

EVALUATION OF METHOD OF PLACEMENT, TIMING, AND RATE OF APPLICATION  
FOR ANHYDROUS AMMONIA IN NO-TILL CORN PRODUCTION.

by

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## Abstract

Anhydrous ammonia (AA) is one of the most commonly used nitrogen (N) fertilizer sources for corn (*Zea mays* L.) in the US. Traditional knife applicators are slow, have high power requirements and create substantial soil disturbance. Thus, there is considerable interest in high speed, shallow placement, and low draft AA applicators like the newly introduced JD 2510 series, particularly for no-till production systems. The objective of this project was to compare a prototype high speed, low draft applicator (JD) with a traditional knife type AA applicator (TRAD) for irrigated and dryland corn production in the Kansas River Valley. Field studies were conducted from 2007 through 2009. Six N rates ranging from 0 – 224 kilograms N per hectare, in 45 kilogram increments, were applied at 3 application timings, Fall (FALL), Preplant (PRE), and Sidedress (SD) with both type applicators. Gaseous AA emissions were collected over a seven to nine day period after each application for both the TRAD and JD applicators for all application timings. The impact of applicator, timing and N rate was also measured on plant stand, earleaf N content, total N uptake, nitrogen use efficiency and grain yield. Statistically higher post application losses of ammonia at high N application rates were seen at all application timings with the JD applicator. However, these N losses were not of agronomic significance, and did not affect grain yield in 2007 or 2008. In 2009, there did appear to be a significant difference between applicators in grain yield, however this was primarily due to a significant yield decrease at the JD SD 224 kilograms N per hectare treatment from high application loss and resulting plant tissue damage. A significant response to N application was seen every year. Optimum N rate varied between years. Fall and Pre treatments had significantly higher grain yield than SD applications in 2008. However, in 2009 there was no significant difference in N application timing.

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## **Dedication**

This is dedicated to Alison and Brutus.

# CHAPTER 1 - The Evolution of Anhydrous Ammonia: A Review of Literature

Few will argue the single greatest agricultural advance since the McCormick mechanical reaper was the Haber-Bosch process that allows nitrogen (N) to be synthesized chemically. This process changed the way our world operates agriculturally, environmentally, and socially. It is responsible for the green revolution that paved the way for high yielding production agriculture that is common in this day and age. The ability to utilize inorganic N in modern crop production also created many issues relating to climate change, global social inequality, and long term environmental impact (Smil, 2001). The Haber-Bosch process allows ammonia to be industrially produced by reacting hydrogen and N over an iron catalyst. Haber was awarded the patent for the process, but it was Bosch that was responsible for industrializing the process while working for BASF. Both Fritz Haber and Carl Bosch would go on to win Nobel prizes for their work (Slack, 1973). It should be noted that this is often referred to as the Haber process, but the wide scale adoption and implementation of the technology was largely the work of Bosch.

Even though our atmosphere is 73% N, the triple bond present in the atmospheric N molecules renders it relatively inert. The Haber-Bosch process is conducted under a high pressure, high heat environment to help break these triple bonds. Industrially the production of Hydrogen gas is known as cracking gas. The most common feedstock currently being cracked is natural gas, but gases from coal and coke ovens can also be cracked very efficiently. There is currently a large natural gas cracking facility in Illinois being converted to a coal gasification cracking facility due to the rising cost of natural gas and availability of local high quality coal (Kramer, 2005). While the Haber-Bosch process is an effective method of synthesizing  $\text{NH}_3$ , it is still linked to the volatile fossil fuel market and subject to market dynamics. Where Ammonia is produced is primarily a function of natural gas price and access to ocean transportation. Countries such as Trinidad, and Russia are current leaders in world production (Polizatto, 2009).

It is important to point out that there were other methods for synthesizing N fertilizers prior to the Haber-Bosch process. It was the Norwegian duo of Birkland and Eyde that developed the electric arc process and built a furnace for the production of nitric acid. The nitric acid was then reacted with limestone to create calcium nitrate. The electric arc process was not

able to compete with the Calcium Cyanamid process that was patented by the Germans Frank and Caro in the late 1890's. The cyanamid process fixes N by reacting atmospheric N with calcium carbide for calcium cyanamid. The cyanamide can then be hydrolyzed with water to form ammonia. It was this process that was the basis for the US Nitrate Plant No. 2 in Muscle Shoals, AL to manufacture ammonium nitrate for munitions. The development of this facility involved damming the Tennessee River to provide the large amount of electricity needed to operate the carbide furnaces, cyanamide ovens, and other equipment needed for the plant to operate at its production rate of 165 Mg of ammonia per day. The caveat of this was that by the time the plant came online, WWI had ended and so did the demand for wartime munitions. The facility was later to become the center point for the Tennessee Valley Authority and after WWII, the National Fertilizer Development Center. While the cyanamid process proved popular through the end of World War I (WWI), it failed to be as economical as the Haber-Bosch process (Slack, 1973).

The drive to implement the Haber-Bosch process industrially was spurred by the demands of Germany's need for a reliable source of ammonium nitrate for munitions in the First World War. Prior to this, Germany had been relying on Chilean Saltpeter or sodium nitrate to manufacture explosives. As WWI snowballed into a global crisis, Germany could no longer count on a reliable source of sodium nitrate for munitions manufacturing. Bosch was responsible for designing the first industrial Haber-Bosch ammonia manufacturing plant in 1913 capable of producing 29.7 Mg of ammonia per day (Snyder and Burnett, 1966). Various manufacturing improvements to the Haber-Bosch process were made over the next 20 years, but the basic process remains the same.

