which indicated greater N uptake by the cover crop with NT/surface broadcasted N management.

Grain Yields

Separate analysis of corn grain yields by residue (soybean and red clover experiments) had different high order interactions (Table 3.5). With the soybean residue experiment, the highest order interaction ($P < 0.05$) was between tillage/N placement and N fertilizer source which required analysis by year. The application timing of N did not affect corn grain yields in this experiment. In the red clover residue experiment, the highest order interaction was ($P < 0.05$) N application timing, tillage/N placement, N fertilizer source, and year.

Differences in corn grain yields following soybean due to tillage/N placement and N fertilizer source only varied among seasons in that 2010 had lower overall yields than 2008 and 2009. Non-treated controls had 2700 to 8470, 1470 to 6850, and 1380 to 3550 kg ha^{-1} lower grain yields ($P < 0.05$) than fertilized treatments in 2008, 2009, and 2010, respectively (Figure 3.13). There was no difference in yields between PCU and NCU with NT/surface broadcasted N and ST/deep banded N management in each season. Strip-till with deep banded N had 1560 to 5380 kg ha^{-1} higher yields than NT/surface broadcast treatments in 2008, 2009, and 2010. Research conducted on soil with moderate to good drainage found ST had yields similar to NT, which implied that yield potential benefits from ST increase for poorly drained soils (Vetsch and Randall, 2004). With high rainfall early in 2010, there were noticeable issues with plant establishment, which indicated increased yields with ST/deep banding were due to improved seedbed conditions over NT and resulted in greater plant populations at harvest. In 2008 and 2009, plant populations did not differ among tillage systems; however, grain yields averaged 40 to 3820 kg ha^{-1} greater with ST compared to NT. Increased yields in 2008 and 2009 may have been due to reduced N loss with deep placement of N compared to surface broadcasting (Grant et al., 2010). It was undetermined what proportion of yield benefits with ST/deep banded N were the result of tillage within the planting row or deep placement, our results indicated that yield benefits from ST/deep banding of N compared to NT/surface broadcasted N increase from wet to moderately wet growing seasons.

In the experiment with red clover, there was no differences in yields ($P < 0.05$) between fall and preplant N applications in NT/surface broadcast treatments regardless of N fertilizer source, excluding NT/surface broadcasting of NCU in 2008 and PCU in 2010 (Table 3.6). These results imply that minimal N loss occurred from PCU and NCU fertilizer with dry and cold weather in the fall up to spring. In each season, yield with fall N applications with ST/deep band were similar to greater than NT/surface broadcast preplant applications of PCU or NCU which may be due to negligible N loss between the period of fall application and plant uptake in the spring when N was deep banded. In 2008 and 2009, early preplant applications of both N sources had similar to greater yields compared to preplant applications when using ST/deep band placement. This indicated that high yields can be maintained with tillage/N applications as early as Mar. (early preplant) which can benefit producers by minimizing time constraints at planting. In 2008, when restricted to single fall, surface broadcast application under NT, PCU significantly increased grain yields by 2860 kg ha^{-1} compared to NCU applications.

Increased yield with PCU compared to NCU were not found in 2009 or 2010, regardless of tillage/N placement or application timing. Therefore, yield benefits from PCU application over NCU were limited over the three year study. This was counter to previous research conducted at our research site that found corn grain yields increased by 1530 to 1810 kg ha^{-1} in poorly drained, low lying areas when PCU was applied compared to NCU (Noellsch et al., 2009). In 2008, early preplant and preplant applications of N (PCU and NCU) with a ST/deep band had 2810 to 3140 greater yields than NT/surface broadcasted treatments. Yields with preplant applications of N with NT/surface broadcast application were greater (2570 to 2620 kg ha^{-1}) than with surface broadcasting of NCU in the fall under NT management. In 2009, ST/deep banded fall application of PCU, an early preplant application of N, and a preplant application of N had greater (2490 to 5190 kg ha^{-1}) yields than all NT/surface broadcast treatments, excluding an early preplant application of PCU. In 2010, yields were lower for all treatments which lead to minimal differences in yield production due to tillage/N placement or N management; however, ST/deep banded N had higher average yields than all NT/surface broadcasting treatments, excluding a preplant application of PCU.

When comparing the high yield production of ST/deep banded PCU or NCU to anhydrous ammonia, a standard N treatment in this region, differences in yields ($P <$ 0.05) were minimal (Figure 3.14). Additional use N-serve (nitrapyrin, nitrification inhibitor) with AA, averaged over the three year study and N application timing had similar yields in both soybean and clover residue. When taking into account N application timing, yield increases from the addition of nitrapyrin with fall applications were not found (results not presented). Therefore, the additional cost of nitrapyrin may not be a economical for farmers when applying AA in the fall. In the soybean residue experiment, both ST/deep banded PCU and NCU produced similar yields to AA which supports the use of ST/deep banding management in claypan soils in the Midwest. However, with clover residue, ST/deep banding of NCU had 1450 kg ha^{-1} lower yields than AA treatments with nitrapyrin (N-serve).

Correlation analysis

Measurements of plant population, corn height, chlorophyll meter reading (SPAD units) taken between the V18 and R3 growth stage, and N concentration in ear leaf samples (R3 to R5 growth stage) were positively correlated (number of data points = 342) with corn yields (Table 3.7). Plant population was found to be positively correlated (r = 0.43) with grain yield. Since differences in plant populations among NT and ST were not always significant, we can assume that only a portion of yield benefits of ST/deep banding placement over NT/surface broadcasting were derived from improved seedbed conditions. Other research indicated that yield differences between NT and ST management practices were largely dependent on plant population differences since ST/deep banding had greater yields in a season where plant population was lower in NT/surface broadcasting treatment (Hendrix et al., 2004). Although these measurements were significantly correlated corn yield ($P < 0.0001$), ear leaf samples and chlorophyll meter readings (SPAD units) had the greatest correlation (r = 0.72 to 0.75). As seen in Figure 3.15, a linear relationship ($R^2 = 0.47$) between ear leaf N content and chlorophyll meter reading was observed at $P < 0.0001$. These results imply chlorophyll meter readings taken between the V18 and R3 growth stage can be correlated to ear leaf N content and are a viable option to predict yield production that is simpler and less expensive than collecting and analyzing ear leaf samples between the R3 to R5 growth stage for N concentration analysis. These results were similar to yield components analyzed for rice production where chlorophyll meter readings (SPAD units) and ear leaf N concentration had similar correlation levels to yield production (Ntamatungiro et al., 1999).

Test Weight

In the soybean residue experiment, test weights differed due to the interaction of tillage/N placement by year, while the main effect of N fertilizer was significant as well (Table 3.8). Similar to the grain yield analysis, N application timing was not a significant factor. When red clover was present, the main effect of tillage/N placement and N fertilizer source were significant ($P < 0.05$) and required analysis by year. Unlike the grain yield analysis, N application timing had no impact on test weight.

In 2010, ST/deep banded N had higher test weight (1.4 kg hL^{-1}) than NT/surface broadcasting management in the soybean residue experiment (Figure 3.16). When red clover was present, ST/deep banding increased test weight 1.1 and 0.6 kg hL^{-1} in 2009 and 2010, respectively (Figure 3.17). Higher test weights with ST/deep banded N corresponded with higher yields and further implied that ST/deep band placement may minimize N loss in wet years compared to NT/surface broadcast application, which lead to greater N uptake and grain quality. When averaged over the three growing seasons in the soybean residue experiment, fertilized treatments had significantly ($P < 0.05$) greater test weight (1.0 kg hL^{-1}) than non-fertilized treatments (Figure 3.18). In the clover experiment, fertilized treatments only had greater test weights than non-fertilized treatments in 2009 (Figure 3.19), possibly due the corn hybrid and/or N fixation by red clover was at a level to compensate for poor grain quality found when no fertilizer N was applied.

CONCLUSIONS

Poorly drained, claypan soils can pose a challenge for selecting appropriate tillage and N management practices for corn production. During wet growing seasons, poorly drained soils had conditions potentially conducive for gaseous N loss and poor plant growth which may have accounted for lowered grain yield potential. Over the three years of this research, rainfall was above average and resulted in lower harvested plant populations and possibly greater N loss causing large yield differences among NT/surface broadcast and ST/deep band applications of N. Tillage in the seeded row and deep banding placement of N (PCU or NCU) with ST may have minimize seed germination stress, N loss potential, and resulted in consistently higher yields with ST/deep banded N compared to NT/surface broadcasted N management during all three seasons. Regardless of PCU or NCU fertilizer application, high yield production with ST/deep banding was maintained with N applications as early as Mar., which could increase a farmer's flexibility of when and what N fertilizer can be applied without impacting yield potential. When using NT/surface broadcasting management, application timing and N fertilizer source had minimal significance on grain yields, which was presumably a function high

N loss due to low plant populations, wet springs, and placement of N on the soil surface or N uptake from clover and winter annual weeds.

High yield production found with a ST/deep band placement not significantly different compared to anhydrous ammonia management. Inclusion of nitrapyrin with AA did not increase yields regardless of when N was applied, and cannot be recommended based on this study. In conclusion, our findings showed that in most circumstances PCU had minimal yield benefits over NCU application. Strip-till/deep banding management was a consistent, high corn grain yielding system that was a viable management option in moderately wet to wet growing seasons in poorly drained soils which could allow farmers more flexibility in N management options.

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Table 3.1. Soil properties for the red clover and soybean residue experiment fields in 2008, 2009, and 2010.

								Exchangeable (1M NH_4AO_c)			
Experiment and year	Depth	Bulk Density	pH (0.01M $CaCl_2$)	Org. matter	Neut. acidity	CEC	Bray I P	Ca	K	Mg	NO_3-N
	cm	g cm^3		g kg^{-1}	-- $cmol_c$ kg^{-1} --		mg kg^{-1}	------	kg ha^{-1}	------	kg ha^{-1}
Clover residue											
2008†	0-10	------	6.8	26	0.17	15.9	15.3	5990	345	538	------
2009	0-10	1.32	6.5	28	1.00	14.9	29.3	5333	380	428	1.8
	10-20	1.38	6.0	23	3.17	17.6	9.3	5414	239	514	2.0
2010	0-10	1.38	6.7	32	0.63	14.9	35.4	5490	368	421	0.8
	10-20	1.47	6.5	23	1.13	15.2	8.8	5432	197	453	0.0
Soybean residue											
2008†	0-10	------	6.2	26	1.7	14.5	30.8	4711	450	494	------
2009	0-10	1.37	6.2	26	1.5	15.3	41.9	5239	384	446	10.4
	10-20	1.41	6.2	19	1.8	16.4	11.2	5640	556	452	4.6
2010	0-10	1.43	6.4	29	1.5	14.7	38.7	4955	501	429	2.8
	10-20	1.50	6.4	24	1.7	14.6	21.9	4901	307	447	1.6

† Bulk density samples, soil nitrate concentration, and soil samples taken at a depth of 10-20 cm, were not obtained or analyzed in the fields used in 2008.

Table 3.2. Dates of planting, applications of nitrogen, herbicides, and insecticide, and harvest in the 2008, 2009, and 2010 growing season from residue experiments.

		Residue experiments	
Year	Field information and management	Clover	Soybean
2008	Planting date	6 May	29 May
	N applications timings		
	Fall	11 Nov.	11 Nov.
	Early preplant	7 Apr.	7 Apr.
	Preplant	5 May	5 May
	Burndown		
	Glyphosate at 1.06 kg ae ha^{-1}	28 Apr.	24 Apr.
	2,4-D Amine at 1.05 kg ai ha^{-1}	28 Apr.	
	Preemergence herbicide		
	Acetochlor at 1.9 kg ai ha^{-1}	16 May	16 May
	Atrazine at 0.94 kg ai ha^{-1}	16 May	16 May
	Glyphosate at 1.06 kg ae ha^{-1}	16 May	16 May
	Harvest date	4 Oct.	10 Nov.
2009	Planting date	23 Apr.	23 Apr.
	N applications timings		
	Fall	3 Nov.	3 Nov.
	Early preplant	4 Apr.	4 Apr.
	Preplant	23 Apr.	23 Apr.
	Burndown		
	Glyphosate at 1.06 kg ae ha^{-1}	28 Apr.	
	Dicamba at 0.28 kg ai ha^{-1}	28 Apr.	
	Preemergence herbicide		
	S-metolachlor at 2.25 kg ai ha^{-1}	4 May	4 May
	Atrazine at 0.84 kg ai ha^{-1}	4 May	4 May
	Glyphosate at 1.06 kg ae ha^{-1}		4 May
	Harvest date	19 Oct.	30 Sept.
2010	Planting date	14 Apr.	14 Apr.
	N applications timings		
	Fall	6 Nov.	6 Nov.
	Early preplant	1 Apr.	1 Apr.
	Preplant	14 Apr.	14 Apr.
	Burndown		
	S-metolachlor at 2.25 kg ai ha^{-1}	16 Apr.	16 Apr.
	Atrazine at 0.84 kg ai ha^{-1}	16 Apr.	16 Apr.
	Mesotrione at 0.23 kg ai ha^{-1}	16 Apr.	16 Apr.
	Dicamba at 0.56 kg ai ha^{-1}	16 Apr.	
	Lambda-cyhalothrin at 0.02 kg ai ha^{-1}	16 Apr.	
	Postemergence		
	Glyphosate at 1.06 kg ae ha^{-1}	22 June	
	Harvest date	28 Sept.	29 Sept.

Table 3.3. Overall ANOVA table for ear leaf N content in the soybean and red clover residue experiments.

	Residue Experiment						
	Num.	Den.	Soybean		Den.	Clover	
Source	df	df	F	Pr > F	df	F	Pr > F
Year	2	18	63.28	<.0001	21	66.98	<.0001
N source	2	90	31.31	<.0001	105	65.99	<.0001
Tillage/placement	1	90	35.65	<.0001	105	30.13	<.0001
N app. timing	2	18	3.15	0.0669	21	1.93	0.1695
N source x Tillage/placement	2	90	7.62	0.0009	105	20.01	<.0001
N app. timing x N source	4	90	3.23	0.0159†	105	1.44	0.2251
N app. timing x Tillage/placement	2	90	1.43	0.2435	105	0.07	0.9347
Year x N source	4	90	5.62	0.0004	105	14.10	<.0001
Year x Tillage/placement	2	90	24.72	<.0001	105	9.94	0.0001
Year x N app. timing	4	18	1.43	0.2649	21	2.92	0.0456
Year x N app. timing x Tillage/placement	4	90	0.25	0.9087	105	4.76	0.0014†
N app. timing x N source x Tillage/placement	4	90	1.68	0.1607	105	0.60	0.6633
Year x N source x Tillage/placement	4	90	2.21	0.0746‡	105	3.12	0.0182†
Year x N app. timing x N source	8	90	1.25	0.2789	105	0.77	0.6262
Year x N app. timing x N source x Tillage/placement	8	90	1.25	0.2778	105	1.08	0.3800

† Significant interaction at $P < 0.05$.

‡Significant interaction at $P < 0.10$.

Abbreviations: Num. = numerator; Den. = denominator; app. = application.

Table 3.4. Corn plant height analysis in clover residue experiment due to the interaction of year by N application timing, tillage/N placement, and N fertilizer source.

Year	N app. timing	Tillage / N placement	N fertilizer source NCU	PCU	Non-treated
			--- Corn height(cm) ---		
2008	Fall	No-till / broadcast	255	272	252
	Fall	Strip-till / deep band	274	265	245
	Early PreP.	No-till / broadcast	276	281	259
	Early PreP.	Strip-till / deep band	279	282	246
	PreP.	No-till / broadcast	278	273	261
	PreP.	Strip-till / deep band	290	283	267
		LSD (0.05)	------------- 28 ------------		
2009	Fall	No-till / broadcast	241	244	217
	Fall	Strip-till / deep band	245	242	231
	Early PreP.	No-till / broadcast	237	255	233
	Early PreP.	Strip-till / deep band	250	256	222
	PreP.	No-till / broadcast	240	246	225
	PreP.	Strip-till / deep band	249	257	229
		LSD (0.05)	------------- 18 ------------		
2010	Fall	No-till / broadcast	154	154	151
	Fall	Strip-till / deep band	187	194	146
	Early PreP.	No-till / broadcast	183	177	152
	Early PreP.	Strip-till / deep band	206	201	149
	PreP.	No-till / broadcast	180	194	141
	PreP.	Strip-till / deep band	198	176	153
		LSD (0.05)	------------- 28 -------------		

Abbreviations: app. = application; PreP. = preplant.

Table 3.5. ANOVA table of the analysis of corn grain yields.

	Residue Experiment						
	Num.	Den.	Soybean		Den.	Clover	
Source	df	df	F	Pr > F	df	F	Pr > F
Year	2	18	61.36	<.0001	21	179.94	<.0001
N source	2	90	279.00	<.0001	105	220.07	<.0001
Tillage/placement	1	90	207.52	<.0001	105	249.17	<.0001
N app. timing	2	18	1.43	0.2663	21	5.15	0.0151
N source x Tillage/placement	2	90	33.65	<.0001	105	56.41	<.0001
N app. timing x N source	4	90	1.10	0.3610	105	5.03	0.0009
N app. timing x Tillage/placement	2	90	0.77	0.4652	105	5.66	0.0046
Year x N source	4	90	14.52	<.0001	105	8.13	<.0001
Year x Tillage/placement	2	90	13.80	<.0001	105	3.17	0.0459
Year x N app. timing	4	18	0.22	0.9212	21	1.10	0.3830
Year x N app. timing x Tillage/placement	4	90	0.13	0.9722	105	1.80	0.1337
N app. timing x N source x Tillage/placement	4	90	1.77	0.1420	105	3.84	0.0059
Year x N source x Tillage/placement	4	90	3.32	0.0138†	105	4.25	0.0031
Year x N app. timing x N source	8	90	0.30	0.9637	105	2.60	0.0124
Year x N app. timing x N source x Tillage/placement	8	90	1.30	0.2539	105	2.24	0.0299†

† Significant interaction at $P < 0.05$.

Abbreviations: Num. = numerator; Den. = denominator; app. = application.

Table 3.6. Corn grain yields with red clover residue and analyzed by the interaction of N application timing, tillage/placement, and N fertilizer source by year.

			N fertilizer source		
Year	N app. timing	Tillage / N placement	NCU	PCU	Non-treated
			-- Grain Yield (kg ha^{-1}) --		
2008	Fall	No-till / broadcast	6500	9350	7780
	Fall	Strip-till / deep band	10450	10250	7100
	Early PreP.	No-till / broadcast	8000	8650	6740
	Early PreP.	Strip-till / deep band	12500	12390	6970
	PreP.	No-till / broadcast	9070	9120	7690
	PreP.	Strip-till / deep band	12320	12160	7070
		LSD (0.05)	------------- 1460 ------------		
2009	Fall	No-till / broadcast	6940	6300	5690
	Fall	Strip-till / deep band	7530	10740	5690
	Early PreP.	No-till / broadcast	6810	9050	5860
	Early PreP.	Strip-till / deep band	11190	11490	5870
	PreP.	No-till / broadcast	7010	7210	5630
	PreP.	Strip-till / deep band	10020	10790	6290
		LSD (0.05)	------------- 1960 ------------		
2010	Fall	No-till / broadcast	4820	4160	4000
	Fall	Strip-till / deep band	5920	6540	4080
	Early PreP.	No-till / broadcast	4870	4990	4090
	Early PreP.	Strip-till / deep band	7750	7150	4200
	PreP.	No-till / broadcast	4640	5430	3780
	PreP.	Strip-till / deep band	5250	8250	4420
		LSD (0.05)	------------- 810 -------------		

Abbreviations: app. = application; PreP. = preplant.

Table 3.7. Correlation analysis between corn grain yields and potential yield indicating measurements.

measurement	Grain yield
Plant height‡	0.42
Prob.>|r|	<.0001
Plant population‡	0.43
Prob.>|r|	<.0001
Ear leaf N†	0.75
Prob.>|r|	<.0001
Chlorophyll reading (SPAD units)‡	0.72
Prob.>|r|	<.0001

†Ear leaf samples were taken between the R3 and R5 growth stage (Ritchie et al., 1993).

‡Plant population, chlorophyll meter readings, and plant height data were collected between the V18 and R3 growth stage.

Table 3.8. ANOVA table of the analysis of corn test weight.