By 1932 the USA was manufacturing 3.4 million Mg of N per year. However, ten years later that figure would double, as the USA found itself in another global conflict. After WWII the use of ammonia as a feedstock for the manufacture of N fertilizers started to develop rapidly. By 1968, the agriculture sector was consuming up to 90% of the ammonia being manufactured in the US (Slack, 1973). The choice of N fertilizers and application methods varied dramatically over the years, but the primary uses of ammonia have been direct application and the synthesis of ammonium nitrate, urea, ammonium phosphate, ammonium sulfate, and liquid N solutions.

While ammonia is the major N feedstock in fertilizer production, different types of N fertilizers have fallen in and out of favor world wide. In the 1960's according to McVickar

(1973), ammonium nitrate was the most widely used N fertilizer worldwide, while in the USA direct application of anhydrous ammonia (AA) was rapidly becoming the most popular source of N. Nitrogen fertilizer usage trends tend to fluctuate over time as price and tradition dictated usage. While ammonium nitrate is no longer the most commonly used fertilizer in the US, it does account for a large share of the N market when solutions like 28% or 32% urea ammonium nitrate (UAN) are accounted for. In Table 1, we can see the how the trends in fertilizer use have changed over the last 40 years.

**Table 1.1 Change in nitrogen fertilizer use from 1968 to 2006**

Fertilizer	1968 (%)§	2006 (%)§§
Anhydrous Ammonia	32.5	32.3
Ammonium Nitrate	25.8	3.3
Urea	15.4	25.5
Ammonium Phosphate	13.7	¶
Ammonium Sulfate	7.2	2.6
N Solutions	5.4	31.3

¶: This nutrient is currently calculated as part of the multiple nutrient fertilizer source and cannot be separated from other such fertilizer products.

§Slack, 1973

§§Terry and Kirby, 2006

We can garner a lot about how AA behaves in soils by thinking about its name. Anhydrous means, quite simply, without water. So when introduced to soils it immediately attaches to water. Because of the nature of this product, various ways of applying AA have been developed over the years. The first uses for AA were developed in the California tree fruit industry in the 1930's, by injecting it into irrigation pipes carrying water to fields. This closed system of incorporating AA proved very useful and economical. The pipes allowed the ammonia to attach to the hydrogen in the water molecules and create ammonium ( $\text{NH}_4^+$ ). This N source has become known as aqueous or aqua ammonia. This type of application relied on a large scale infrastructure of irrigation pipes that is not found in many crop production areas. A problem that was encountered early was the uneven distribution of N in furrow irrigation. Often N concentrations would be much higher at the head of a furrow than at the tail. The N was also concentrated on the soil surface above rooting zones. A common problem encountered in areas with hard water was the precipitation of Ca and Mg. This precipitate would form on the walls of

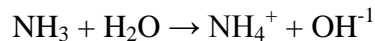
irrigation pipe, and could obstruct a large line in a matter of weeks (Blouin, 1979). Utilizing aqueous ammonia in sprinkler irrigation systems proved to be less successful. The evaporation from guns often caused N losses as high as 50%. On average, sprinkler systems lost about 25% of the applied N with water temperature and pH being major factors in evaporative loss. The ammonia was also very corrosive to the brass and bronze material in the sprinkler systems (Leavitt, 1966). For the fertilization of crops like rice, AA offered producers several options. The rice crop could be fertilized through aqueous ammonia in the irrigation water several weeks after planting, or a direct soil application prior to planting. However, direct application of AA to soil prior to planting was shown to be superior in Texas rice production (Smith, 1966).

The next step in the development of AA utilization came in the form of direct application. Prior to the utilization of AA in irrigation water, it was considered a feed stock for other types of N fertilizers. If AA was to become a viable N source for mainstream use, a system of direct application had to be developed. The principle of dispensing AA behind a knife or shank at varying depths was widely embraced early in development, but these crude designs lacked an accurate metering system that compensated for varying ground speed and rates. By the mid 1940's the John Blue Company devised a metering pump for AA that was powered by a ground drive wheel. This ground drive wheel design allowed for even distribution and metering of AA regardless of variation in ground speed. This type of metering system would be improved upon over the next ten years and when combined with differential regulators and multiple orifice types paved the way for widespread adoption of direct application of AA (Leavitt, 1966).

One factor that has not changed dramatically over the years has been AA knife design. The knife design used by Blue and Eno in 1954 is not significantly different than the knife design that is found on most AA applicators today. The concerns and weakness of this design are also unchanged. Escaping AA is generally noted by a visual cloud and the pungent odor that accompanies this cloud of water vapor, ammonium hydroxide, and free ammonia. While Jackson and Chang (1947) conducted much of the early work on the retention of AA, their focus was on laboratory procedures to measure AA volatilization. They surmised that a soils ability to hold and retain AA was directly influenced by application depth, soil temperature, soil texture, CEC, pH, and tilth (Jackson and Chang, 1947). Blue and Eno (1954) evaluated the retention of AA in the sandy coastal plains of the Southeastern US. Their field work confirmed what Jackson and Chang (1947) had proved in the laboratory; the quantity of soil that AA comes into contact

with plays a direct role in the rate of retention by the soil. While all of the above factors played a large part in the retention of AA in soils, Blue and Eno (1954) determined that most of the AA losses occurring were actually happening between the knife and the packing wheel that closed the application slit.

To better understand the transformations that occur when AA is injected into soil it is important to understand how N behaves in soil under various influences. After injection into the soil, AA will attempt to attach to the hydrogen present in soil moisture in the following reaction (Parr and Papendick, 1966):



This creates a protonated form of  $\text{NH}_3$ ,  $\text{NH}_4^+$ , which has a high affinity for clay minerals and is readily sorbed on cation exchange sites. The by-product of this protonation is a marked increase in soil pH (Dontsova et al., 2005). From this point  $\text{NH}_4^+$  can proceed in several different directions.

### **Nitrification**

The conversion of  $\text{NH}_4^+$  into either nitrite ( $\text{NO}_2^-$ ) or nitrate ( $\text{NO}_3^-$ ) is a cumulative or stepwise process. Nitrosomonas are autotrophic bacteria that conduct the transformation of  $\text{NH}_4^+$  to  $\text{NO}_2^-$  in the presence of oxygen. The next transformation to  $\text{NO}_3^-$  involves the addition of  $\text{O}_2$  and the work of another autotrophic bacteria, Nitrobacter. These processes require substantial amounts of oxygen, and as a result soils with better pore structure and aeration are more likely to nitrify ammonium. While this process uses oxygen it also releases large amounts of  $\text{H}^+$ , thereby decreasing soil pH. Well drained environments, with adequate temperature, increase the activity of these soil organisms (Hauck, 1980). The effects of soil pH on the nitrification of ammonium is often ignored in agricultural production since most soil in these areas are between 5.5 and 8.0. Kyveryga et al. (2004) showed that there was a positive relationship between increased rates of nitrification as soil pH increased from 6 to 8 when AA is used as a N source. They also found that the effects of soil temperature accounted for much of the year to year variability in nitrification.

### **Direct Plant Uptake**

Direct uptake by higher plants is another possible fate of  $\text{NH}_4^+$  in the soil. There has been much debate over the years as to whether  $\text{NO}_3^-$  or  $\text{NH}_4^+$  was a better source of N. Research has been conducted on corn to show either type of N fertilizer works equally well (Blair et al., 1970). However it has been recognized that the type of N used influences the uptake of other nutrients. Numerous studies show the use of ammonium N increases the plant uptake of phosphorus and sulfur, while the use of nitrate N resulted in higher levels of calcium and magnesium in the plant (Blair et al, 1970). The use of nitrate and ammonium sources of N also have different effects on the acidity of soil solution pH. The long term use of nitrate will increase the soil pH, while the use of ammonium will cause a decrease in pH. This is caused by the exchange of  $\text{H}^+$  ions in ammonium use, and the exchange of  $\text{OH}^-$  with nitrate use (Havlin, et al. 2005).

Certain types of plants also utilize types of N differently. Blair et al. (1970) demonstrated that corn will utilize either ammonium or nitrate equally well. However, certain crops have an affinity to specific types of N, or intolerance for others. The uptake of N is also varying at different levels of soil pH. Nitrate uptake is optimum in soils with a pH of 4.5-6.0, but ammonium uptake is greatest in soils with a pH of 6.0-7.0 (Hageman, 1980). McCants et al., (1959), showed the sole use of ammonium in flue-cured tobacco (*Nicotainia tabacum*) production resulted in thick leaves that were hard to cure, had excessive levels of nicotine, and poor smoking qualities.

It is simply not possible to say that one type of N is superior to another. Rather, certain crops may have higher yields under specific fertility regimes. Ammonium would be the preferred type of N taken up, as it saves plant energy. Ammonium can be used directly for the synthesis of protein, while nitrate must be reduced so it can be turned into protein (Tisdale et al, 1985).

### **C: N Decomposition**

Another fate of ammonium is to be utilized by soil dwelling organisms to facilitate the break down of carbon compounds. The amount of N that is immobilized depends on the carbon source. Nitrogen generally starts being immobilized in the soil when there is greater than a 30:1 C:N ratio in the early stages of organic matter decomposition. Most agricultural residues like corn and wheat fodder are approximately 80-90:1 C: N ratio. Generally, the higher the lignin

content, the greater the C: N ratio and more N is needed to utilize the carbon. However, this N is not tied up indefinitely. Once the natural processes of decomposition take place, the ratios will begin to shift as the carbon is consumed by the N fueled heterotrophic microorganisms. When the C: N ratios recede to below 20:1 the soils will begin to mineralize N. This mineralized ammonium N will be released as the C:N ratio reaches its equilibrium (Tisdale et. al., 1985). Chaves et al. (2007) makes an interesting point about utilizing high carbon material to capture N that might ordinarily be lost to leaching in high input production systems. However, it is not always possible to predict the release of immobilized N to the benefit of an actively growing crop.

## **Fixation**

The phenomenon known as fixed ammonium, as described by Hans Nommik in Soil Nitrogen (1965), is another possible fate of ammonium in the soil. Ammonium fixation primarily occurs when ammonium attaches to clay particles, or colloids in the soil. There are two types of clay particles, but only one that fixes ammonium or potassium. These types of clay can be disseminated by the ratio of silicate: aluminum. The first type is what Nommik (1965) refers to as a 1:1 ratio or a two layer type of mineral. This clay mineral is of little consequence when fixing ammonium because the ammonium or potassium that is fixed is not tightly held. The more important type of clay mineral is 2:1 ratio of silica: aluminum that is also known as the three layer clay mineral. These minerals are generally known as micas or micaceous clays. In these materials, the lattice layers in a hydrated state have a hexagonal shape that can be occupied by divalent or univalent cations. As the ion charge on the outer edges of the lattice structure changes through dehydration, the exchange of high valence for low valence ions takes place. This creates a negative charge in the lattice, which can be readily occupied by the positively charged  $\text{NH}_4^+$  or  $\text{K}^+$  ion. Ultimately, soils likelihood to fix ammonium is dependent on clay mineral composition, how the soil has weathered, and the amount of K that has been removed as a result of weathering (Nommik, 1965).