	Residue Experiment						
	Num.	Den.	Soybean		Den.	Clover	
Source	df	df	F	Pr > F	df	F	Pr > F
Year	2	18	54.17	<.0001	21	1048.54	<.0001
N source	2	90	36.86	<.0001†	105	5.72	0.0044
Tillage/placement	1	90	33.99	<.0001	105	23.65	<.0001
N app. timing	2	18	0.19	0.8280	21	4.84	0.0187
N source x Tillage/placement	2	90	0.03	0.9740	105	2.44	0.0920
N app. timing x N source	4	90	1.18	0.3236	105	0.16	0.9580
N app. timing x Tillage/placement	2	90	0.64	0.5302	105	2.28	0.1072
Year x N source	4	90	1.87	0.1222	105	2.51	0.0462†
Year x Tillage/placement	2	90	12.08	<.0001†	105	9.06	0.0002†
Year x N app. timing	4	18	0.16	0.9572	21	0.56	0.6933
Year x N app. timing x Tillage/placement	4	90	0.58	0.6745	105	0.78	0.5401
N app. timing x N source x Tillage/placement	4	90	0.35	0.8454	105	2.09	0.0875
Year x N source x Tillage/placement	4	90	0.96	0.4327	105	1.73	0.1480
Year x N app. timing x N source	8	90	0.40	0.9159	105	0.42	0.9091
Year x N app. timing x N source x Tillage/placement	8	90	1.29	0.2608	105	0.76	0.6370

† Significant interaction at $P < 0.05$.

Abbreviations: Num. = numerator; Den. = denominator; app. = application.

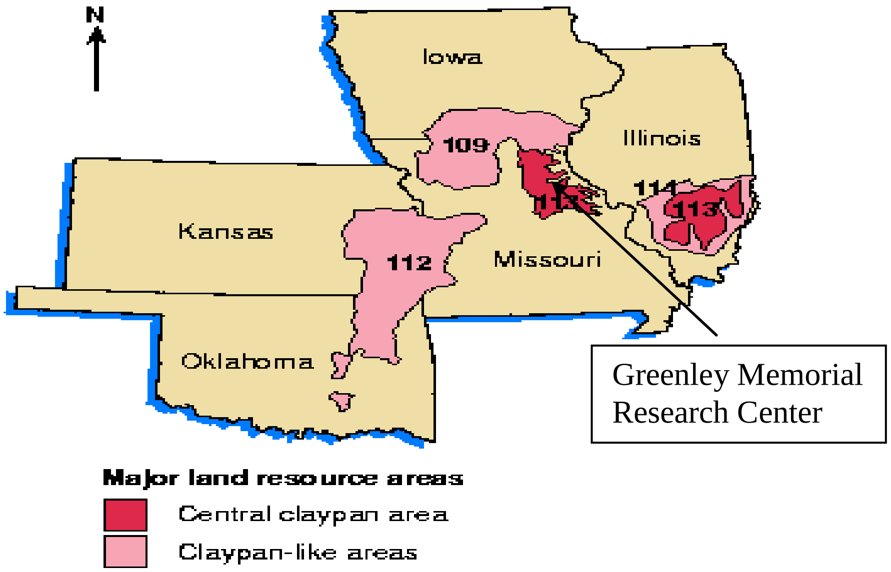

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Figure 3.1. Central Claypan region in the United States.
Source: USDA Agricultural Handbook 296, 1981. Map prepared by CARES, 1998.

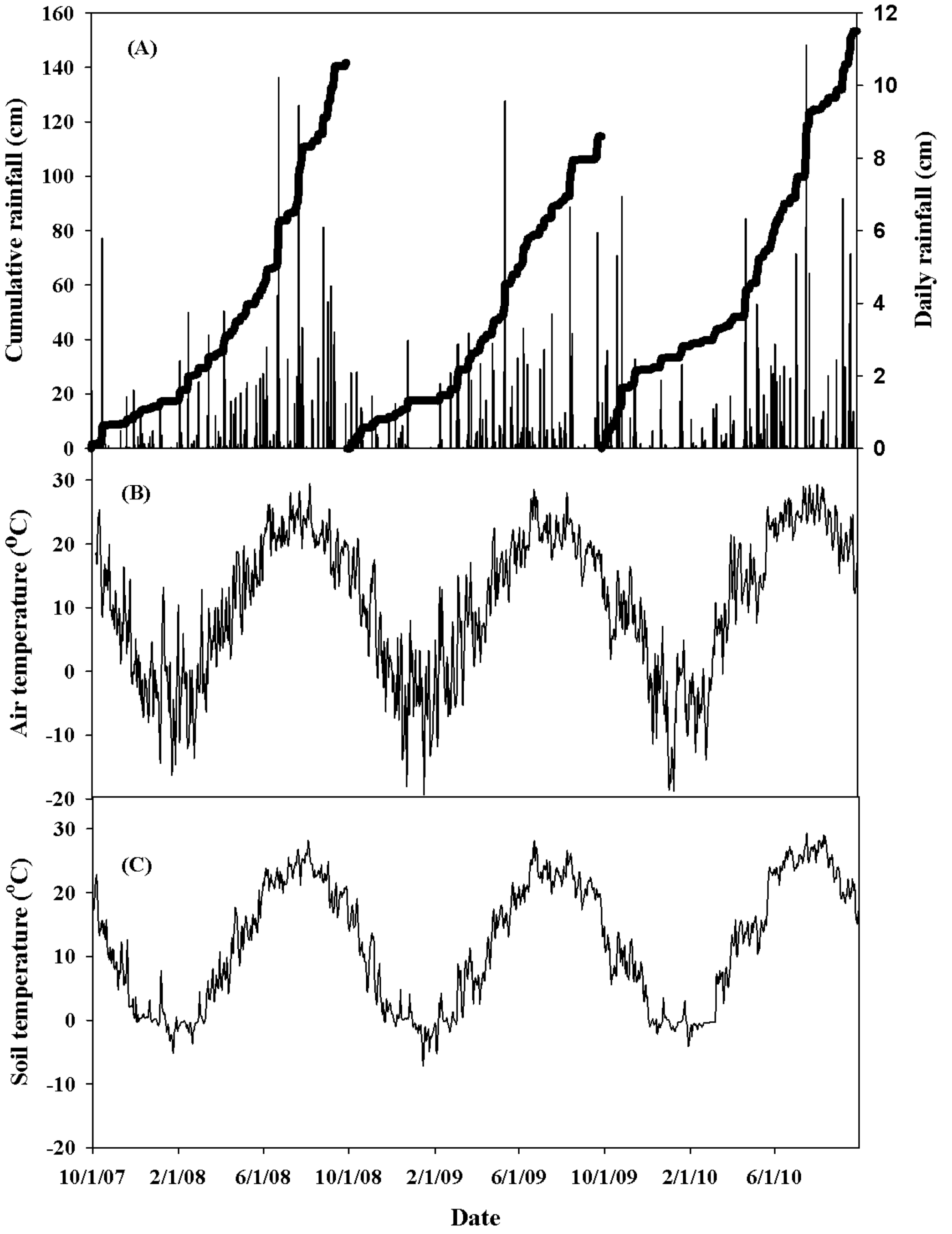

Figure 3.2. Daily (bars) and cumulative rainfall (lines) (A), daily average air temperature (B), and soil temperature (C) at 5 cm depth with soybean residue from fall 2007 to 2010.

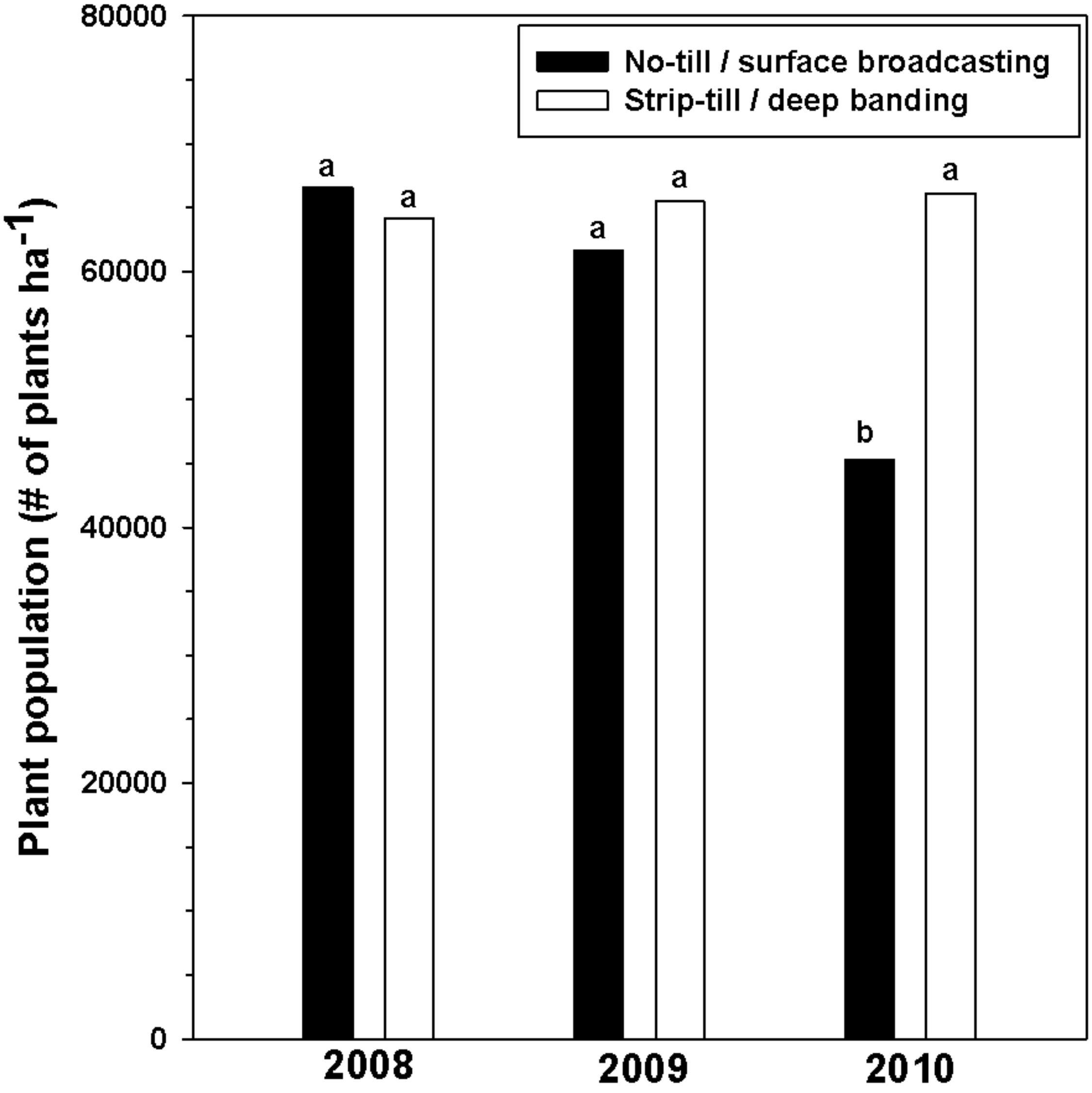

Figure 3.3. Corn plant population following soybean production due to tillage / N placement for 2008, 2009, and 2010. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

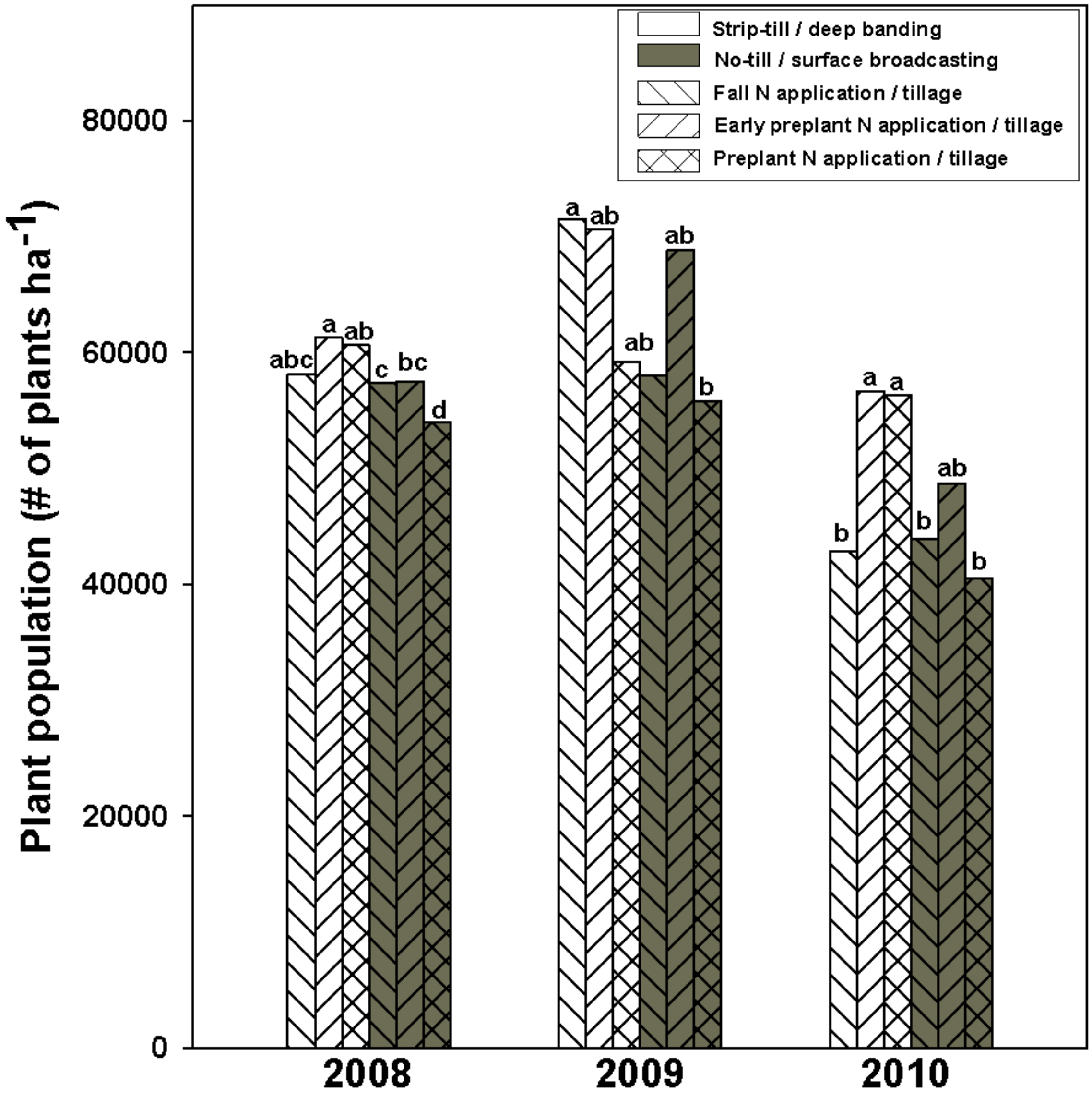

Figure 3.4. Corn plant population following soybean production and red clover crop due to the interaction of tillage/N placement and N application timing for 2008, 2009, and 2010. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

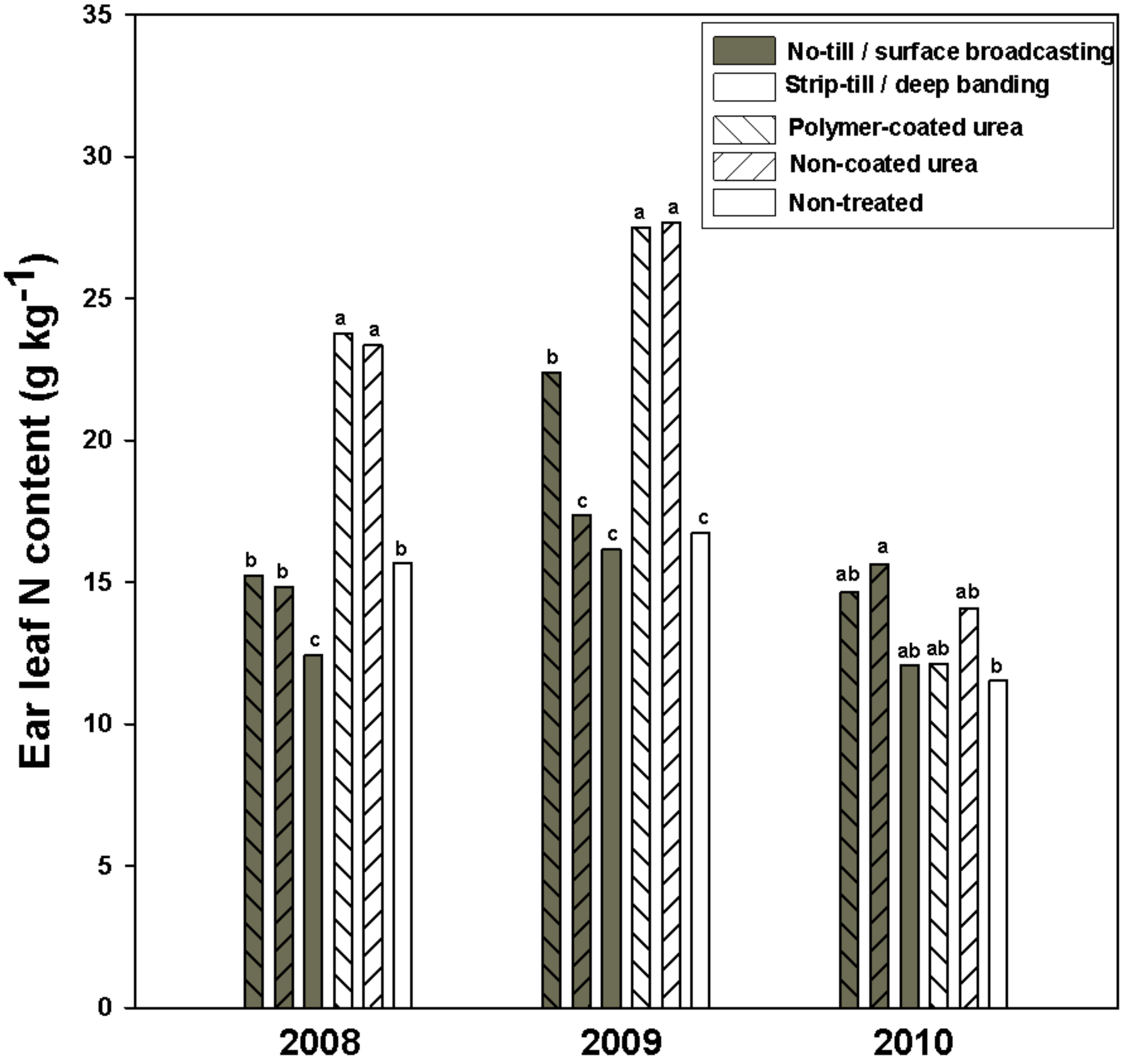

Figure 3.5. Ear leaf N content following soybean production due to the interaction of tillage/N placement and N fertilizer source for 2008, 2009, and 2010. Ear leaf samples were taken between the R3 and R5 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.10$).