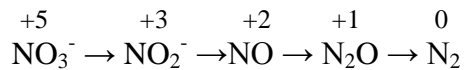
Another type of fixation that is not discussed as often as clay mineral fixation is ammonia fixation to soil organic matter (SOM). This is because it is hard to distinguish from the utilization of ammonia by soil dwelling organisms to facilitate the breakdown of carbon materials in or on



the soil known as immobilization. Organic matter fixation of ammonia occurs in the time period immediately following AA application. During this time period, biological activity will decrease due to the high levels of free ammonia and increased pH. As result, immobilization will not occur until the free ammonia dissipates and pH levels return to acceptable levels to support soil biological activity (He et al., 1990).

## Denitrification

Denitrification is a primary loss pathway for applied N in agricultural systems (Coyne, 2008). Denitrification is the reduction of nitrogen oxides in a anaerobic environment. Linn and Doran (1984) showed that water filled pore space in soil played a very important role in determining pathways of nitrification and denitrification by restricting O<sub>2</sub> and affecting microbial populations. In production agriculture the nitrogen oxide of primary interest is nitrate (NO<sub>3</sub><sup>-</sup>). Since denitrification is a reduction process, it proceeds from a high oxidative state to a low oxidative state as seen below:



The primary driver of denitrification on agricultural soil is waterlogged, anaerobic soil conditions and the availability of nitrate. The denitrifying bacteria responsible for this stepwise reduction are normally found in all agricultural soils (Coyne, 2008).

Ammonium cannot be lost to denitrification. Ammonium must first be nitrified, and nitrification only occurs in well aerated soil conditions. Other sources of N such as ammonium nitrate are more likely to be rapidly lost to denitrification if the nitrate is not immediately assimilated by a actively growing crop.

N sources like urea are prone to denitrification loss if applied prior to planting and allowed to nitrify and then anaerobic soil conditions are encountered later in the growing season. However, if urea is not allowed to nitrify, prior to anaerobic conditions, it is not likely to be lost to denitrification. A prime example of this is the use of urea fertilizers just prior to flooding in rice production (3 weeks after planting). If urea is applied prior to planting typically a nitrification inhibitor is typically utilized (Tucker and Murdoch, 1984). Anhydrous ammonia applied prior to planting is less likely to be lost to denitrification than other N sources, ammonical or otherwise, due to its self inhibiting nature. The extreme changes in soil pH, coupled with free ammonia, drastically restrict the activity of nitrifying organisms. This “self

inhibiting” behavior reduces the risk of nitrification and subsequent denitrification losses if applied prior to planting. Nitrous oxide (N<sub>2</sub>O) has become product of interest in recent years as it has been linked to influencing global climate change according to the Intergovernmental Panel on Climate Change (2001).

### **Application Losses of Anhydrous Ammonia**

Ammonia can also be lost directly at application as Blue and Eno (1954) pointed out. These losses are generally composed of water, ammonia, and ammonium hydroxide. While the exact amount of ammonia lost at application varies tremendously, several factors can impact retention of AA including application depth, soil temperature, soil texture, CEC, soil moisture, pH, and tith. One of the side effects of injecting AA into soils is the incredible chemical changes that occur in the ammonia adsorption zones.

While the above factors play a role in sorption of AA, the factor that most directly controls retention of AA is the amount of soil contact during application. Blue and Eno determined that AA injection created zones along the application lines with high concentrations of ammonia that also had very high pH. Their work showed that at the application point, ammonia levels could be as high as 585 mg kg<sup>-1</sup> ammonia, with a pH of 9.1, when a 289 kg N ha<sup>-1</sup> rate was applied. When evaluating soil 3 inches to the right of this application line, ammonia concentration was 0 mg kg<sup>-1</sup> and pH was 5.7 at the same soil depth. They surmised that the retention zones of injected AA are not greater than 13 cm across, and that most of the ammonia will be confined to the immediate 8 cm of the zone. This creates soil conditions that are not conducive to the survival of soil microorganisms. Free ammonia, ammonia that has not attached to water molecules and made the transition to ammonium, is highly toxic to living organisms. It is this free ammonia that causes damage to the root systems of plants and the burning of foliage. This zone will also be temporarily devoid of soil microorganisms, but if ammonia applications occur when soils are below 10° C, the activity of the microorganisms would be minimal at best (Tisdale et al., 1985).

### **Ammonia Application Methods**

As previously mentioned, the initial design of AA application knives has not changed significantly in the last 70 years. The methods of metering, processing, delivering has

progressed rapidly, and moved in step with many of the advances in precision agriculture. One primary reason the design of these tools has not changed is that they are very simple and effective at making sure that AA is retained in areas where it is applied. However, knives are not the only tool for effectively delivering AA. Anhydrous ammonia has also been successfully applied behind sweep plows with multiple discharge points on the underside of the sweep blade (Matus et. al., 1999). This practice has also been used in conjunction with the application of a liquid P fertilizer, since ammonical forms of N has been shown to increase uptake of P (Blair et. al., 1970). The primary draw back to these methods of application is the amount of energy needed to move these implements through the soil at depths that will ensure adequate retention.