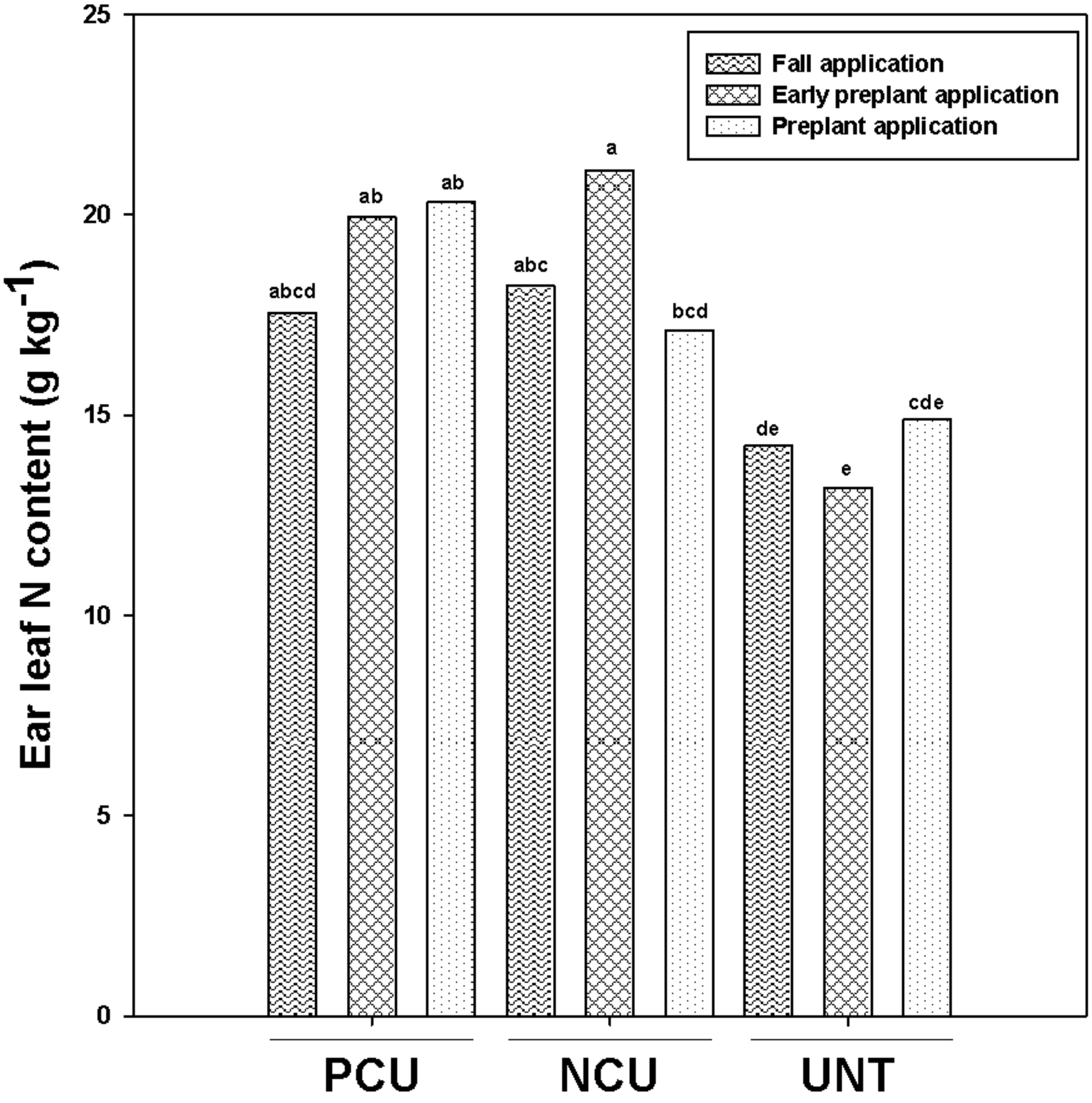

Figure 3.6. Ear leaf N content following soybean production due to the interaction of N application timing and fertilizer source averaged over the 2008, 2009, and 2010. Ear leaf samples were taken between the R3 and R5 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

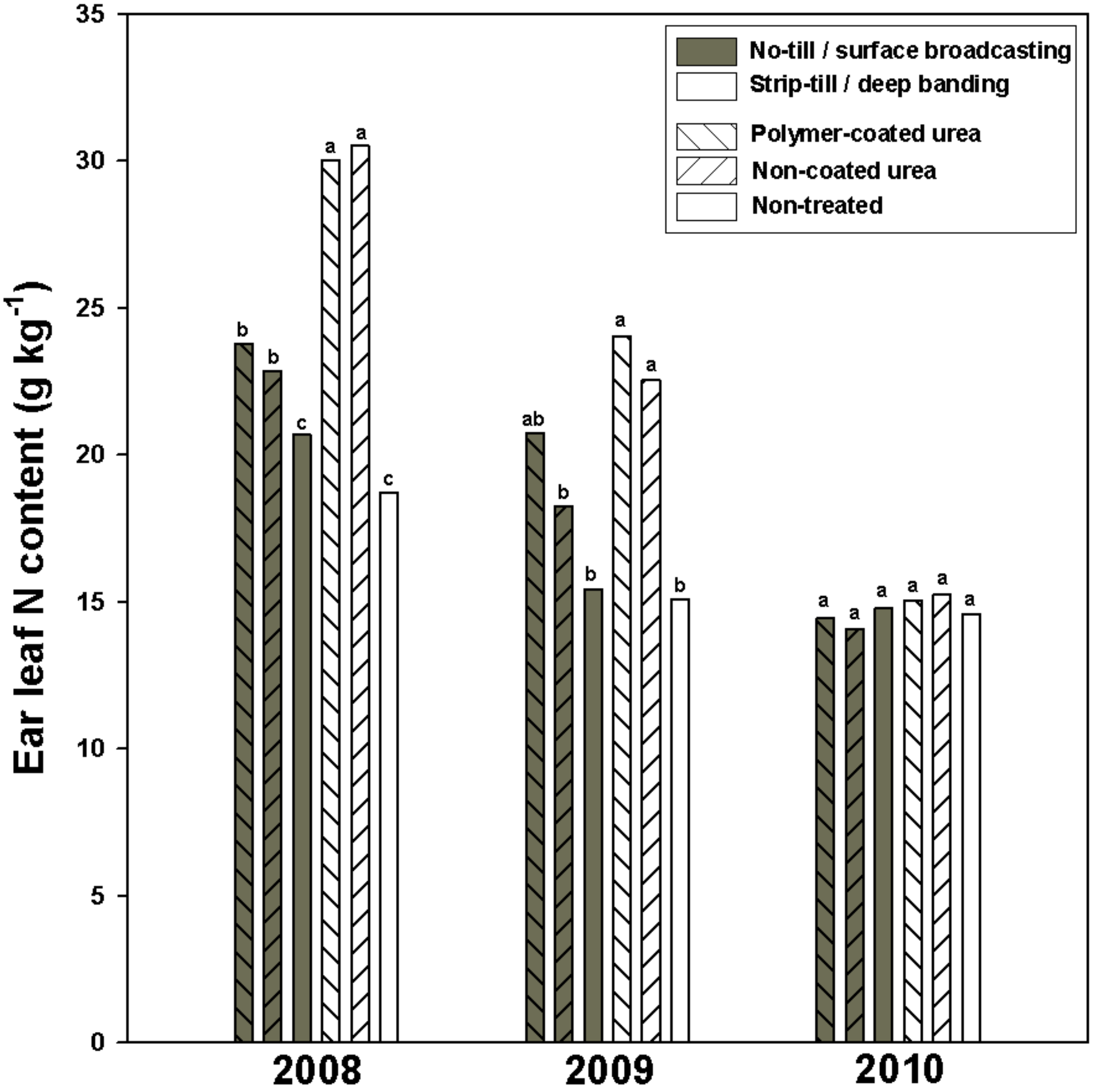

Figure 3.7. Ear leaf N content following soybean production with red clover cover crop due to the interaction of tillage/N placement and N fertilizer source for 2008, 2009, and 2010. Ear leaf samples were taken between the R3 and R5 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD (*P* < 0.05).

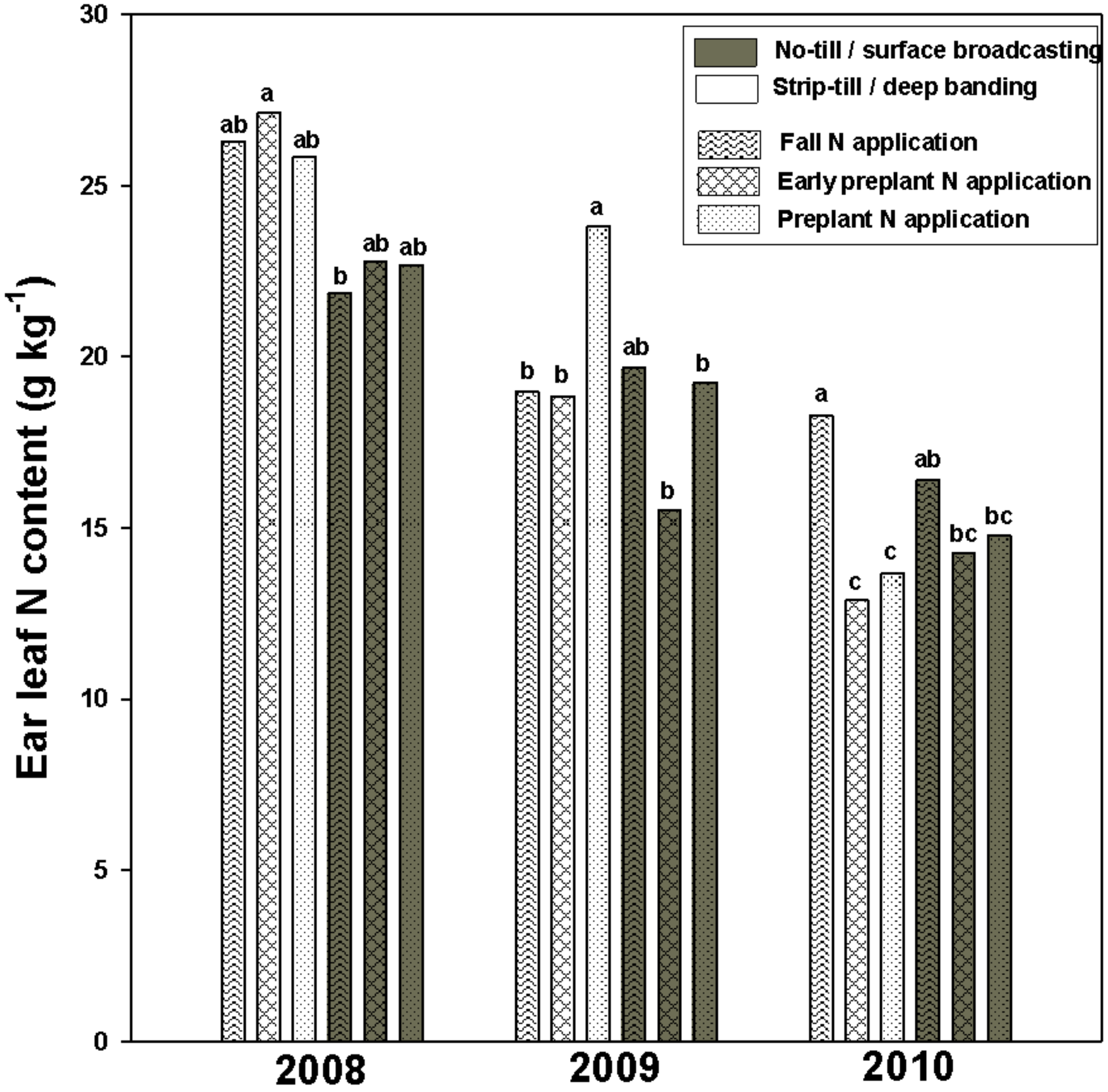

Figure 3.8. Ear leaf N content following soybean production with red clover cover crop due to the interaction of tillage/N placement and N application timing for 2008, 2009, and 2010. Ear leaf samples were taken between the R3 and R5 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

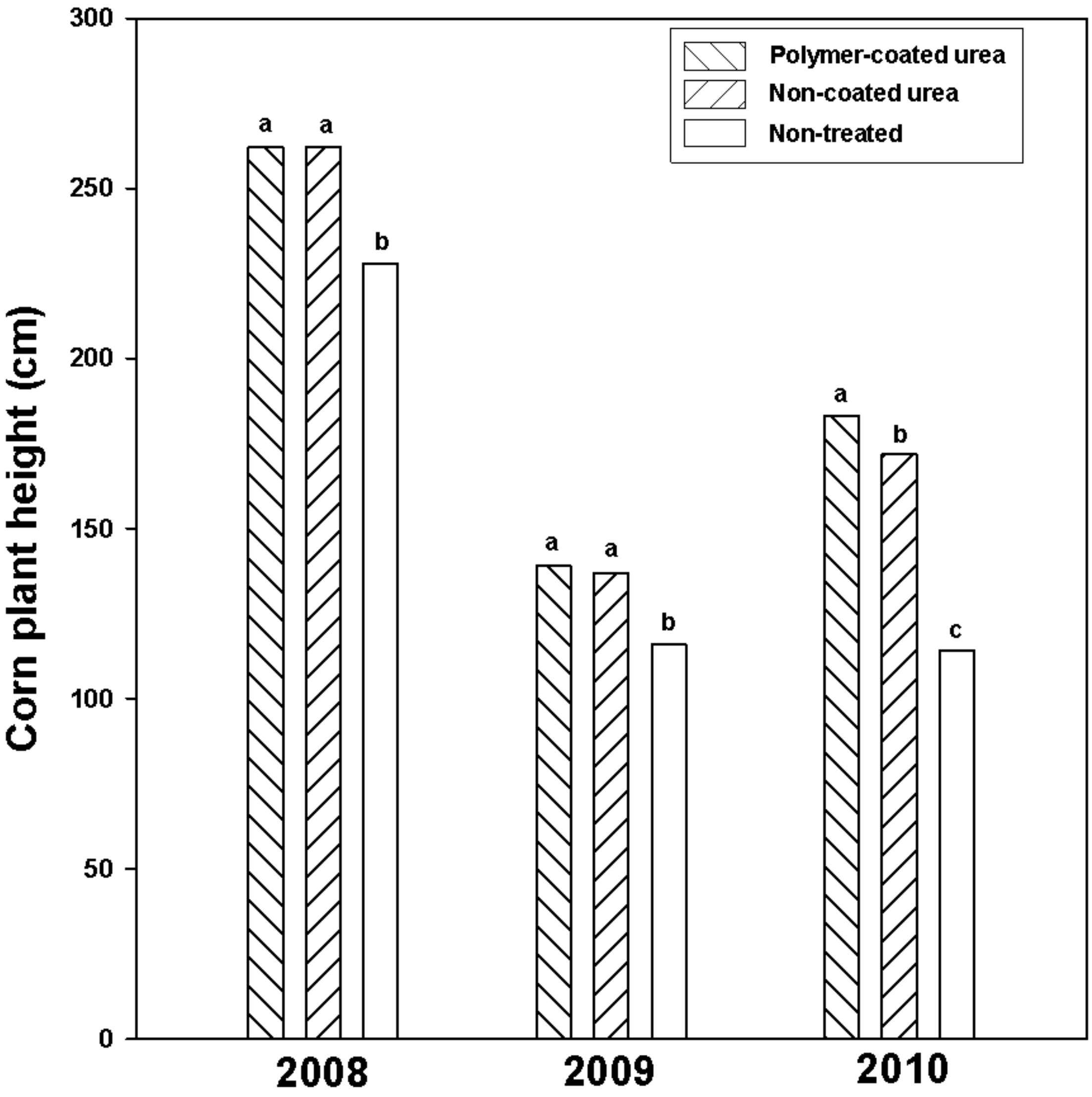

Figure 3.9. Corn plant height following soybean production due to N fertilizer source analyzed by year (2008, 2009, and 2010). Plant height measurements were taken between the V18 and R3 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher’s Protected LSD ($P < 0.05$).

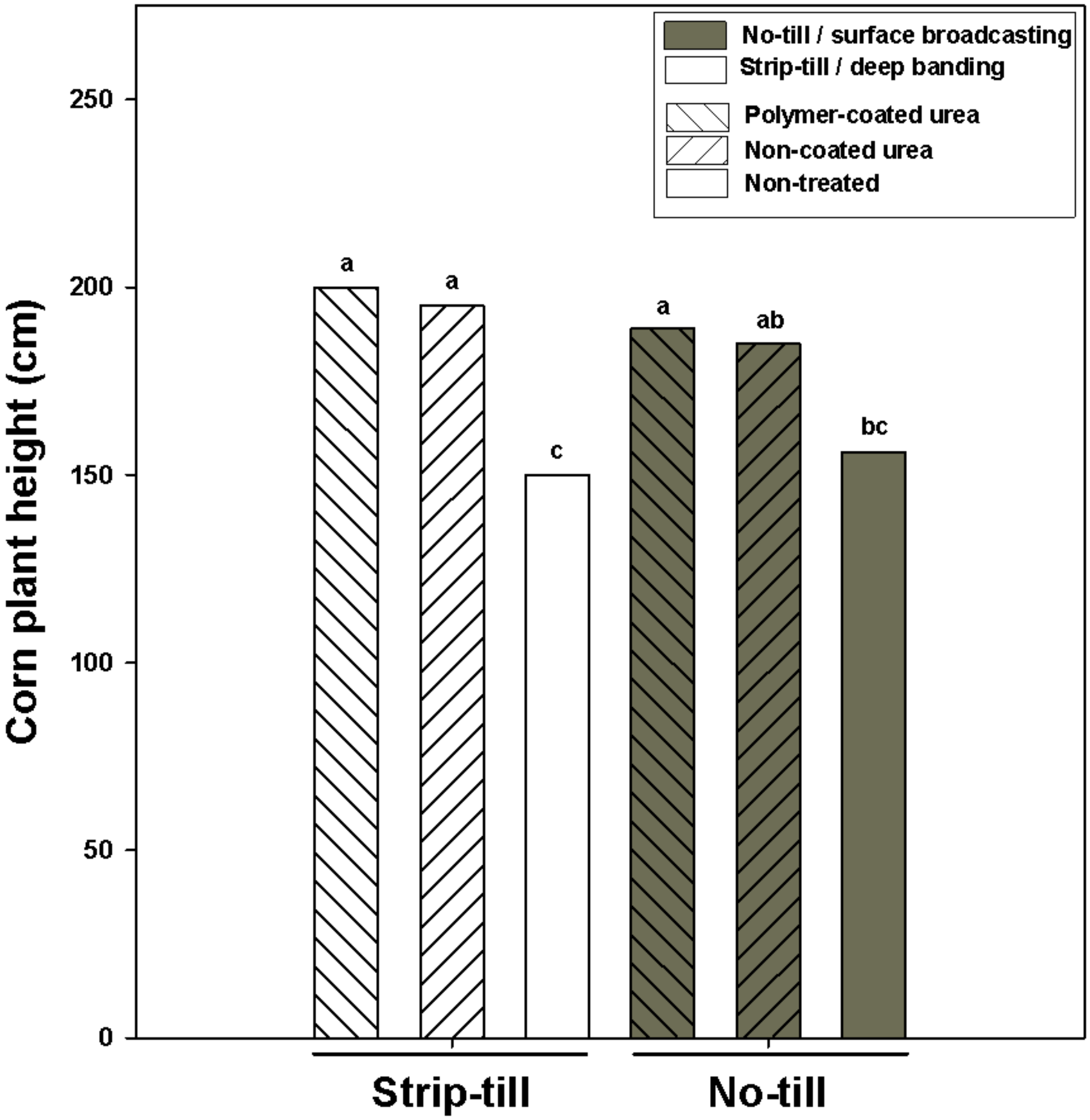

Figure 3.10. Corn plant height following soybean production due to the interaction of tillage/N placement and N fertilizer source averaged over 2008, 2009, and 2010. Plant height measurements were taken between the V18 and R3 growth stage. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

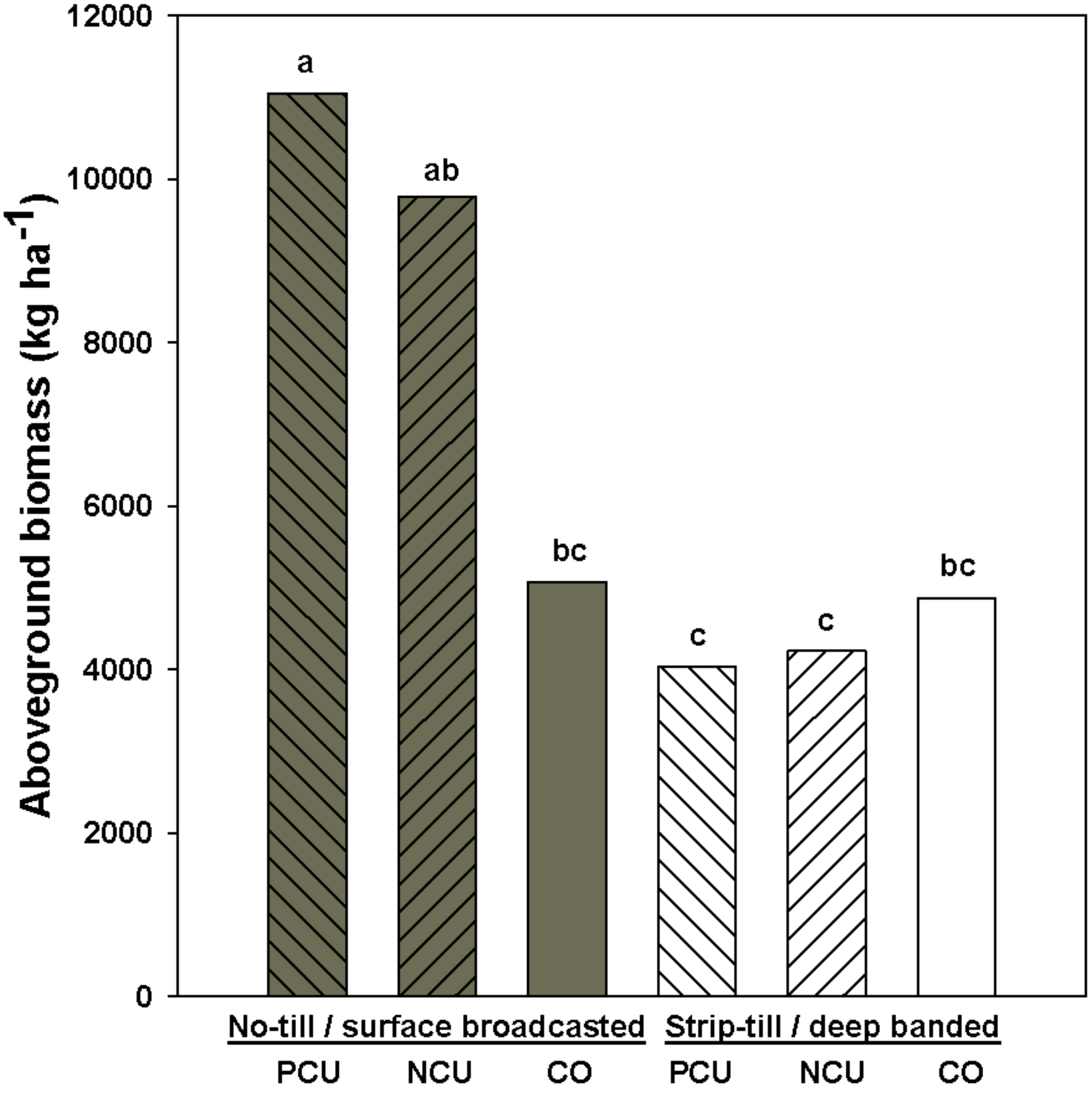

Figure 3.11. Aboveground biomass of winter annual weeds for soybean residue treatments (without red clover) for tillage/N placement and N fertilizer source averaged over N application timing and the three year study. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD (*P* < 0.05).

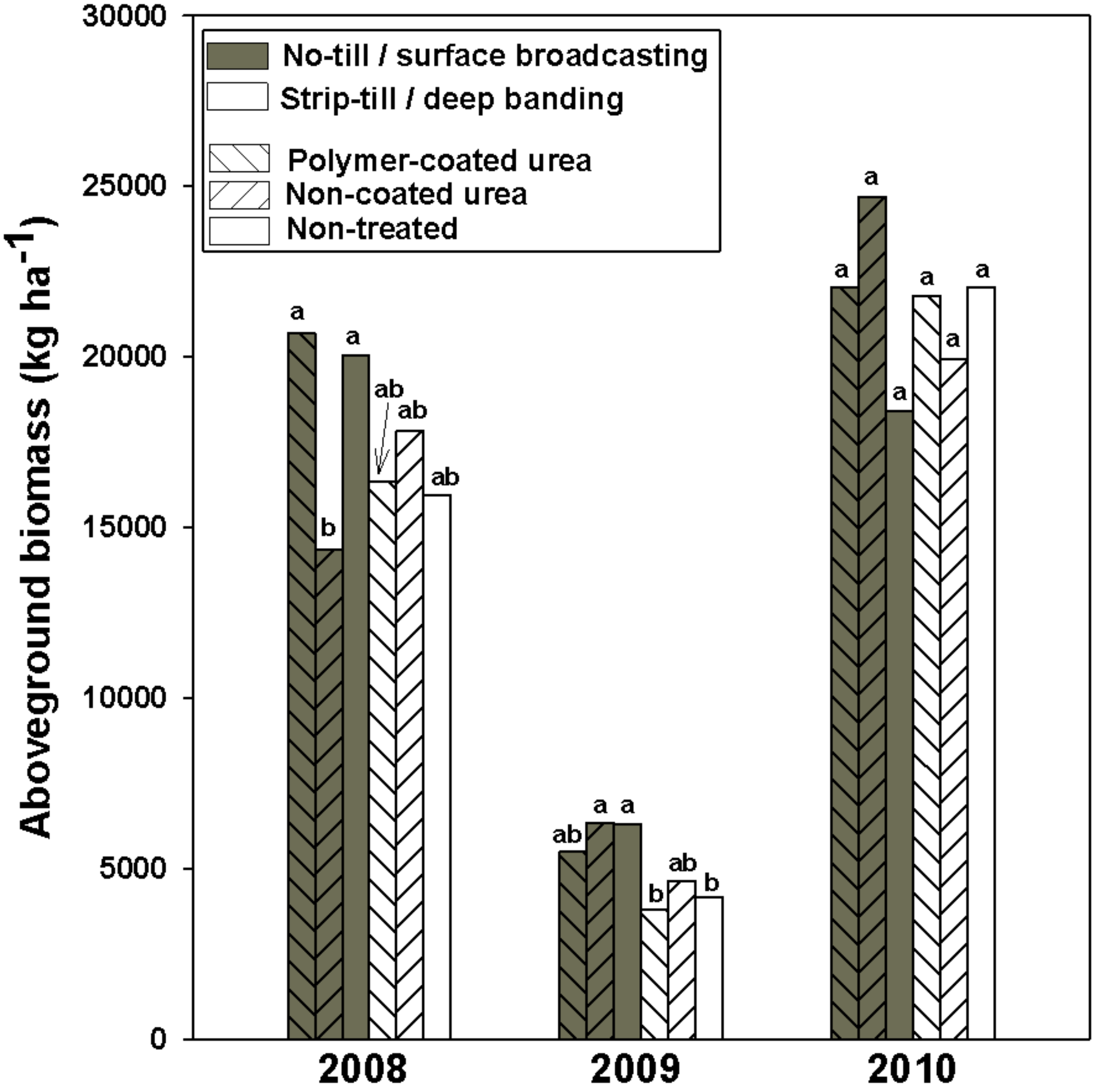

Figure 3.12. Aboveground red clover biomass prior to burndown for tillage/N placements and fertilizer sources in 2008, 2009, and 2010. Letters over bars indicate differences among treatments within a given year using Fisher’s Protected LSD (*P* < 0.10).

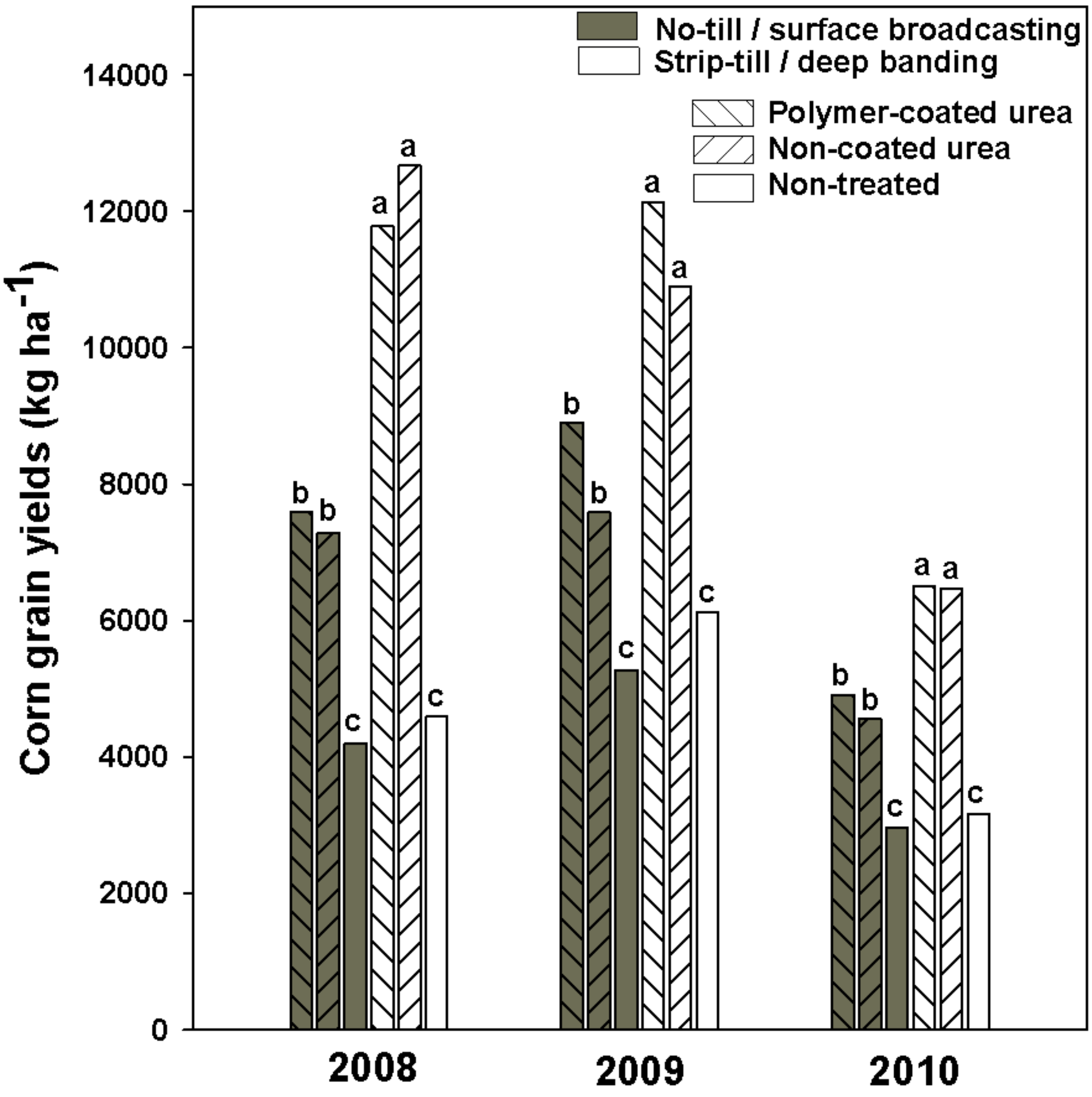

Figure 3.13. Corn grain yield following soybean production due to the interaction of tillage/N placement and N fertilizer sources in 2008, 2009, and 2010. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

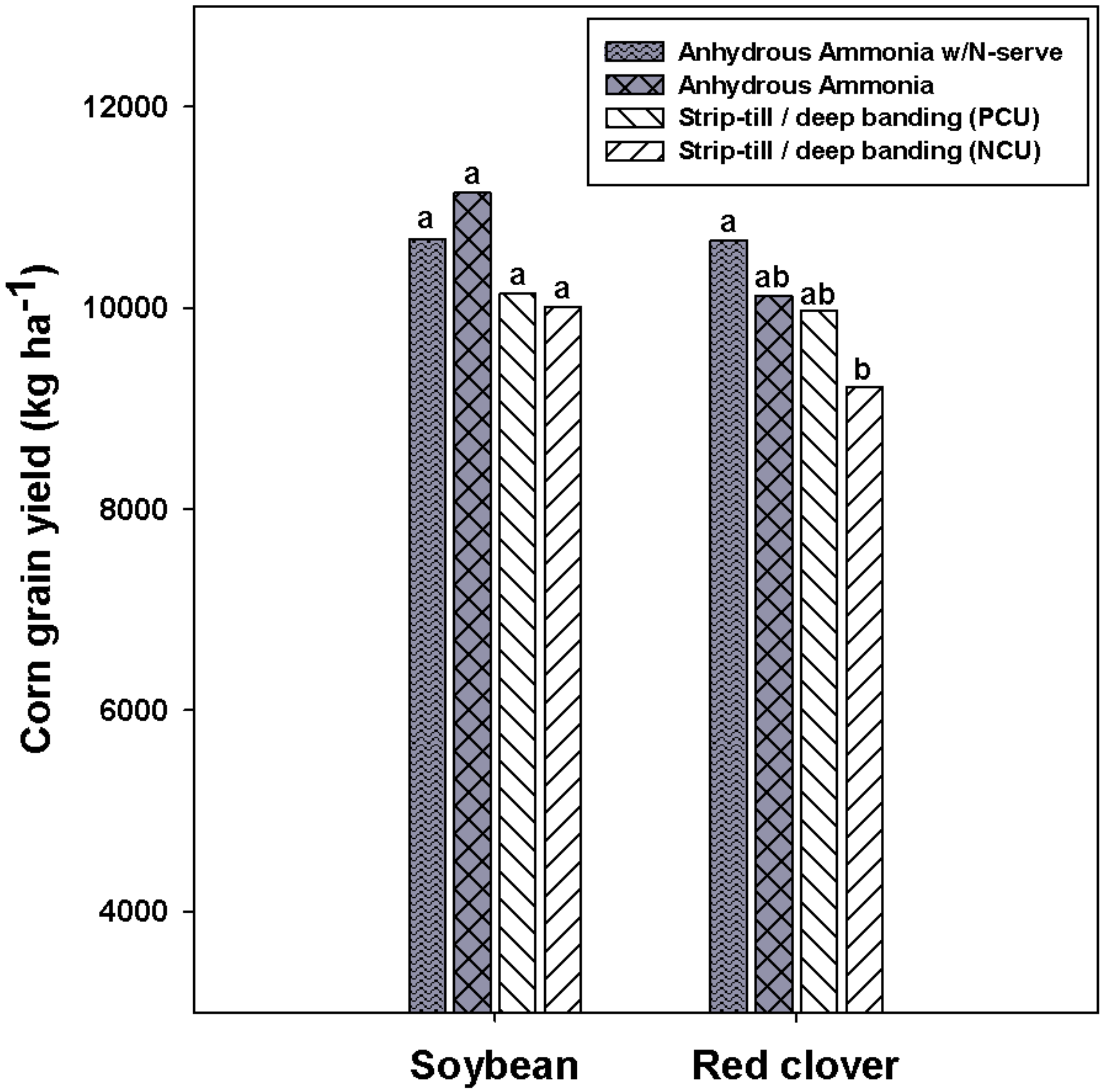

Figure 3.14. High yielding corn grain yield production systems analyzed separately for residue cover (soybean and red clover) by management system. Data were averaged over years and application timings. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

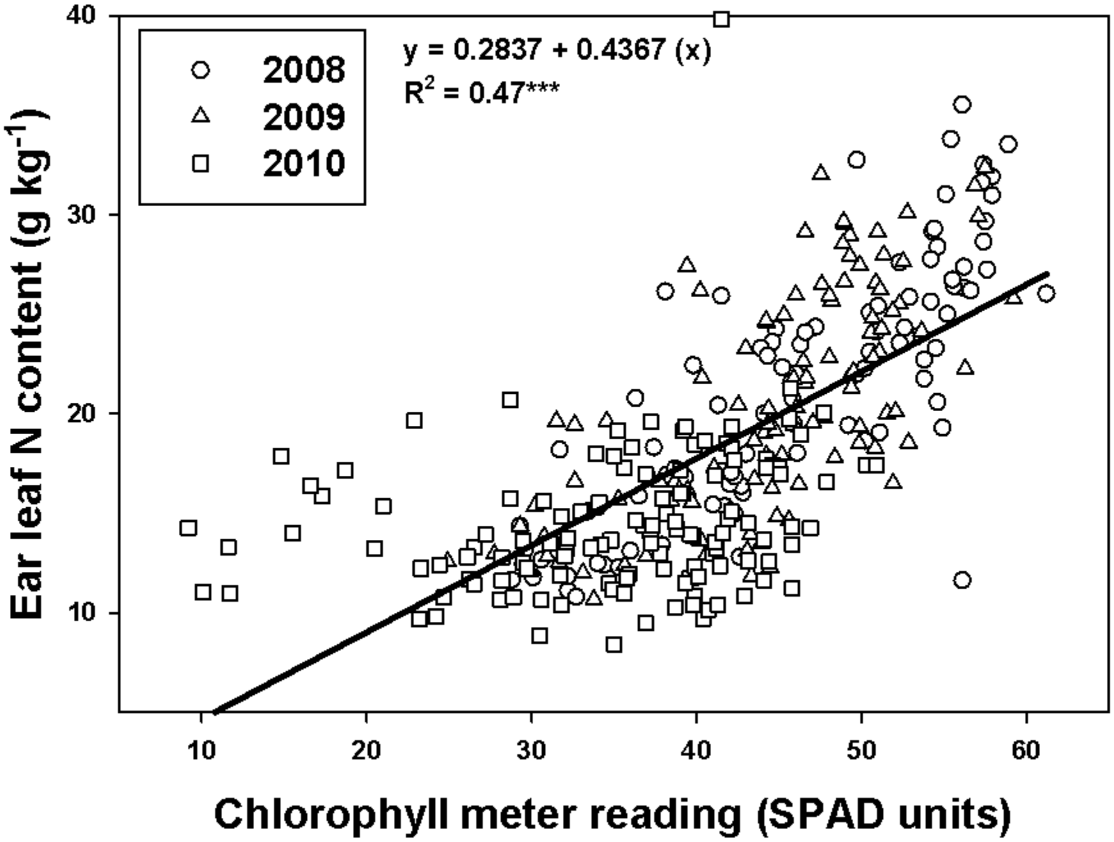

Figure 3.15. Linear regression analysis of ear leaf N content (R3 to R5 growth stage) and chlorophyll meter reading (V18 to R3 growth stage) combined over 2008, 2009, and 2010 (number of data points = 342, R^{2***} was significant at $P < 0.0001$).

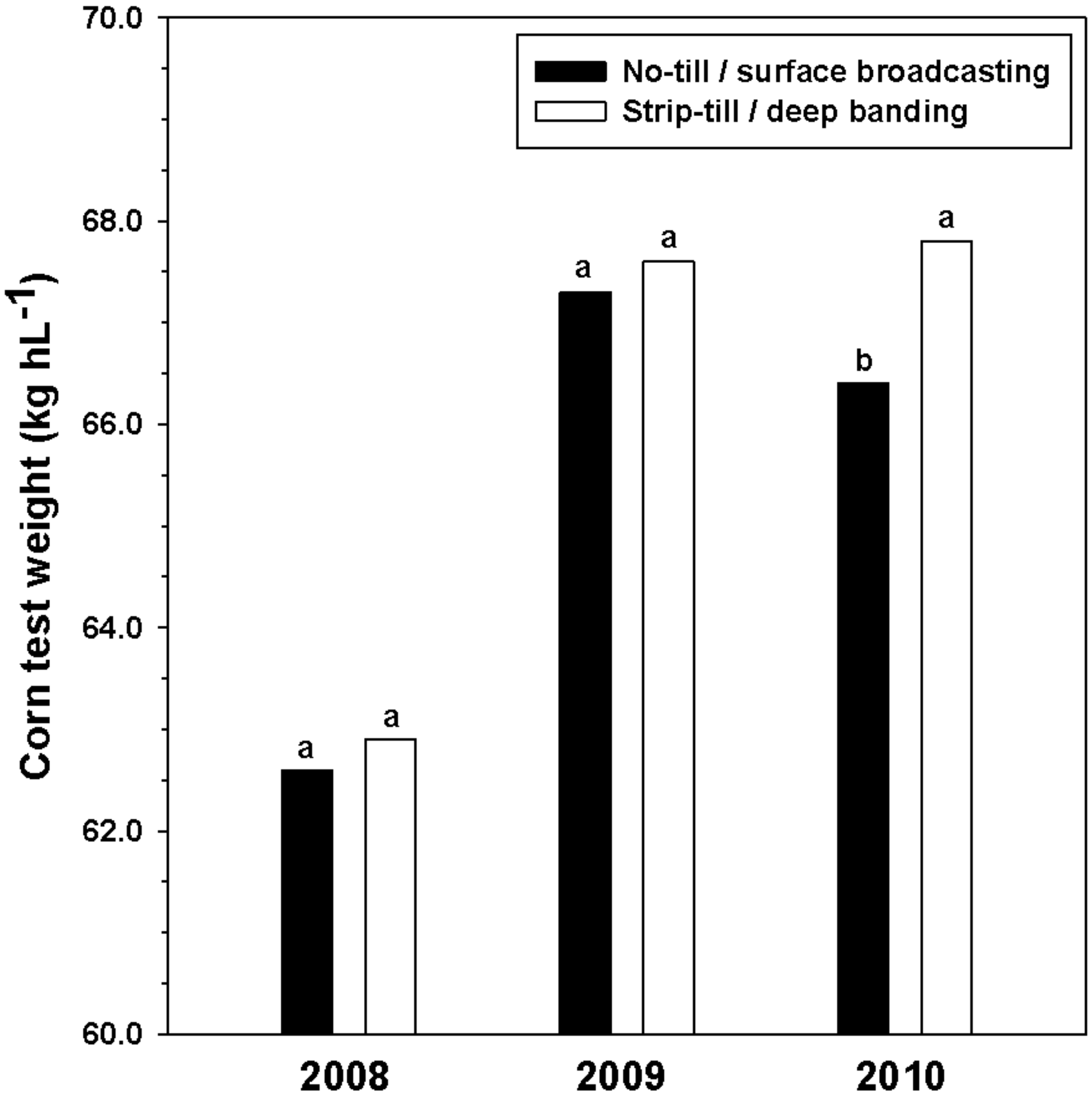

Figure 3.16. Corn test weight following soybean and analyzed by tillage /N placement for each year. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD (*P* < 0.05).