There have been alternatives to this design presented in recent years that utilize a large coulter wheel as a means of delivering AA to depths that will be sufficient to ensure adsorption. An offset closing wheel is placed behind the application coulter to close the application slot. This type of tool would offer several advantages and disadvantages to producers. It would allow the producer to operate at much higher speeds with lower energy requirement. It is also a less invasive tool than the traditional AA knife. Hanna et al. (2005) conducted research using a single disc AA injector on several different soil types and tillage systems. Losses of AA during application and after application were measured at multiple application depths and speeds. The testing of this new design had lower AA retention rates than a traditional knife type applicator, and was not yet ready to be considered a replacement for the knife type injector. The other conclusions they presented match much of what is known about the injection of AA with traditional knife type applicator. That loss tends to be greater in coarser textured soils than in fine textured soils, and that losses were generally lower at greater application depths. They also observed what Blue and Eno (1954) pointed out in the very early AA application research, that AA is more likely to gasify from its liquid state at higher temperature. This can have a drastic effect on the retention rates of AA in the soil. The designs of applicators are a constant and ever changing process, and research into the efficacy of these tools is ongoing.

### **Timing of Ammonia Applications**

Timing the applications of AA is a powerful management tool for many producers, and the versatility of application timing has also evolved to incorporate applications at planting, preplant, and sidedress. Traditionally, in the eastern corn belt, the advantage of fall applications

of AA was the ability to apply fertilizer in a time frame that did not coincide with tillage and planting preparation. It also allowed fertilizer dealers to spread out the sales of ammonia, and reduce the storage and transportation vessels needed for agricultural use.

The efficiency of N fertilizer applications is also dependant on timing. There has been extensive research conducted evaluating the practice of fall AA applications versus spring and sidedress. In a comprehensive review of the literature, Bundy (1986) concluded that fall applied AA is an acceptable practice in areas where winter temperatures retard nitrification and soil textures are fine to medium. Bundy (1986) also states that in some cases a 10 - 15% decrease in efficacy is seen when fall applied N is compared to preplant applications of N. This gap in nitrogen use efficiency between timings is largely the product of year to year variability in climate.

Since soil microorganisms are not active at low soil temperatures, significant nitrification of ammonia is not likely to occur over the winter if soil temperatures remain below 4.5° C. Because AA is primarily used in corn production, there is not a crop to actively take up this ammonium in the soil over the winter months. With the advent of spring and warmer temperatures, soil organisms and crops will begin to utilize this N.

However, there are certain parts of the Midwest where soil temperatures do not consistently stay low enough to restrict nitrification. Hageman (1980), states that the temperature at which most soil stops nitrifying ammonium is 4.5 degrees C. This is where the use of nitrification inhibitors such as nitrapyrin (2-chloro-6-(trichloromethyl)pyridine) or other nitrification inhibitors are especially useful. Nitrapyrin works as a bactericide by inhibiting the work of Nitrosomonas, but not interfering with the conversion of nitrite by Nitrobacter. The length of time that nitrapyrin will remain effective in retarding nitrification is dependant on several factors including organic matter, soil type, temperature, tillage, and soil moisture (Hauck, 1980). According to Keeney (1986), the half life of nitrapyrin is between 2 and 13 weeks. So, for many producers, nitrapyrin can provide insurance that their investment in N is not going to nitrify and be lost to leaching or denitrification prior to crop utilization. There are several caveats to the use of nitrapyrin products. The first being it is rather expensive, and may not be needed every year. It is also very corrosive to storage tanks and fittings, and as a result, is recommended to be injected into the manifold for distribution along with the AA instead of actually being mixed with AA in the tank. Keeney (1986) also makes some very salient points

about how nitrification inhibitors perform best in soil temperature that are not conducive to nitrification. He also concludes that while nitrapyrin is effective at restricting nitrification in late fall and early spring applications, its longer term efficacy is dependant of soil conditions like organic matter, soil temperature, or pH. The long term use of nitrapyrin has also raised some interesting questions about how these practices affect a soils long term ability to nitrify ammonium. The conclusions that Shi and Norton (2000) present indicate that soils with long term use of nitrification inhibitors have lower potential for nitrification than soils that have no history of inhibitor use.

By the 1950's, work began evaluating the feasibility of applying AA at, or just prior, to the planting of small grains in the Great Plains region. The primary concern in this practice was seedling injury due to the large amounts of free ammonia in the soil. This is still a valid concern, but not as much in wheat production as in corn due to the ability of wheat to produce tillers, and the lower N rates applied and closer applicator spacing used with wheat reducing the effective rate and ammonia concentration. This allowed the crop population to compensate to some extent for minor seedling damage. Studies looking at preplant applications of AA found that germination was reduced with N rates as low as  $14 \text{ kg N ha}^{-1}$  when soil moisture rates were low because there was not enough moisture in the soil for the ammonia to make the transition to ammonium (Olson and Dreier, 1956). But as Varvel (1982) demonstrates, lowered populations do not also equate to lower yield or grain quality. Varvel found that application placement was the key factor in applying AA prior to planting spring wheat, and that seed/AA separation distance of 5-11 cm. was adequate. Varvel's results also correlate with what earlier research suggested, that sufficient soil moisture was critical in successfully utilizing AA prior to planting. Matus et al. (1999) conducted studies that evaluated the prospects of one pass seeding and fertilizing using AA. There were two different application methods using a knife to side band and sweep wing tip applicator on the air seeder. These application methods differed greatly according to the amount of soil disturbance produced. The yields of the AA/seeding type operation were not different from the plots that were fertilized at seeding with ammonium nitrate or urea. Yield did not reflect serious crop injury even at the highest rate.