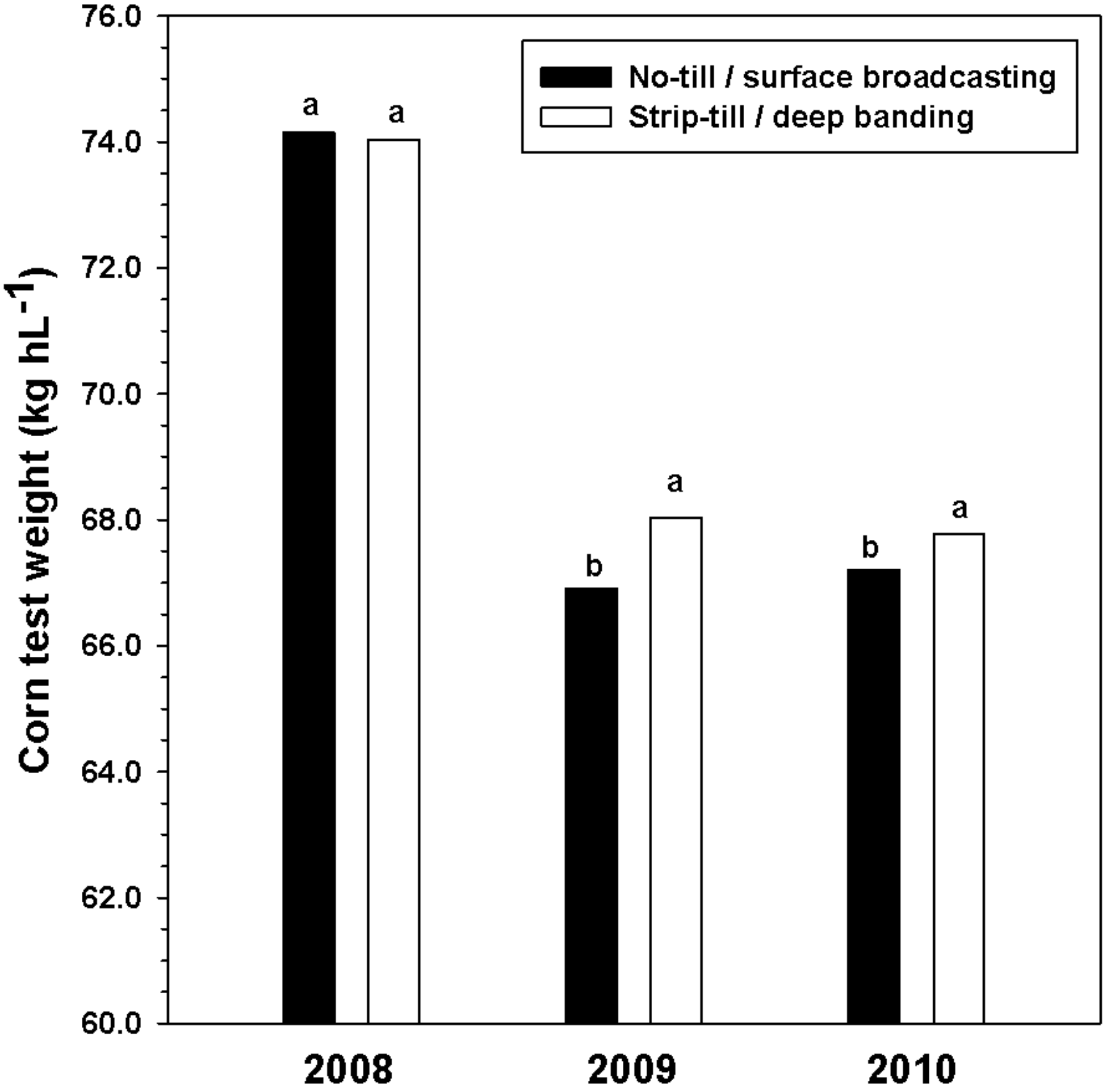

Figure 3.17. Corn test weight following soybean with red clover cover crop and analyzed by tillage/N placement for each year separately. Letters over bars indicate differences among treatments within a given year using Fisher’s Protected LSD ($P < 0.05$).

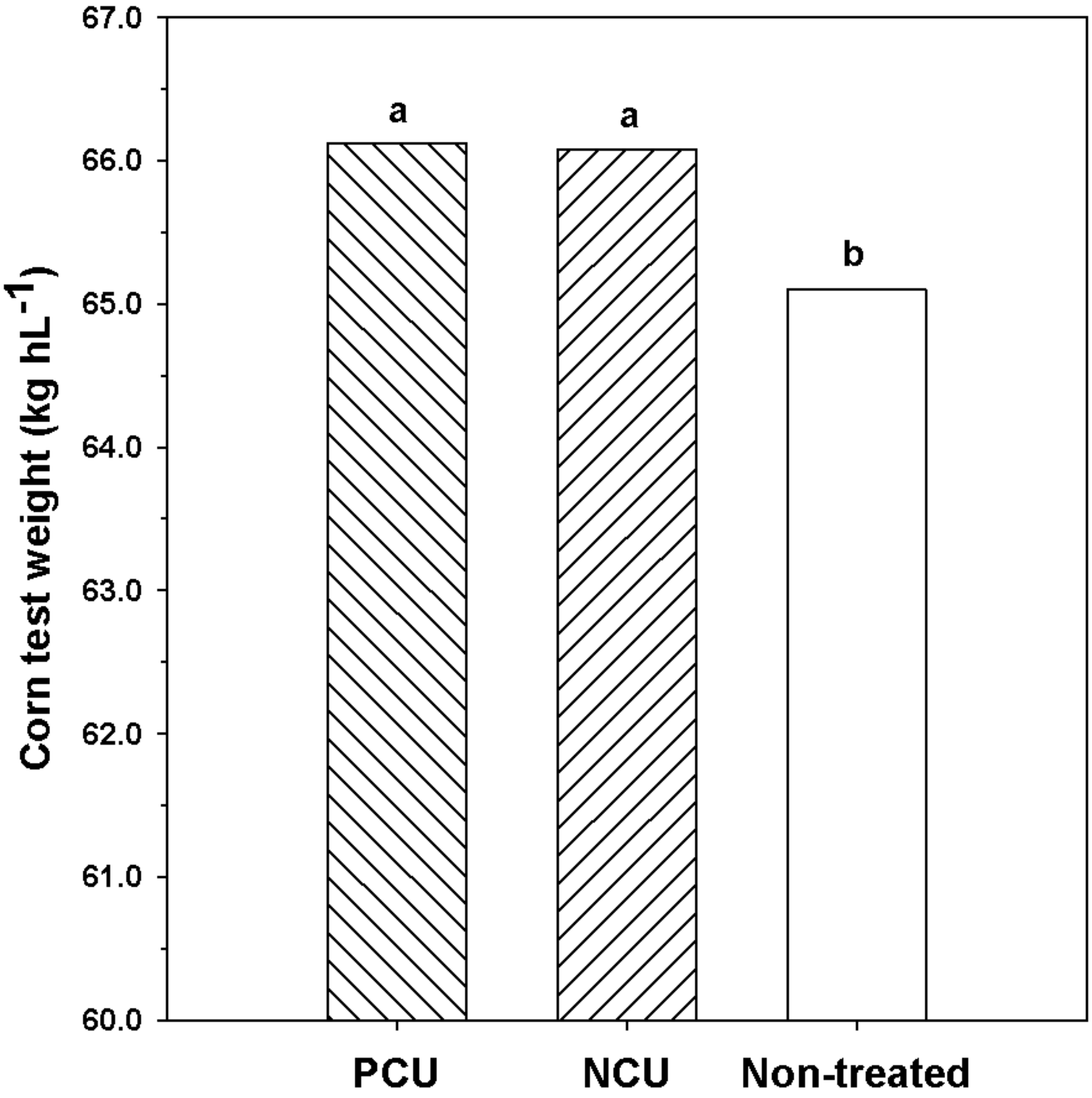

Figure 3.18. Corn test weight following soybean and analyzed by N fertilizer source, averaged over three growing seasons. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

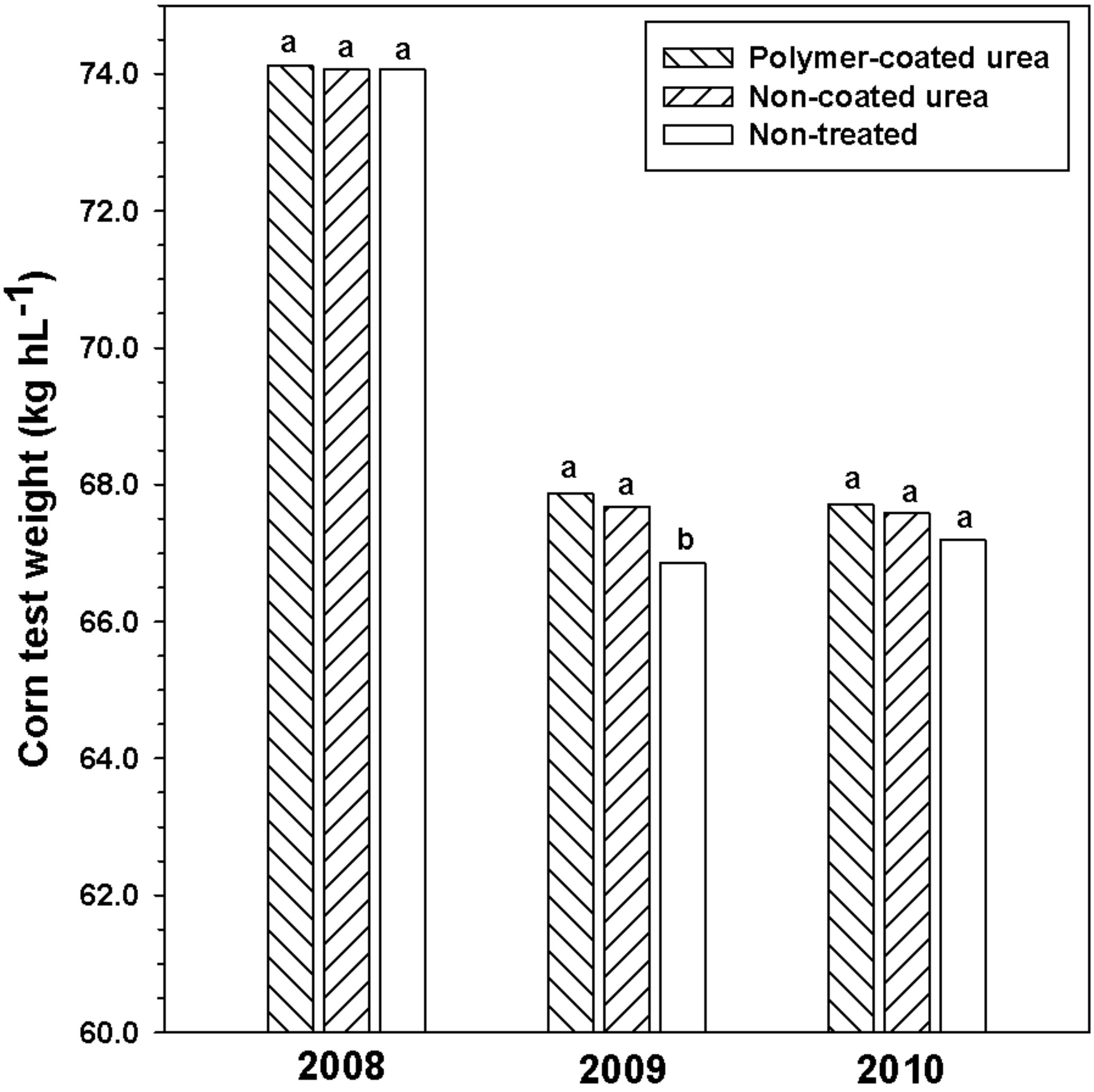

Figure 3.19. Corn test weights following soybean with red clover cover crop and analyzed by N fertilizer source for each year separately. Letters over bars indicate differences among treatments within a given year using Fisher's Protected LSD ($P < 0.05$).

CHAPTER 4

POLYMER-COATED UREA APPLICATION RATIOS AND TIMINGS AFFECT WHEAT AND DOUBLE-CROP SOYBEAN YIELDS

ABSTRACT

Double cropping soft red winter wheat (*Triticum aestivum* L.) with soybeans [*Glycine max* (L.) Merr.] allows producers to maintain wheat in their crop rotation in upstate Missouri. Increased surface residues with no-till management and N source may affect soybean emergence and yields while residual N could be utilized by double-cropped soybean. The objectives of this research were to evaluate release of urea from PCU from fall to spring application timings, and evaluate fall to spring application timings of PCU and ratios of PCU with urea on wheat and double-crop soybean response. The experimental design was a 2 (N rate) x 7 (application timing) x 5 (N fertilizer source/blend) factorial in a completely randomized block design, with five replications and a non-treated control. During all three growing seasons, there were significant 2-way interactions of N rate with timing and source for wheat production (yield and test weight), and timing by N source for wheat yields. In 2008 and 2010, wheat yields significantly ($P < 0.05$) increased with increasing N rates (0, 84, and 112 kg ha^{-1}) at each application timing (Oct. to Apr.). Comparing Oct. to Apr. N fertilizer applications, N source treatments increased yield by 500 to 650 kg ha^{-1} (AN and NCU), decreased yield by 560 kg ha^{-1} (100% PCU), and were similar (75/25 and 50/50 bends of PCU and NCU) over this period. Treatments of 100% PCU in Nov. produced similar yields compared to NCU applications in Mar. and Apr., and an Apr. application of AN. In 2008, test weights were greatest with PCU followed by ratios of PCU/NCU and ammonium nitrate, while in

2009 it was opposite. Soybean yields generally increased with lower N rates and earlier applications, and were positively correlated with winter wheat yields. Yields increased by 40 to 60 kg ha^{-1} with 100% PCU applications prior to soybean planting (Oct. to Apr.) compared to 100% NCU and PCU/NCU ratio of 75%/25%. PCU application ratios should vary depending on the application date. Polymer-coated urea maximized double-crop soybean yields in 2008 and 2009 compared to other N sources.

INTRODUCTION

Several studies have evaluated the impact of nitrogen (N) management on winter wheat (*Triticum aestivum* L.) response (Flowers et al., 2001; Halvorson et al., 2004; McKenzie et al., 2010). Although site conditions can result in variable winter wheat production response to N management, individual relationships between management practices, such as N application timing, fertilizer source, and application rate with winter wheat production are for the most part understood with producers typically still applying 30% N fertilizer in the fall and 70% in the spring. The introduction of enhanced efficiency fertilizer such as polymer-coated urea (PCU), may allow more flexibility in application rates and timings.

Applying N at fall planting up to Feb. can be enticing to producers because of convenience, cost-effectiveness, lower N fertilizer costs, and favorable soil conditions for application. Optimal N application timings for winter wheat have been reported during the periods of greatest plant N demand during the G25 to G30 growth stages (Zadoks et al., 1974) which corresponds with a Mar. to Apr. application timing (Flowers et al., 2001; Weisz et al., 2001). N applied earlier than the G25 and G30 growth stage is more susceptible to adverse weather conditions, which increase potential N loss, reduce N availability in the spring, and may lower yield potentials. Polymer-coated urea used under these conditions technology may minimize these detrimental effects.

Controlled release fertilizers are an alternative N management option that may minimize N loss and yield reductions associated with applications of N before the G25 to G30 growth stage and may allow farmers to apply the full rate of N with P and K in the fall and decrease challenges with late spring applications due to wet conditions. Polymer-coated urea fertilizer (PCU) was designed to slowly release urea into the soil environment over time (Wilson et al., 2009). Limiting the amount of urea available for microbial N transformations after application may reduce potential environmental N loss compared to traditional dry urea fertilizer (Blaylock et al., 2004, 2005; Motavalli et al., 2008). After application of PCU, urea must first dissolve within the prill, then at a rate dependent on soil moisture and temperature, diffuse out of the polymer coat and into the soil environment (Fujinuma et al., 2009). Polymer-coated urea has reduced germination issues associated with non-coated urea (NCU) applications at planting, and allowed earlier (Nov. to Feb.) application dates resulting in an average yield increase of 270 kg ha^{-1} compared to NCU (Nelson et al., 2008). Surface applications of PCU have also been found to reduce volatilization loss by 60% compared with NCU (Rochette et al., 2009). Low soil temperatures in the fall through the winter may greatly reduce the urea-N release from PCU, making N loss from late fall or winter applications of N for winter wheat production negligible compared to spring applications. In Southern Alberta’s dry prairie region, surface broadcast applications of PCU in the spring had approximately 200 to 900 kg ha^{-1} lower yields due to excessive delay in N release compared to ammonium nitrate (AN) and NCU with and without a urease inhibitor (McKenzie et al., 2010). Blending PCU with NCU may potentially increase overall yields in winter wheat systems by providing a readily available N source and another N source that releases urea-N into the soil over time.

Winter wheat grain yields have been reported to increase with N rate (Halvorson et al., 2004), but yields were unlikely to increase when there was greater than 120 kg ha^{-1} of inorganic N within the soil profile (Olson et al., 1976). Excessive N applications will increase production costs, lower N recovery, and have been reported to reduce yield production and grain quality when winter wheat experienced severe water stress during the growing season (Kolberg et al, 1996; Bundy and Andraski, 2004). No-till wheat production is common in the Midwest to minimize soil loss on highly erodible soils such as claypan soils. Adoption of no-till (NT) management is a soil conservation practice and is widely considered to increase soil fertility, yields, and profits by minimizing soil disturbance, erosion, and production costs (Triplett and Dick, 2008). These benefits have lead to an increase in NT production in the United States from 6 to 22.6% (25.3 million ha) from 1990 to 2004 (Conservation Technology Information Center, 2006). However, no-till practices may exacerbate issues of plant emergence (Weisz and Bowman, 1999) and N availability (Carefoot et al., 1990) with winter wheat due to impacts on soil conditions (i.e. higher bulk density, lower temperature, higher moisture content) and increased N immobilization in surface residues (Halvorson et al., 2004; Kelley and Sweeney, 2007). Dry N fertilizers (i.e. urea) are typically surface applied in NT practices which can increase the potential for N loss compared to N placement within the soil profile. It has been reported that on average, injection of N into the soil profile increased wheat yields over surface broadcasting regardless of winter or spring application timing (Schlegel et al., 2003). With greater potential for immobilization of N due to surface residues and loss with NT practices, increasing the rate of N applied and/or later applications may be required to provide adequate amounts of N for wheat uptake in order to sustain high yielding and quality winter wheat production (Staggenborg et al., 2003)

Soybean [*Glycine max* (L.) Merr.] double-cropped with soft red winter wheat is a common practice in the Midwest United States (Kyei-Boahen and Zhang, 2006). Double cropping soybeans allows producers to generate income and maintain wheat in the crop rotation, and may also improve soil conditions by increasing soil organic matter, and lowering the potential for erosion through increased soil cover. However, double-cropped soybean yields have been reported to be 16 to 33% lower than full-season soybean (Pfeiffer, 2000), which is thought to be largely due to delayed soybean planting into late June to early July (MacKown et al., 2007). Although research is limited, increased crop residues from winter wheat may also delay soybean emergence and growth which may negatively impact soybean growth and yield.