## **SUMMARY**

While there are certain caveats to the use of AA, it has still proved to be one of the most widely used fertilizers based on sheer economics. Anhydrous ammonia currently costs 50-60% less than UAN or urea, and is widely used despite concerns for safety and security. It allows producers to spread workload over different seasons, and if managed effectively, is an excellent N source for many of the crops produced in the Midwest and Great Plains. Nitrogen is the most limiting plant nutrient in our current system of modern agriculture due to its mobility and a lack of understanding on the part of producers as to how to effectively manage N fertilizers for maximum N use efficiency.

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## **CHAPTER 2 - Comparison of High Speed Low Draft Anhydrous Ammonia Applicator to a Traditional Knife Type Applicator in Irrigated Maize Production in Kansas.**

### **Abstract**

Corn production systems in the Midwest and Great Plains regions of the US have traditionally relied on anhydrous ammonia (AA) as a primary source of nitrogen (N) fertilizer. While AA is the most economical source of N, it also requires large amounts of energy to place the AA deep enough in the soil that there is little chance of loss through gaseous emissions. The John Deere Company has introduced a high speed, low draft nutrient (JD) applicator that is intended to reduce energy input and increase applications speeds, allowing producers to cover more area in a more timely fashion when compared to traditional applicators that rely on a AA knife (TRAD). The objectives of this study were to: 1) compare the gaseous emissions from both types of applicators, 2) determine quantitative post application emission losses across multiple N rates and timing of applications, and 3) determine if these losses have any impact on crop growth and yield.

In 2007, a limited study was used to evaluate and fine tune methodologies. No emissions data was collected in 2007. The main study was conducted in 2008 and 2009 under supplemental irrigation on a Rossville silt loam near Silver Lake, KS. Anhydrous Ammonia was applied at three different timings, at six N rates, and with both a traditional knife type applicator and with the JD high speed, low draft applicator. Emissions were collected three times over a 7-9 day period immediately following each application of AA in 2008 and 2009. Each year corn was grown following soybeans, and was managed in a no-till system. Profile nitrate soil tests ranged from 3.9 to 6.4 mg kg<sup>-1</sup> in the 0 to 61 cm soil layer. Both years, at all timings, there was a consistent increase in gaseous loss at all application timings as N rate increased for both applicators with losses ranging from 0.011 to 22.26 kg NH<sub>3</sub> ha<sup>-1</sup>. There was also a significantly greater amount of gaseous loss with the JD applicator than with the TRAD applicator. This was the result of extreme levels of loss at the high N rates with the JD applicator due to shallow placement depths. Soil moisture played a significant role in the retention of AA in soil.

However, none of this gaseous loss could be correlated to a decrease in grain yield, since the losses occurred at an N rate in excess of the optimum N rate.

## **Introduction**

How AA behaves when it is injected into agricultural soils has not been studied in recent years since it is generally accepted that if AA is placed 15-20 cm below the soil surface, losses will be minimal. Early work in this field focused on soil qualities such as soil texture, organic matter (OM), pH and application depth in laboratory and field experiments. Often this research was subject to contention due to the physical and chemical factors that affected AA retention and sorption in agricultural systems.

There are two commonly accepted ammonia adsorption mechanisms in soils, physical adsorption and chemisorption. Chemisorption is considered to be the most dominant force in retaining AA in the soil. Chemisorption primarily relies on the protonation of  $\text{NH}_3$  into  $\text{NH}_4^+$  from soil moisture. This protonation also helps to drive the physical sorption, as the by product of the protonation is an increase in soil pH. Physical adsorption also helps to explain how a soil is capable of retaining amounts of  $\text{NH}_3$  greater than its chemisorption capacity (Nommik and Vahtras, 1982). A soils titratable acidity to pH of 9 has been shown to have a 1:1 stoichiometric relationship with the physical ammonia retention capability of a soil (Izaurrealde, et al. 1987). This work pointed out that CEC played a lesser roll in physical sorption of  $\text{NH}_3$  than previously thought, but the increase in pH did increase the CEC, resulting in an increased adsorption capacity for  $\text{NH}_4^+$ . However, physical sorption is generally considered weak and temporal, as soil pH will decrease precipitously over the weeks following application. As pH decreases, the  $\text{NH}_3$  that was physically adsorbed can be lost to diffusion from the application zone (Parr and Papendick, 1966). This may help explain why significant amounts of ammonia may be lost over time following applications in dry soils.

The early research of Jackson and Chang (1947) conducted in controlled laboratory environments generally focused on soil chemical properties, and regarded factors like soil moisture and texture as secondary to soil chemical properties. This conflicted with the work of several other researchers (Stanley and Smith. 1956, McDowell and Smith., Swart, et al. 1971) who concluded that soil moisture could play a large role in the retention of AA in sandy soil, if

the soils were excessively wet, or if the depth of application was especially shallow in laboratory studies.

Field research into the retention of anhydrous ammonia in direct application was first conducted in sandy coastal plain soils. This work evaluated the movement and retention of AA, and determined that the greater the amount of soil that AA comes in contact with, the greater the probability it will not be lost as gaseous emissions (Blue and Eno, 1954). Stanley and Smith (1956) conducted laboratory experiments to evaluate the effect of soil moisture and depth of placement on the retention of AA. They found that AA retention was high when soils were at optimum moisture content in a Putnam silt loam, or when placed in air dry soils at least six inches deep. Stanley and Smith also raised the issues of applying AA when soils are too wet, and found that often wet soils tended to lose ammonia gradually as the soils dried and ammonia moved upward. McDowell and Smith (1958) further expounded this work in heavier textured soils, and found that increased clay content raised a soil's ability to absorb agriculturally applied AA. This work also pointed out the high level of variability that is present in field scale application of AA.

Very little work has been done evaluating the efficacy of single disc, low draft AA applicators. Hanna et al. (2005) evaluated a similar applicator, but only evaluated the level of loss during application and in the 70 minutes immediately following application. They concluded that losses were significantly greater in, coarser and drier, sandy soils than in heavier, finer textured soils when using a single disc applicator compared to a TRAD applicator.

## **Materials and Methods**

A preliminary study that evaluated plant stands, N uptake, and grain yield was conducted in the spring of 2007 at a upland location in Willard, KS (39° 5' 36" N, 95° 56' 27" W). The plots were arranged in the field as four replicated blocks with treatments arranged within the blocks using a split plot design, with two application timings, pre-plant and side-dressed, serving as main plots, and applicator and N rate randomized within timing as subplots. Five N application rates were used, of 0, 90, 134, 179 and 224 kg N ha<sup>-1</sup> for both the high speed applicator and the traditional applicator. A 45 kg application rate was planned, but a rate that low was not able to be applied with the equipment provided.

The primary irrigated site was established in the fall of 2007 near Silver Lake, Kansas (39°5' 52"N, 95° 49' 33"W) in a center pivot irrigated field that was split east and west between corn and beans. In the 2008 growing season, the site was on the west side of the pivot, and in 2009 the site was on the east side of the pivot. Treatment structure consisted of three separate application timings, Fall (FALL), Spring preplant (PRE), and Sidedress (SD) in a split plot arrangement of a randomized complete block design. Both applicators applied AA at six N rates of 0, 45, 90, 134, 179 and 224 kg N ha<sup>-1</sup> at each of the above timings. Depth, placement method, and speed of application for each applicator can be found in Table 2.1. Plot size was 3.0 by 76 meters. All collection and harvest data was collected from the center two rows 45 to 60 meter area of the plot. This allowed application equipment to get up to speed and equilibrate. Plot areas were managed using no-till techniques. Application dates and cultural practices are listed in Table 2.2. Soils present are listed in Table 2.3.

Sidedress ammonia applications were made at the V-6 growth stage, with both applicators configured for an every-other row application, applying an effectively doubled rate in bands centered between the first and second and third and fourth rows of the plot. Plots were carefully observed for visual damage to vegetation from leakage of ammonia following application.

**Table 2.1 Description of applicators and methodology**

Applicator	Placement Depth (cm)	Application Speed (km/hr)	Method of placement
TRAD	20	9.6	Knife with 2 sealing wings
JD	11	16	Rolling Coulter
Timing	Spacing (cm)	Orientation	
Fall	75	Under the row	
Spring Preplant	75	Under the row	
Sidedress	150	Row Middle	

**Table 2.2 Cultural practices and application dates.**

Year	2007	2008	2009
Location	Willard, KS	Silver Lake, KS (West of Pivot)	Silver Lake, KS (East of Pivot)
Fall Application Date	N/A	17-Nov	19-Nov
1st Extraction Date	N/A	19-Nov	20-Nov
2nd Extraction Date	N/A	23-Nov	23-Nov
3rd Extraction Date	N/A	26-Nov	26-Nov
Spring Application Date	30-Apr	15-Apr	22-Apr
1st Extraction Date	N/A	16-Apr	24-Apr
2nd Extraction Date	N/A	20-Apr	26-Apr
3rd Extraction Date	N/A	22-Apr	28-Apr
Planting Date	14-May	2-May	11-May
	Golden Harvest H-9006 BT	Producers 7624 VT3	Producers 7624 VT3
Hybrid			
Maturity	112 day	116 day	116 day
Sidedress Date	18-Jun	16-Jun	19-Jun
1st Extraction Date	N/A	17-Apr	22-Jun
2nd Extraction Date	N/A	18-Apr	24-Jun
3rd Extraction Date	N/A	23-Apr	28-Jun
Supplemental Irrigation	NA	89mm	89mm
Harvest Date	27-Oct	30-Oct	17-Oct

**Table 2.3 Description of soils (0-15 cm) present at study sites**

Year	Soil Series	Taxonomic Class	pH	OM g kg <sup>-1</sup>	Nitrate	P mg kg <sup>-1</sup>	K
2007	LadySmith Silty Clay Loam	Fine, smectitic, mesic Udertic Argiustolls	6.1	12	15.2	15	200
2008	Rossville Silt Loam	Fine-silty, mixed, superactive, mesic Cumulic Hapludalls	7.2	19	11.3	11.5	335
2009	Rossville Silt Loam	Fine-silty, mixed, superactive, mesic Cumulic Hapludalls	6.9	19	9.5	12.5	397

## Ammonia volatilization

Numerous methods for measuring ammonia volatilization have been employed, and most vary as to the amount of air flow over the plot during collection. This study used a static method similar to that used by Beyrouty et al. (1987) and Nommik (1965).

The NH<sub>3</sub> trapping chambers were constructed of 20 gauge sheet metal with outer dimensions of 30.5 cm x 17.8 cm x 10.2 cm (L x W x H). Within this chamber 2 pieces of foam (model PF1, [www.foamdistributing.com](http://www.foamdistributing.com)) were suspended to trap volatilizing ammonia. The upper piece of foam served as a buffer to prevent atmospheric contamination, while the lower piece of foam served to trap volatilizing AA. Foam was cut to snugly fit inside of each trap.

Polyurethane foam that was used was 2.54 cm thick and had a density of 0.24 g cm<sup>-3</sup>. Two pieces of foam were placed in a sealed bag along with 100mL of solution of 0.7 M H<sub>3</sub>PO<sub>4</sub> in 50% glycerol. The bag was then squeezed several times to assure that the solution was absorbed by the foam. Once in the field, the two pieces of foam were placed in the traps. Immediately following NH<sub>3</sub> application, two acid traps per plot were centered directly over the application slots over the row parallel with the direction of travel. The traps were then firmly pressed into the ground over the application slot so to not allow any atmospheric disturbance.