Residual N and residue management following high yield wheat may affect double-crop soybean performance. Soybean yields can potentially be increased with additional N available at planting before nodules form, and during the R3 growth stage (pod development) when biological nitrogen fixation (BNF) is found to decrease (Scharf and Wiebold, 2003). However, a large amount of soil N available as early as planting has been shown to reduce nodulation and BNF (Harper and Gibson, 1984) which may lower soybean yields. Applications of AN at 180 kg N ha^{-1} split-applied on the surface at planting and at V6 growth stage had a 18% reduction in BNF, while PCU banded at 20 cm at planting limited BNF reduction to 4%; however, yields were similar between these treatments and increased yields by 5% compared to non-fertilized treatments (Salvagiotti et al., 2009). In 48 locations in Missouri spanning a variety of soil and weather conditions, N fertilization at planting did not increase soybean yields (Scharf and Wiebold, 2003). However, a double-cropping soybean study with late planting into July found soybean yields increased with N fertilization which peaked at 59 kg N ha^{-1} (Taylor et al., 2005). Residual N below 84 kg N ha^{-1} and yields above 4000 kg ha^{-1} favored yield increases due to N availability (Osborne and Riedell, 2006). However, there has been no research evaluating the correlation between winter wheat N management and yield with soybean production in a double-crop system. In addition, the ratio of PCU to NCU for winter wheat production has had limited research. Research evaluating PCU's impact on winter wheat and the subsequent effect on of N management decisions on soybean production in a wheat-soybean double-crop system is limited. The objectives of this research were to evaluate release of urea from PCU from fall to spring application timings, and evaluate fall to spring application timings utilizing a mix of PCU with urea fertilizer on wheat and double-crop soybean response

MATERIALS AND METHODS

Site Description and Experimental Design

This study was initiated in the fall of 2007 and included three consecutive wheat-double-crop soybean growing seasons (approximately Oct. through Sept.) in Northeast

Missouri's claypan region at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N 92° 11' 24.9" W) near Novelty, MO (Figure 4.1) on a Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiqualfs) with approximately 2 to 5% slope in 2008 and 2009 and on a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs) with approximately 0 to 1% slope in 2010. Depth to the claypan at this research station ranged from 31 to 46 cm (data not presented). Soil properties, including macro and micronutrients are summarized in Table 4.1 from soil samples taken at a depth of 15 cm. The experimental design was a 2 x 7 x 5 factorial in a completely randomized block design, with five replications and a non-treated control. Plots were approximately 3 by 9 m. Fertilized treatments consisted of two N application rates (84 and 112 kg ha^{-1}), seven application timings (day 5 through 30 in Oct., and 12 through 18 in Nov., Dec., Jan., Feb., Mar., and Apr.), and five dry fertilizer source/blend(s) (100% AN, 100% PCU, 100% NCU, 75% PCU:25% NCU, and 50% PCU:50% NCU). Polymer-coated urea used in this study was ESN (Agrium Advanced Technology, Denver, CO). All N fertilizers were broadcast applied to the soil surface using a hand spreader.

'Pioneer 25R56' soft red winter wheat was no-till seeded at 135 kg ha^{-1} in 19-cm rows (Great Plains, Assaria, KS). Soybean cultivars ('Asgrow 3602' in 2008, 'Pioneer 94Y01' in 2009, and 'Asgrow 3539' in 2010) were planted following wheat harvest in 19-cm rows at 495,000 seeds ha^{-1}. Planting dates, maintenance fertilizer, and crop protection applications are reported in Table 4.2. Grain yields were determined with a small-plot combine (Wintersteiger Inc., Salt Lake City, Utah) and adjusted to 130 g kg^{-1} prior to analysis. Grain samples were collected and test weights of winter wheat treatments were determined (GAC 2100, DICKEY-john Corporation, Auburn, IL). Soybean grain samples were collected and analyzed for protein and oil (Foss Infratec, Eden Prairie, MN).

Urea release rates were obtained by placing a known weight of PCU (approximately 10 g) on the soil surface in heat sealed standard mesh, fiberglass insect screen (Phifer Wire Products, Inc., Tuscaloosa, Alabama). For each timing application, an individual bag was removed after each subsequent month up to June, washed in iced water, dried, and weighed to determine the percent of urea-N release. Weather data was collected on-site using an automated Campbell weather station, which included daily rainfall, soil temperature taken at a depth of 5 cm with corn residue, and air temperature.

Statistical Analysis

Analysis of variance was performed on winter wheat grain yields, test weights, soybean yields, protein, oil, and total urea-N release from PCU using the SAS v9.2 (SAS Institute, Cary, North Carolina) statistical program to determine the treatment effects. PROC GLM and Fisher's Protected LSD at $P = 0.05$ were used to separate means and determine significant treatment differences. PROC CORR was used to determine whether soybean population or yield was correlated with winter wheat grain yields.

RESULTS AND DISCUSSION

Weather Conditions

From 2000 to 2010, the average annual air temperature, soil temperature and precipitation were 11.5^{o}C, 12.4^{o}C and 95 cm, respectively (Missouri Historical Agriculture Weather Database, 2010). Average air and soil temperature during the three consecutive seasons (10.7 and 11.7^{o}C) starting in 2007 was similar to the past 10-year average, respectively, while total rainfall was above average and varied from 115 cm in 2008-2009 to 153 cm in 2009-2010 (Figure 4.2a, 4.2b, and 4.2c). Although total rainfall was above average for all three seasons, 2007-2008 and 2009-2010 seasons had over 35 cm more rainfall than 2008-2009 which represented 33% of the average annual rainfall. As annual rainfall increases, we would expect greater release of applied urea, but distribution of rainfall in relation to N application is also an important factor in urea release.

Release of Urea from Surface Applied PCU

The percentage release of urea from PCU applied to the soil surface varied considerably due to seasonal variability of rainfall in relation to application timing (Figure 4.3). Rainfall distribution was similar in 2007-2008 and 2008-2009 with majority of the rainfall occurring after Apr.; however, 2009-2010 had an abnormally wet fall which accounted for a greater percentage of urea-N released from PCU fertilizers applied in the fall and early winter. Urea release with Oct. applications was approximately 10 to 35% greater ($P < 0.05$) than Feb. to Apr. applications in 2007-2008 and 2009-2010. In 2008-2009, applications in Oct. had approximately 15 to 65% greater urea release than all other application timings. Applications in Oct. released less than 10% urea after one month in 2007-2008 and 2008-2009. However, 45% of the urea released in 2009-2010 was likely due to higher fall rainfall. Midseason N applications in Feb. averaged 64% release of urea-N which was similar to that released in Nov. and Jan. in 2007-2008, Nov. to Jan. in 2008-2009, and only Jan. in 2009-2010. Significant variation in urea released from PCU applied in Feb. or earlier between seasons may have been due to variation in weather among the seasons. Applications of PCU in Mar. to June averaged 54% or less urea released. Surface applied PCU release data indicated that PCU fertilizer N may require the addition of a fast-release fertilizer source when applied after February in order to supply adequate plant available N during high wheat demand in Mar. and April.

Winter Wheat Grain Yields

Overall analysis of soft red winter wheat grain yields had no significant interaction with year and all of the treatment variables (N rate, N source, N application timing), but there were several three way interactions (Table 4.3). Significant interactions occurred between year x rate x N application timing ($P < 0.05$), year x rate x N source(s) ($P < 0.1$), and year x N application timing x N source ($P < 0.1$). In all three years, fertilized treatments had 550 to 2080 kg ha^{-1} greater winter wheat grain yields than the non-fertilized control regardless of time of N application (Table 4.4). Yield differences in 2008 and 2010 between N application timing (averaged over N fertilizer source) or N fertilizer source (averaged over N application timing), had 170 to 430 kg ha^{-1}greater yields ($P < 0.05$ and $P < 0.10$) when N was applied at 112 kg N ha^{-1} compared to 84 kg N ha^{-1}, except for Apr. applications of N fertilizer sources in 2010. These findings coincide with recent research which found winter wheat grain yield increased with N applications up to 134 kg N ha^{-1} when averaged over multiple N sources (Cahill et al., 2010). In this study grain yield production varied between years and required separation of yield by year for all three significant interactions.

Winter wheat grain yield in 2008 was highest among study seasons, and yield by rate and application timing, ranged from 3550 to 5630 kg ha^{-1}. Nitrogen applied in Nov.

at 112 kg ha^{-1} had the highest yields which were 250 to 2080 kg ha^{-1} greater ($P < 0.05$) than other combinations of N rate and application timing (Table 4.4). Nitrogen applications at the G30 growth stage (Apr.), typically the optimal application time (Baethgen and Alley, 1989), at 112 kg N ha^{-1} had the next highest yield production which was 160 to 1830 kg ha^{-1}greater than all other treatment combination besides 112 kg N ha^{-1} applications in Mar. and October. The lowest average yield production for treatments with N applied at 112 kg N ha^{-1} occurred with Dec. and Feb. applications. In 2009, wheat grain yield production was less than 2008 and ranged from 2150 to 3520 kg ha^{-1}. Nitrogen applied in Feb. (84 kg N ha^{-1}), Jan. (84 kg N ha^{-1}), and Oct. (112 kg N ha^{-1}) had 314 to 1370 kg ha^{-1} greater yields than N applications in Dec. (112 and 84 kg N ha^{-1}) and non-fertilized control plots. Minimal differences in grain yield between application timings may be a function of lower total rainfall which may have reduced the overall potential for N loss and crop production. The 2010 season had 35 cm more rain than the 2009 season and 33% above the past 10 year average. This may have increased the potential for N loss resulting in N limitations for crop growth with earlier and lower application rates of N source which resulted in yield production similar to 2009 (1850 to 3420 kg ha^{-1}). Nitrogen applied at 112 kg N ha^{-1} in Mar. had 250 to 1570 kg ha^{-1} greater yield than all other treatments (N rate x N application timing) besides the Dec. application at 112 kg N ha^{-1}. Applications of N from Dec. through Apr. had 200 to 1570 kg ha^{-1} greater yields than Oct. and Nov. application timings regardless of N rate, except for Dec. and Feb. applications at 84 kg ha^{-1}.

In 2008, N treatments of 100% PCU, 75% PCU: 25% NCU, and 50% PCU / 50% NCU applied at 112 kg N ha^{-1} had 170 to 1820 kg ha^{-1} greater yields ($P < 0.10$) than all other N rate x fertilizer source treatments (Table 4.4). When applied at 84 kg N ha^{-1}, yield from ammonium nitrate treatments were lower (150 kg ha^{-1}) compared to 100% PCU treatments. Nitrogen applications at 112 kg N ha^{-1} found 100% NCU treatments had lower yields (170 to 250 kg ha^{-1}) than 100% PCU, 75% PCU / 25% NCU, and 50% PCU / 50% NCU treatments presumably due to higher N fertilizer loss. On average, addition of PCU fertilizers in most instances increased winter wheat yield production, but may require N application rates at the high end to overcome slower release of urea-N available for microbial N transformations. Minimal differences in yield occurred in 2009 due to N rate and fertilizer source. However, treatments of 100% NCU at 84 kg N ha^{-1}, 50% PCU / 50% NCU at 84 kg N ha^{-1}, 100% PCU at112 kg N ha^{-1}, and non-fertilized control plots had lower yields (270 to 1370 kg ha^{-1}) in comparison to 75% PCU / 25% NCU at 84 kg N ha^{-1} and 50% PCU / 50% NCU at 112 kg N ha^{-1}. Although the potential for N loss may have been low in 2009, NCU has the greatest potential for gaseous N loss (Rochette et al., 2009) and treatments with high percentage of NCU appeared to have had enough N loss to justify higher application rates of N. Nitrogen treatments of ammonium nitrate, and 75% PCU / 25% NCU had no yield differences between N applied at 84 and 112 kg N ha^{-1}. Lack of significance between treatments of N rate x N application timing and N rate x N fertilizer source in the 2009 season may have been a combination of lower overall N loss potential and increased variability in grain yield production which raised the least significant difference by as much as 50 and 40 kg ha^{-1}, respectively, compared to the LSD values in 2008 and 2010. In 2010, 100% PCU and AN treatments at 112 kg N ha^{-1} had 170 to 1350 kg ha^{-1} greater grain yields than all other treatments. Treatments of 100% NCU and 50% PCU / 50 % NCU were probably the most vulnerable to N loss and may have lead to subsequent N limitations. When applied at 84 kg N ha^{-1}, 100% NCU and 50%PCU / 50% NCU treatments had 210 to 480 kg ha^{-1} lower grain yields than all other N source treatments with N applied, except for ammonium nitrate (84 kg N ha^{-1}), and 75% PCU / 25% NCU (84 kg N ha^{-1}) treatments. These results further support claims that PCU can minimize N loss compared to NCU fertilizers in wet soil conditions with high potential for N loss which can increased N uptake, and yield of corn (Noellsch et al., 2009).

When averaging over N rate and evaluating application timing and fertilizer source interaction effects on yield production we start to observe more logical, consistent relationships among the three seasons, although the magnitude in yield production varied. In 2008, AN treatments applied in Apr. had the highest yield production (5600 kg ha^{-1}), which was 220 to 1310 kg ha^{-1} greater ($P < 0.10$) than all other N source treatments, excluding Nov. applications of AN, NCU, PCU, 75% PCU / 25% NCU, and Apr. applications of NCU (Table 4.5). Comparing applications at Oct. thru Apr. we found N source treatments which increased yields by 500 to 650 kg ha^{-1} (AN and NCU), decreased by 560 kg ha^{-1} (100% PCU), and were similar (75/25% and 50/50% bends of PCU and NCU) over this period. Treatments of 100% PCU in Oct. produced similar yields compared to NCU applications in Mar. and Apr., but had 230 kg ha^{-1} lower yields than Apr. applications of AN. In 2009, yield differences were again minimal due to lower rainfall, N loss potential, and variability in yield. The highest yield in 2009 were obtained from AN and 75% PCU / 25% NCU applications in Feb. and Apr. (3790 kg ha^{-1}), respectively. In 2010, AN treatments applied in Apr. had the highest average yield (3360 kg ha^{-1}), but were not significantly different than all N treatments applied in March. All N source treatments, excluding 100% PCU, yields were found to increase yield by 460 to 940 kg ha^{-1} going from Oct. to April. The trend of increasing yields with Oct. to Apr. applications of PCU/NCU blends ranging from 100% PCU to 100% NCU treatments appeared to be magnified as the % NCU applied increased in N source treatments, due to the greater potential for N loss compared to PCU in wet soil conditions reported in claypan soil (Noellsch et al., 2009). Treatments containing 50, 75, and 100% PCU applied in the fall had 380 to 990 kg ha^{-1} lower yields than readily available N sources (AN and NCU) applied in Mar. and April. Our results imply that use of PCU minimized yield reductions with fall applications; however, in extremely wet growing seasons, applications timed closer to the G25 and G30 growth stage are potentially more important in terms of yield than applications of PCU. Nonetheless, farmers have fertilizer technology options that allow them to target fall or spring applications.

Winter Wheat Test Weight

The test weight of wheat is commonly used as a measure of grain quality, and can affect the monetary value of grain yield (Hossain et al., 2003). Overall analysis of test weights in winter wheat production found no significant interaction between year, N rate, N application timing, and N fertilizer source (Table 4.3). Paralleling winter wheat grain yield analysis, the interaction of year x rate x N fertilizer source(s) and year x rate x N application timing was significant at $P = 0.05$ and 0.10, respectively. All other three way interactions were not significant. Results from this study indicate that high grain yield were not consistently correlated with high test weight due to seasonal variation in weather which affected plant growth, N uptake, and grain filling. When averaged over N fertilizer source, test weights generally increased with lower N application rates within each application timing; however, the opposite relationship was observed in 2008 (Table 4.6). In 2008 and 2009, test weights of N fertilizer sources treatments were typically higher than non-fertilized control plots, but increased test weights were not always observed when rates increased from 84 to 112 kg N ha^{-1}. Higher test weights appeared to coincide with yield increases with higher N rates, which implied greater plant uptake of N. Coinciding with the analysis of N rate x application timing from 2010; test weights were significantly higher ($P < 0.05$) in the non-fertilized control plots than fertilized plots regardless of N fertilizer sources.

In 2008, grain yields were much greater than in 2009 and 2010 which were dryer and wetter seasons, respectively. Growing conditions were more optimal in 2008, which promoted greater N uptake and may account for higher test weights. As seen in Table 4.6, test weights ranged from (72.8 to 74.5 kg hL^{-1}) average over N fertilizer source. February application at 84 kg N ha^{-1} was the only timing treatment to not have higher test weights than non-fertilized control plots ($P < 0.10$). The greatest test weights were found in Mar. and Apr. applications of N fertilizer sources regardless of N rate (84 and 112 kg N ha^{-1}) presumably because plant uptake of N was not limited when a lower rate of N was applied during the G25 and G30 growth stage. Earlier applications in Oct., Nov., and

Jan. appear more prone to N loss and had 0.5 to 1.0 kg hL^{-1} lower test weights when N was applied at 84 kg N ha^{-1}. However, test weights obtained with 112 kg N ha^{-1} in Oct, Nov. and Jan. were similar to later applications in Mar. and Apr. at 84 kg N ha^{-1}. Spring application timings at 112 kg N ha^{-1} had some of the largest average test weights, but grain yields in these applications were not greater than N applications in Oct., which further illustrate that higher grain yields did not always coincide with quality. When averaged over N application timing for each N fertilizer sources, test weight and grain yield were similar in most instances. Nitrogen fertilizer treatments of 100% PCU, 75% PCU / 25% NCU, and 50% PCU / 50% NCU had 0.5 to 0.8 kg hL^{-1} higher test weights going from application rates of 84 to 112 kg N ha^{-1} ($P < 0.5$). Fertilized non-coated urea and ammonium nitrate treatments had 0.7 to 2.0 kg hL^{-1} lower test weight than 100% PCU (84 and 112 kg N ha^{-1}) and both treatment blends of PCU and NCU applied at 112 kg N ha^{-1}.

In 2009, test weights were lower than 2008 and ranged from 69.2 to 72.4 and 68.5 to 72.2 kg hL^{-1} when evaluating the interaction of N rate x application timing and N rate x fertilizer source, respectively. Drier overall conditions in 2009 may have minimized the potential for N loss and differences in test weights between treatments. In some cases grain quality may have been significantly reduced because N was readily available to the plant. Nitrogen fertilizers applied in Apr. (112 kg N ha^{-1}) had 1.2 to 3.2 kg hL^{-1} lower test weights ($P < 0.10$) than all other treatments including the non-treated control plots, except for Mar. application timings at 112 kg N ha^{-1} (Table 4.6). Nitrogen applications at 112 kg N ha^{-1} generally had lower test weights than at 84 kg N ha^{-1}, which was magnified with late application timings and/or treatments of PCU which should have lowered the potential for N loss. Although not significantly greater than most treatments, applications in Jan. with N applied at 84 kg N ha^{-1} had the highest average test weight (72.4 kg hL^{-1}). In contrast to the 2008 season, 100% PCU fertilizer treatments applied at 112 kg N ha^{-1} had the lowest test weight (68.5 kg hL^{-1}) and was the only treatment to have 2.8 kg hL^{-1} lower test weight than the non-fertilized control plot ($P < 0.05$). Differences in yield and quality between individual treatments in 2008 and 2009 illustrated N availability, apparent loss, and wheat production can vary considerably for a single treatment due to seasonal variation in weather.

Total annual rainfall in 2010 was extremely high and we expected N availability to be increasingly limited with earlier N applications and/or NCU application; however, test weights generally increased with earlier applications and/or NCU while grain yields decreased. Non-fertilized control plots had 1.8 to 5.0 kg hL^{-1} greater test weights than all other treatments when averaging over N fertilizer source or N application timing (Table 4.6). Low overall grain yield production and an abnormally high average test weight in non-fertilized control plots may partially explain why fertilized treatments had significantly lower test weights. When evaluating fertilized plots, early N applications in Oct. at 84 and 112 kg N ha^{-1} and Nov. at 84 kg N ha^{-1} with low grain yields had the greatest test weights (69.7 to 69.9 kg hL^{-1}) and had 1.3 to 3.2 kg hL^{-1} higher test weights than all other fertilized application timing treatments ($P < 0.10$). Nitrogen applications between Dec. and Mar. had similar test weights regardless of the application rate. Similar to 2009, Apr. applications of N fertilizers had the lowest test weights of the application timing treatments (66.7 to 67.1 kg hL^{-1}). When averaging over N application timings, fertilizer treatments of 100% NCU applied at 112 kg N ha^{-1} had the highest test weights (69.2 kg hL^{-1}) obtained from fertilized plots and were 0.9 to 2.0 kg hL^{-1} greater than all other fertilizer treatments except for 100% PCU, 100% NCU, and 75% PCU / 25% NCU applied at 84 kg N ha^{-1} ($P < 0.05$). Although the results seem to imply increased N availability reduced grain quality, excluding treatments of 75% PCU / 25% NCU, test weights were not different within N fertilizer source treatments between application rates of 84 and 112 kg N ha^{-1}.

Correlation between Winter Wheat and Soybean Production

Double-crop soybean is typically planted to add value to wheat in the cropping system in upstate Missouri. It was important to evaluate whether winter wheat management impacted soybean plant establishment, grain yield, and quality, which could indicate and capture the presence of residual N in the cropping system. With limited literature available on the impact of wheat residues on double-crop soybean production in a NT practice, we hypothesized that soybean yields would decrease with greater winter wheat production due to the amount of residue produced, which could impact nutrient availability/immobilization, soil moisture, and temperature. Averaging over the 2008 and 2009 season, soybean yield was positively correlated ($P < 0.0001$) with winter wheat grain yield (Table 4.7). However, soybean height and population had a strong negative correlation ($P < 0.0001$) with wheat and soybean yield. Lower soybean population and height found with higher wheat yields is most likely due to greater amounts of wheat residue, but we would have expected soybean population to be positively correlated with soybean yields. However, this result demonstrated soybeans ability to compensate for yields when plant populations is reduced because of reduced competition for resources such as nutrients and water, which was similar to other research (Lee et al., 2008).

Soybean Production

Soybean yield, protein concentration, and oil concentration following soft red winter wheat in a double-crop production system was analyzed for treatment effects from winter wheat production; however, soybean data in 2010 were not included in the analysis because the data was not available. Yields in 2008 (4790 kg ha^{-1}) were greater than the average soybean yields reported from single-cropping soybean systems (3420 kg ha^{-1}), as well as double cropped soybean (1890 kg ha^{-1}) in Missouri from 1999 to 2008, but yields in 2009 (2106 kg ha^{-1}) were considerably lower than the average single cropped soybean yields (USDA, 2010). Differences in grain yields may have been due to the contrasting rainfall conditions in 2008 and 2009. High level interactions observed in wheat yields between year, N rate, N application timing, and N fertilizer source were not found in soybean production (Table 4.8). The only significant interaction ($P < 0.05$) was year x N rate, while the main effect of N fertilizer source was significant ($P < 0.10$) for soybean yield. Although we hypothesized that later N applications would increase soybean production through increase N availability at planting, application timing did not have a significant impact on soybean yields.

Soybean yield and oil concentration in the 2007-2008 increased with lower rates of N application, while non-fertilized control plots had 150 kg ha^{-1} and 3.6 g kg^{-1} greater yield and oil concentration than N applied at 112 kg N ha^{-1} ($P < 0.05$), respectively (Table

4.9). However, protein concentration in the non-fertilized control was 5.8 to 8.0 g kg^{-1} lower than protein concentration found with N applications of 84 and 112 kg N ha^{-1}. In 2008-2009, soybean yields were considerably lower than in the previous season and yields ranged from 2080 to 2130 kg ha^{-1}. Non-fertilized control plots had 30 to 50 kg ha^{-1} greater yield than treatments with N applied, as was found in the 2007-2008 season. Since yields did not increase with N rate, it is assumed carry over N from winter wheat applications did not increase soybean yields, which parallels previous research done in this region (Scharf and Wiebold, 2003). Contrary to 2007-2008, oil concentration increased from 165 to 167 g kg^{-1} due to increasing N application (0 to 112 kg N ha^{-1}), with each rate significantly different from the other. While the protein concentration was 1.9 to 2.7 g kg^{-1} greater in non-fertilized control plots and decreased with larger application rates of N (347 to 349 g kg^{-1}). Although it is undetermined, differences in overall soybean production due to total annual rainfall and its distribution may have resulted in the alternating relationship of oil and protein concentration with N rate between seasons.

Differences in soybean yield between 2007-2008 and 2008-2009 due to the main effect of N fertilizer source were not significant and were averaged over years (Table 4.8). Regardless of the N rate and application timing for winter wheat production, PCU fertilizer application had 40 and 60 kg ha^{-1} greater yield ($P < 0.10$) than treatments of 100% NCU, and 75% PCU / 25% NCU, respectively (Figure 4.4). Fertilizer treatments of 50% PCU / 50% NCU treatments had similar yield compared to 100% PCU treatments, and was 40 kg ha^{-1} greater than treatments of 75% PCU / 25% NCU. Significantly greater soybean yields following PCU application for winter wheat could be due to increased carryover of N after wheat harvest which may have stimulated early soybean growth; therefore, minimizing yield reductions reported with delayed planting of soybean as early as June (MacKown et al., 2007). However, since soybean yield typically decreased with later N application and high rates, slow-release of urea from PCU may have limited soybean nodulation damage reported with preplant N applications compared to more readily available N fertilizer sources (Harper and Gibson, 1984). However, nodulation was not evaluated in this study.

CONCLUSIONS

Wheat yields increased with N rate (0 to112 kg N ha^{-1}), but the amount yields increased over these N rates varied across seasons depending on factors, such as the potential for N loss, N fertilizer source, applications timings. Late N applications occurring in Mar. and Apr. averaged relatively higher winter wheat grain yields as expected but were not always significantly greater than fall/early winter applications if the potential for N loss was minimal and/or PCU was applied. Polymer-coated urea is a viable N fertilizer source for fall applications, and may even increase grain yields over NCU fertilizers in seasons with high rainfall and N loss potential. Potential yield benefits from blending of PCU and NCU fertilizers compared to 100% PCU treatments were the greatest when applied in Mar. or April.

Test weight of winter wheat varied considerably within and between N treatments due to the variability in weather between growing seasons. In wet growing seasons, N management practices with later N applications and/or fertilizers are required to maintain the level of N uptake needed to maintain high grain quality. Moderately dry growing seasons minimized the potential for N limitations regardless of N management practices; therefore, lower rates of N application, fall application, or non-controlled release fertilizers supplied enough N to maintain grain quality. However, not all results followed a consistent pattern as stated in our hypotheses and further investigation will be required to elucidate N management practices impact on winter wheat test weight (quality).

Nitrogen management practices which increased winter wheat yields were positively correlated with soybean yields and negatively correlated with soybean population and height. The ability of soybean plants to compensate for low plant populations negated the potential negative impact of winter wheat yields on double-crop soybean yields. In most instances, seed oil content increased with yields, while seed protein concentration decreased. Contrary to our hypotheses, higher N rates and later application timings, which may have increased fertilizer N carry over and residual soil N from winter wheat production, did not increase soybean yields. However, greater soybean yields following winter wheat, PCU applications compared to N sources more susceptible to loss may have be due to increased early soybean growth which could have reduced yield reductions associated with late planting of soybean (July).

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Table 4.1. Soil properties prior to planting winter wheat in 2007-2008, 2008-2009, and 2009-2010 growing seasons.

Year†	pH§	Organic matter	Neut. acidity	CEC	Bray I P	Exchangeable (1 M NH_4AO_c)							S
						Ca	K	Mg	Zn	Mn	Fe	Cu	
		g kg^{-1}	-- cmol$_c$ kg^{-1} --		mg kg^{-1}	------- kg ha^{-1} --------			---------------- mg kg^{-1} ------------------				
2007-08	6.6	23	0.5	14.1	26.5	5183	343	446	------	------	------	------	---
2008-09	6.9	28	0.0	17.2	17	6695	307	520	0.6	11.0	35.9	0.95	4.9
2009-10	5.9	24	2.0	15.3	8	5116	246	439	0.5	18.5	49.9	0.81	5.8

† A different field at each site was used each year.

‡ Micronutrients and sulfur were not evaluated in 2007-08.

§ 0.01 M $CaCl_2$

Table 4.2. Maintenance fertilizer, crop protection products, and wheat or soybean planting date for the 2007-2008, 2008-2009, and 2009-2010 growing seasons.

Field information and management	2007-2008	2008-2009	2009-2010
Winter Wheat			
Seeding date	5 Oct. 2007	30 Oct. 2008	30 Sept. 2009
Fertilizer ($N-P_2O_5-K_2O$ kg ha^{-1})	10-60-140	10-52-100	10-52-100
Fungicide - pyraclostrobin ‡	------------	--------------	40 g ai ha^{-1}
Application date	5 Oct. 2007	25 Oct. 2008	30 Sept. 2009†
Soybean			
Seeding date	7 July 2008	3 July 2009	1 July 2010
Burndown with Glyphosate (N-(phosphonomethyl)glycine)	1.06 kg ae ha^{-1}	1.06 kg ae ha^{-1}	1.52 kg ae ha^{-1}
Fungicide - Saflufenacil§	------------	------------	70 g ai ha^{-1}
Fertilizer ($(NH_4)_2SO_4$)	------------	20 g L^{-1}	------------
Application date	10 July 2008	3 July 2009	1 July 2010
Burndown with Glyphosate (N-(phosphonomethyl)glycine)	1.06 kg ae ha^{-1}	1.52 kg ae ha^{-1}	1.52 kg ae ha^{-1}
Burndown with Lactofen¶	------------	------------	96 g ai ha^{-1}
Fertilizer ($(NH_4)_2SO_4$)	------------	20 g L^{-1}	------------
Application date	26 Aug. 2008	5 Aug. 2009	11 Aug. 2010†

† Application included 0.25% vol./vol. nonionic surfactant.

‡Pyraclostrobin (carbamic acid, [2-[[[1-(4-chlorophenyl)-1*H*-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester).

§ Saflufenacil (N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide).

¶ Lactofen (2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(tri-fluoromethyl) phenoxy]-2-nitrobenzoate).

Crop protection practices required varied among the 2008, 2009, and 2010 season.

Table 4.3. ANOVA table soft red winter wheat grain yield and test weight from 2007-2008, 2008-2009, and 2009-2010 seasons.

Source	df	Grain Yield		Test Weight	
		F-value	Pr > F	F value	Pr > F
Rep	4	47.17	<.0001	62.37	<.0001
Year	2	2580.99	<.0001	563.28	<.0001
Rate	2	1289.48	<.0001	37.78	<.0001
N app. timing	6	5.27	<.0001	4.91	<.0001
N source	4	2.75	0.0269	2.92	0.0202
Year x Rate	4	18.18	<.0001	83.50	<.0001
Year x N app. timing	12	9.11	<.0001	3.95	<.0001
Year x N source	8	1.45	0.1702	4.59	<.0001
Rate x N app. timing	12	1.77	0.0483	1.40	0.1608
Rate x N source	8	2.11	0.0323	2.96	0.0028
N app. timing x N source	24	1.18	0.2510	0.89	0.6216
Year x Rate x N app. timing	24	2.59	<.0001†	1.48	0.0622‡
Year x Rate x N source	16	1.49	0.0968‡	2.66	0.0004†
Year x N app. timing x N source	48	1.28	0.0957‡	0.39	1.0000
Rate x N app. timing x N source	48	0.73	0.9163	0.78	0.8557
Year x Rate x N app. timing x N source	96	0.79	0.9315	0.43	1.0000

† Highest significant interactions at α = 0.05.

‡ Highest significant interactions at α = 0.10.

Abbreviations: App. = application; df = degrees of freedom; N = nitrogen.

Table 4.4. Soft red winter wheat grain yields by N rate and application timing or fertilizer source(s) from the 2008, 2009 and 2010 growing seasons.

		N application timing†							N fertilizer source‡				
									100%	100%	100%	75/25%	50/50%
Year	Rate	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	AN	NCU	PCU	PCU / NCU	
	kg ha^{-1}	kg ha^{-1}							kg ha^{-1}				
2008	0	3550	3550	3550	3550	3550	3550	3550	3550	3550	3550	3550	3550
	84	4920	5200	4720	4840	4490	5090	5140	4880	4800	5030	4960	4900
	112	5300	5630	5120	5220	4730	5340	5380	5110	5120	5340	5370	5290
	LSD	160							130				
2009	0	2150	2150	2150	2150	2150	2150	2150	2150	2150	2150	2150	2150
	84	3340	3420	3000	3500	3520	3260	3370	3430	3230	3470	3520	3080
	112	3480	3340	3160	3430	3420	3310	3410	3440	3380	3110	3400	3500
	LSD	310							220				
2010	0	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
	84	2400	2520	2850	3000	2820	3070	3110	2820	2720	2990	2840	2750
	112	2600	2800	3270	3170	3200	3420	3110	3190	2960	3200	3050	3020
	LSD	170							140				

† Fisher's Least Significant Difference at alpha = 0.05.

‡ Fisher's Least Significant Difference at alpha = 0.10.

Abbreviations: AN = ammonium nitrate; NCU = non-coated urea; PCU = polymer-coated urea.

Table 4.5. Soft red winter wheat grain yields by application timing or fertilizer source from the 2008, 2009 and 2010 growing seasons.

			N application timing						
Year	N fertilizer source†	Ratio (%)	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
			----------	----------	----------	kg ha^{-1}	----------	----------	----------
2008	AN	100	4950	5470	5120	4790	3970	5040	5600
	NCU	100	4920	5390	4710	4830	4290	5190	5420
	PCU	100	5370	5460	4950	5380	5130	5230	4810
	PCU/NCU	75 / 25	5160	5430	4980	5280	4830	5330	5130
	PCU/NCU	50 / 50	5150	5320	4840	4860	4850	5290	5350
		LSD (0.10)	----------	----------	----------	220	----------	----------	----------
2009	AN	100	3630	3600	3060	3430	3790	3190	3360
	NCU	100	3450	3140	3130	3420	3510	3190	3290
	PCU	100	3120	3300	3000	3520	3240	3600	3230
	PCU/NCU	75 / 25	3410	3430	3300	3450	3300	3550	3790
	PCU/NCU	50 / 50	3430	3430	2920	3530	3510	2880	3290
		LSD (0.10)	----------	----------	----------	460	----------	----------	----------
2010	AN	100	2680	2510	3230	3140	2780	3340	3360
	NCU	100	2250	2440	2840	3040	3000	3130	3190
	PCU	100	2750	3010	3160	3220	3190	3330	2970
	PCU/NCU	75 / 25	2370	2860	3170	3090	3020	3240	2860
	PCU/NCU	50 / 50	2420	2480	2910	2940	3050	3190	3170
		LSD (0.10)	----------	----------	----------	260	----------	----------	----------

† Grain yields averaged over applications of 84 and 112 kg N ha^{-1}.

Abbreviations: AN = ammonium nitrate; NCU = non-coated urea; PCU = polymer-coated urea.

Table 4.6. Soft red winter wheat test weight for the rate*application timing and rate *fertilizers source interactions in the 2008,2009, and 2010 growing seasons.

		N application timing‡							N fertilizer source†				
									100%	100%	100%	75/25%	50/50%
Year	Rate	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	AN	NCU	PCU	PCU / NCU	
	kg ha^{-1}	kg hL^{-1}							kg hL^{-1}				
2008	0	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8
	84	73.5	73.5	73.3	73.6	73.2	74.0	74.1	73.2	73.0	74.2	73.8	73.7
	112	73.7	74.5	73.7	74.2	73.6	74.3	74.3	73.1	73.5	75.0	74.5	74.2
	LSD	0.5							0.5				
2009	0	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3
	84	71.3	72.3	71.8	72.4	71.9	70.4	71.2	71.7	71.9	71.6	72.2	70.8
	112	71.3	71.4	70.7	71.3	70.7	69.8	69.2	70.8	71.5	68.5	71.0	71.4
	LSD	1.0							1.0				
2010	0	71.7	71.7	71.7	71.7	71.7	71.7	71.7	71.7	71.7	71.7	71.7	71.7
	84	69.8	69.7	67.9	67.7	68.3	67.9	66.7	67.8	68.5	68.4	68.8	68.0
	112	69.9	68.4	67.8	67.6	68.0	67.7	67.1	67.2	69.2	67.8	67.8	68.3
	LSD	0.9							0.9				

† Fisher's Least Significant Difference at alpha = 0.05.

‡ Fisher's Least Significant Difference at alpha = 0.10.

Abbreviations: AN = ammonium nitrate; NCU = non-coated urea; PCU = polymer-coated urea.

Table 4.7. Correlation between soft red winter wheat grain yield and soybean production in a double cropping system during the 2008 and 2009 season.

	Variables			
Variables	Winter wheat grain yield	Soybean yield	Soybean height	Soybean population
Winter wheat grain yield	1.0000	0.6100	-0.6552	-0.4463
Prob. > |r|		<.0001	<.0001	<.0001
Soybean yield	0.6100	1.0000	-0.9114	-0.6831
Prob. > |r|	<.0001		<.0001	<.0001
Soybean height	-0.6552	-0.9114	1.0000	0.7396
Prob. > |r|	<.0001	<.0001		<.0001
Soybean population	-0.4463	-0.6831	0.7396	1.000
Prob. > |r|	<.0001	<.0001	<.0001	

† Pearson Correlation Coefficients, N = 1050.

Table 4.8. ANOVA table of the analysis of soybean production in a winter wheat/soybean double cropping system; analysis includes yield, protein and oil concentration from the 2007-2008 and 2008-2009 seasons.

				Concentration			
		Yield		Protein		Oil	
Source	df	F value	Pr > F	F value	Pr > F	F value	Pr > F
Rep	4	46.72	<.0001	17.10	<.0001	25.54	<.0001
Year	1	42715.60	<.0001	494.12	<.0001	1578.92	<.0001
Rate	2	22.61	<.0001	10.11	<.0001	3.60	0.0279
N app. timing	6	0.65	0.6883	0.36	0.9048	0.16	0.9880
N source	4	2.18	0.0695‡	1.45	0.2159	1.01	0.4025
Year x Rate	2	6.66	0.0013†	38.85	<.0001†	48.83	<.0001†
Year x N app. timing	6	0.56	0.7661	1.47	0.1851	1.18	0.3170
Year x N source	4	0.98	0.4201	1.79	0.1284	1.22	0.2987
Rate x N app. timing	12	0.53	0.8933	0.42	0.9546	0.19	0.9989
Rate x N source	8	1.36	0.2098	0.98	0.4492	0.86	0.5500
N app. timing x N source	24	0.88	0.6265	1.06	0.3876	0.81	0.7275
Year x Rate x N app. timing	12	0.34	0.9806	0.82	0.6269	0.91	0.5317
Year x Rate x N source	8	0.43	0.9043	1.43	0.1802	1.29	0.2438
Year x N app. timing x N source	24	0.88	0.6265	0.98	0.4920	0.62	0.9194
Rate x N app. timing x N source	48	0.77	0.8696	0.88	0.7002	0.77	0.8759
Year x Rate x N app. timing x N source	48	0.67	0.9607	0.94	0.5934	0.65	0.9670

† Highest significant interactions at α = 0.05.

‡ Highest significant interactions at α = 0.10.

Abbreviations: App. = application; df = degrees of freedom; N = nitrogen.

Table 4.9. Impact of N rate on double crop soybean production including yield and the concentration of protein and oil analyzed by year.

	Growing Season†		
Rate	2007-08	2008-09	2009-10‡
kg ha^{-1}	----------- Yield (kg ha^{-1}) -----------		
0	4880a	2130a	-----
84	4760ab	2100b	-----
112	4730b	2080b	-----
	----------- Protein (g kg^{-1}) -----------		
0	331b	349a	-----
84	338a	347b	-----
112	339a	347b	-----
	------------- Oil (g kg^{-1}) --------------		
0	179a	166c	-----
84	176b	167b	-----
112	175b	167a	-----

† Letters following yields (by year) denote Fisher's Least Significant Difference ($\alpha = 0.05$).

‡ Data not obtained at publication.

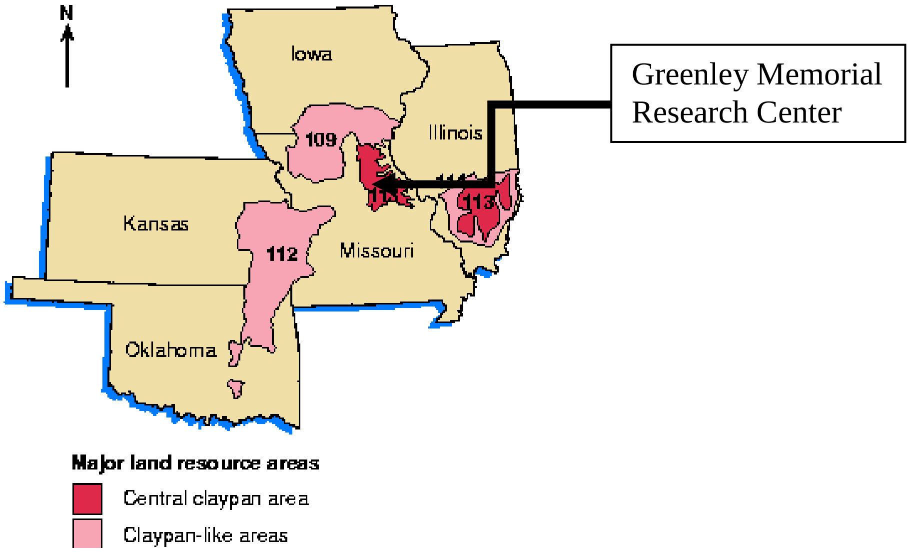

Figure 4.1. Central Claypan Region in the United States.
Source: USDA Agricultural Handbook 296, 1981. Map prepared by CARES, 1998.

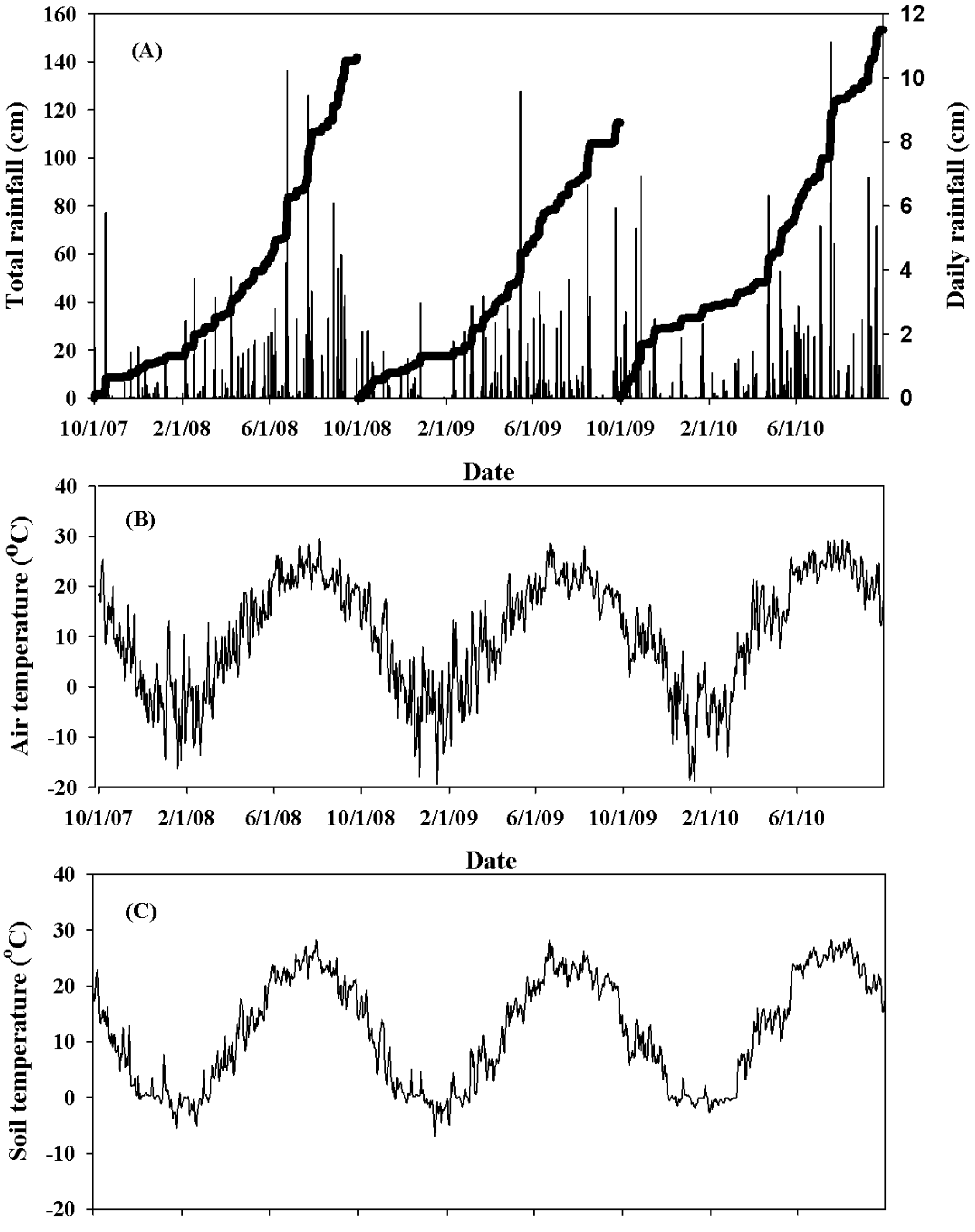

Figure 4.2. Daily rainfall (bars), cumulative rainfall (line) (A), air temperature (B), and soil temperature at 5 cm depth with corn residue (C) at the University of Missouri, Greenley Memorial Research Center over the three year winter wheat-soybean double-crop studies.

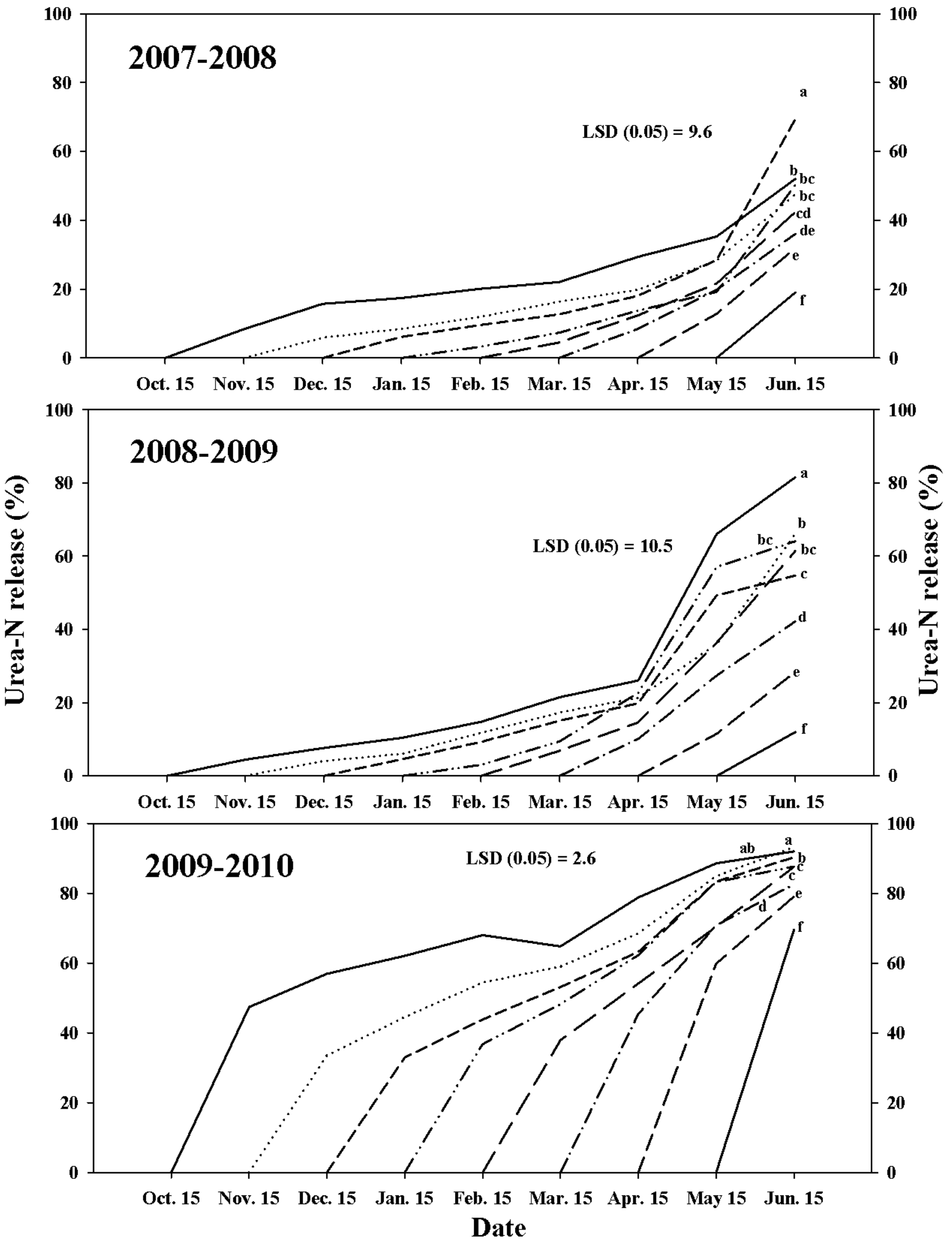

Figure 4.3. In-field study of the percent urea released from PCU fertilizer applied to the soil surface by season, with applications starting on 15 Oct. to 15 June.

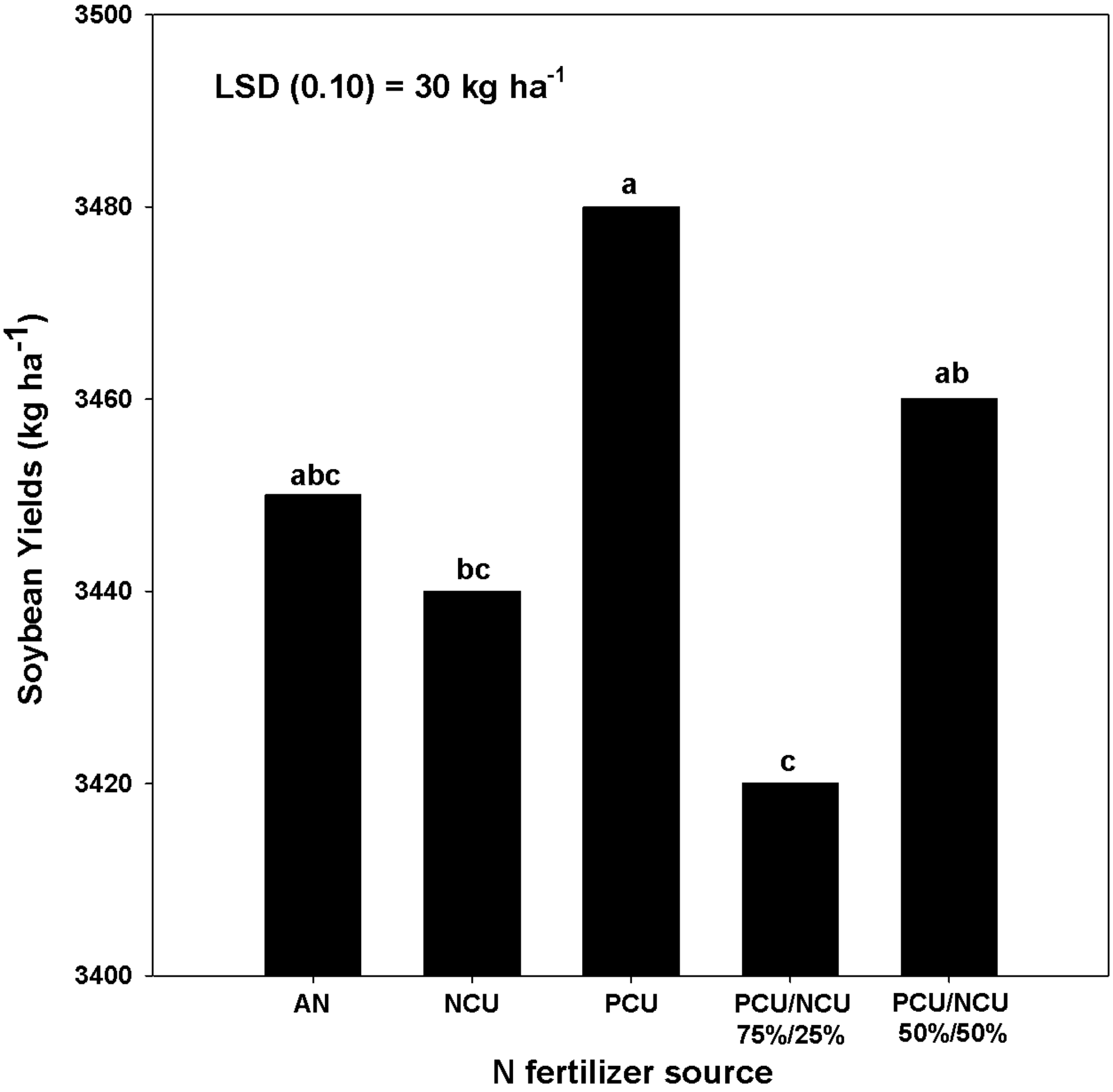

Figure 4.4. Double-crop soybean yield as impacted by N fertilizer source applications from Oct. to Apr. for wheat averaged over 2007-2008 and 2008-2009.

CHAPTER 5

OVERALL CONCLUSIONS

Claypan soils have poor internal drainage which can lead to greater periods of saturated, anaerobic conditions. While NO_3^- leaching is minimal through the claypan layer, there is a naturally high potential in claypan soils for N_2O loss through nitrification and denitrification processes which may reduce crop production and increase greenhouse gas emissions. Due to these conditions, improved tillage and N management in claypan soils are important in order to maintain high crop production and to reduce soil N_2O emissions. Therefore, the overall objective of this research was to determine if tillage and/or N management would increase crop production and/or reduce soil N_2O emissions in poorly drained claypan soils.

One objective was to evaluate what factors impact soil N_2O flux and determine whether slow release PCU fertilizer or ST with deep banded N could reduce soil N_2O emissions from corn production by lowering N_2O emissions and increasing grain yields compared to using NCU fertilizer and NT/surface broadcast. Soil N_2O flux was as much as 450 times greater than natural levels between 30 to 60 days after N fertilization which was partially attributed to air and soil temperature and soil water content. Poorly drained claypan soils combined with wet growing season conditions resulted in amounts of N loss as N_2O higher than most soils, but this study found less than 4% of N fertilizer applied was lost as N_2O. Alternative management practices, such as PCU and ST/deep banded N, did not reduce cumulative growing season emissions of N_2O compared to traditional management of NCU application and NT/surface broadcasting of N as was hypothesized.

The lack of statistical differences in soil N_2O flux among the treatments in this research was possibly due to the naturally high spatial variability in soil N_2O flux observed in the field among the replicates and the subsamples within the same plot. This high observed variability in soil N_2O flux deserves more in-depth research to determine its causes since it is a common problem in research examining changes in soil N_2O flux due to different agricultural management practices.

Use of ST and deep banding of N fertilizer increased corn grain yields over NT/surface broadcast management. A calculation of the cumulative N_2O emitted per unit grain yield showed that pre-plant ST/deep banding lowered the amount of N_2O emitted per Mg of grain produced by 28%. This statistic combining cumulative soil N_2O loss with grain yield is useful since it allows for the comparison of the relative effectiveness of each management practice on both environmental loss in relation to corn production. Based on the results of this study, pre-plant ST and deep banding of N fertilizer in corn production on claypan soils in relatively wet climatic years show some promise in reducing cumulative soil N_2O emissions per unit grain yield compared to no-till and surface broadcast N fertilizer application. Further research on the effectiveness of these tillage/N fertilizer placement practices may need to be assessed with fall, ST practices and banding timing, in other soil types, and under normal to drier climatic conditions.

The second objective was to evaluate differences in corn grain yield response due to N application timing (i.e., fall, early preplant, prelant), tillage/fertilizer placement (i.e., ST/deep banded and NT/surface broadcasted), and N fertilizer source (i.e., PCU and NCU), including a fertilized check (i.e., AA) and a non-fertilized control. Over three years, rainfall was above average which resulted in seed germination stress and low plant populations which combined with a high potential for gaseous N loss resulted in 8 to 41% greater yields with ST/deep banding of N compared to a NT/surface broadcast application. Tilling of the planting row and deep banding placement of different N fertilizer sources (i.e., PCU or NCU) with ST was effective at maximizing final plant stands and reducing potential for N loss. During moderately wet to very wet growing seasons, ST/deep banding of N maintained or exceeded yields compared to NT/surface broadcast applications, while producing yields similar to the injected AA. Contrary to what was hypothesized, application timing of N and the N fertilizer source had minimal impact on yields. Therefore, based on this study, ST/deep banded N is a viable alternative management option in poorly drained claypan soils which can maximize yield production while increasing the flexibility in N fertilizer use without lowering yield potentials.

The last objective was to evaluate the differences in NT, double cropped, winter wheat/soybean production due to N application timing (i.e., Oct., Nov., Dec., Jan., Feb., March, and April), fertilizer source (i.e., PCU, NCU, AN, and blends of PCU and NCU), and rate (0, 84 and 112 kg N/ha). Release of urea from PCU was less than 50% when fall applied and increased up to 95% by 15 June. As expected, winter wheat yield and grain quality increased with N rate. Based on this study, PCU was a viable alternative N fertilizer source for fall applications, while the blending of PCU with NCU showed yield benefits when N was applied in February or later during wet growing seasons with high potential for N loss. Double-crop soybean yields were ranked PCU = 50%PCU:50%NCU

$= \text{AN} \geq \text{NCU} \geq 75\%\text{PCU}{:}25\%\text{NCU}$. Therefore, fertilizer selection for winter wheat not only affects wheat yields, but also impacts double-crop soybean yield potential.

All of the studies conducted for this research highlight the importance of examining alternative agricultural management practices, including tillage and fertilizer source, timing and method of application, to improve crop production and minimize environmental N loss, especially under wet soil and climatic conditions that may occur in Missouri.

Appendices

Appendix 1. Corn ear leaf N content in the 2008, 2009, and 2010 for the interaction of N application timing, tillage/N placement, and N fertilizer source following soybean production. Ear leaf samples were taken between the R3 and R5 growth stage (leaf collar method).

Year	N app. Timing	Tillage / N placement	N fertilizer source NCU	PCU	Non-treated
			---- Ear leaf N (g kg^{-1}) -----		
2008	Fall	No-till / broadcast	14.9	14.6	13.1
	Fall	Strip-till / deep band	24.3	21.5	16.1
	Early PreP.	No-till / broadcast	16.3	14.9	12.4
	Early PreP.	Strip-till / deep band	26.1	24.6	11.4
	PreP.	No-till / broadcast	13.0	16.2	11.8
	PreP.	Strip-till / deep band	19.7	25.2	19.5
2009	Fall	No-till / broadcast	17.8	17.7	17.1
	Fall	Strip-till / deep band	25.8	27.1	17.2
	Early PreP.	No-till / broadcast	17.1	23.7	19.0
	Early PreP.	Strip-till / deep band	28.8	27.3	14.6
	PreP.	No-till / broadcast	17.3	25.8	12.5
	PreP.	Strip-till / deep band	28.5	28.3	18.4
2010	Fall	No-till / broadcast	13.4	12.8	11.4
	Fall	Strip-till / deep band	13.2	11.7	10.6
	Early PreP.	No-till / broadcast	22.0	15.7	10.0
	Early PreP.	Strip-till / deep band	16.4	13.5	11.6
	PreP.	No-till / broadcast	11.5	15.4	14.9
	PreP.	Strip-till / deep band	12.6	11.1	12.4

Abbreviations: app. = application; PreP. = preplant.

Appendix 2. Corn ear leaf N content in the 2008, 2009, and 2010 for the interaction of N application timing, tillage/N placement, and N fertilizer source following soybean production with red clover cover crop. Ear leaf samples were taken between the R3 and R5 growth stage (leaf collar method).

Year	N app. timing	Tillage / N placement	N fertilizer source		
			NCU	PCU	Non-treated
			---- Ear leaf N (g kg^{-1}) -----		
2008	Fall	No-till / broadcast	20.78	23.54	21.23
	Fall	Strip-till / deep band	28.97	29.58	20.31
	Early PreP.	No-till / broadcast	23.01	23.44	21.89
	Early PreP.	Strip-till / deep band	31.81	31.93	17.63
	PreP.	No-till / broadcast	24.75	24.35	18.93
	PreP.	Strip-till / deep band	30.78	28.53	18.19
2009	Fall	No-till / broadcast	21.16	20.70	17.16
	Fall	Strip-till / deep band	20.34	21.62	14.99
	Early PreP.	No-till / broadcast	15.91	18.16	12.52
	Early PreP.	Strip-till / deep band	20.59	22.89	13.07
	PreP.	No-till / broadcast	17.72	23.41	16.64
	PreP.	Strip-till / deep band	26.73	27.53	17.14
2010	Fall	No-till / broadcast	15.1	16.3	16.4
	Fall	Strip-till / deep band	19.2	18.0	17.5
	Early PreP.	No-till / broadcast	15.2	15.1	13.9
	Early PreP.	Strip-till / deep band	13.1	14.0	12.1
	PreP.	No-till / broadcast	14.6	13.7	15.7
	PreP.	Strip-till / deep band	15.8	13.8	12.0

Abbreviations: app. = application; PreP. = preplant.