The foam in the traps was changed every 24 to 96 hours. The lower piece of foam was immediately placed in a sealable plastic bag, and the trap was reloaded with fresh acid soaked foam. Three collections were made over the period of a week after the FALL, PRE, and SD applications starting in with the FALL 07 through SD 09. The Fall 07 timing only evaluated the 0, 179 and 224 kg N ha<sup>-1</sup> rates, while all other timings evaluated all six N rates. The location of the traps in each plot remained static throughout the collection period. If there was a likelihood of precipitation, shower caps were placed over the traps to prevent water from saturating the foam.

The NH<sub>4</sub><sup>+</sup> that was contained in the collected sponge was extracted using two washings of 100 mL of 2 M KCl solution. Potassium chloride was dispensed into the bag containing the ammonia retaining foam, then the bags were manipulated to assure complete equilibration. The extractant solution was then squeezed into a volumetric cylinder, and brought up to a standard volume of 250 ml. An aliquot was taken from this 250 ml sample and analyzed using an



indophenol colorimetric reaction as described by Alpkem Corporation. (1986) (RFA Methodology No. A303-S021. Ammonia Nitrogen. Clackamas, OR 97015). Gravimetric soil moisture content was calculated at application times using DSSAT.

### **Tissue Sampling and Analysis**

Fifteen ear leaves were collected for N analysis at the early silking growth stage (R1) each year. Shortly after black layer, ten plants were collected from the first and fourth rows of each plot to estimate the amount of plant biomass and the N content of the stover at physiological maturity. These samples were dried at 60°C and ground to pass through a 0.5 mm stainless steel sieve. Tissue samples were analyzed for N after digestion using H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O<sub>2</sub> (Linder and Harley, 1942; Thomas et al., 1967). Concentrations in the digest sample were measured with a Rapid Flow Analyzer (Model RFA-300) using RFA methodology No. A303-S072 for Total Kjeldahl N (Alpkem Corporation. Clackamas, OR 97015). Total N uptake of the above ground plant was determined by combining the N content in the stover and the N content in the grain.

### **Grain Yield and Analysis**

Yield was determined by mechanically harvesting the center 2 rows of the 45-60 meter area of the plots. Yields were adjusted to 155 g kg<sup>-1</sup> moisture content. A sub-sample was collected, dried and ground to pass through a 0.5 mm stainless steel sieve. Grain analytical methods were identical to tissue methods given above.

### **Statistical Analysis**

Data for gaseous losses, population, and yield were analyzed using the MIXED Procedure in SAS (SAS, 2004). Data was analyzed separately each year. All LSDs are calculated at probability level of 0.05 with the GLM Procedure.

## **Results and Discussion**

### **Gaseous AA Emissions**

Soil moisture and depth of placement directly influenced the retention of AA applied. When AA was applied at an 11cm depth with the JD applicator, losses were significantly greater than when applied at depths of 20 cm with the TRAD applicator, especially at higher N rates. Losses with the shallow placement were especially high during the times when soils were dry. Table 2.4 shows the levels of gaseous loss at each time of AA application. Extremely low levels of loss typically occurred when AA was applied into optimum soil moisture conditions. As soil moisture decreased below  $0.16 \text{ cm}^3/\text{cm}^3$ , the rate of AA loss increased. Figures 2.1 and 2.2 show applicator\*rate interactions for low (moist) and high (dry) loss timings. The shallow placement method had significantly greater levels of loss at all rates, and at all timings.

The application times that typically had the greatest levels of loss at high N rates were FALL 07, FALL 08, and PRE 08 (Figure 2.2). The PRE 08 application had the greatest amount of loss of all application timings, followed by the two FALL applications. These timings were marked by extremely high losses of ammonia at the  $224 \text{ kg N ha}^{-1}$  rate when applied with the JD applicator. Occasionally losses over time would equal 10% of the applied N rate. The SD 08, SD 09 and PRE 09 were marked by very minimal losses even at the highest N rates as seen in Figure 2.1.

The effect of AA loss due to width of applicator spacing was also evaluated by comparing the SD treatment with 150 cm wide spacing to that of FALL and PRE applications with 75cm wide spacing. The SD application effectively doubled the rate being applied to the same application slot, however the main effects of application timing across all rates and both applicators do not reflect any significant losses compared to the FALL and PRE applications. Soil moistures during SD in both years were above  $0.16 \text{ cm}^3/\text{cm}^3$ , and as a result the potential for loss was very low even at extremely high N rates and shallow application. The seven day period following SD application was also marked by significant precipitation events that may have quenched any free ammonia that would have been prone to loss through volatilization.

Applicator\*N rate interaction at every timing is due to low levels of variation present between applicators at low N rates as seen in Figures 2.3, 2.4, 2.5, and 2.6.

**Table 2.4 Gaseous ammonia loss data by application timing, method of placement and N rate.**

Source of variation		FALL 07	PRE 08	SD 08	FALL 08	PRE 09	SD09
		kg NH <sub>3</sub> ha <sup>-1</sup>					
Applicator							
	JD	1.72A	2.34A	0.09A	1.07A	0.25A	0.06A
	TRAD	0.04B	0.24B	0.02B	0.16B	0.08B	0.01B
	LSD (0.05)	0.41	0.67	0.04	0.27	0.1	0.02
N Rate kg N ha-1							
	0	0.02C	0.02B	0.02C	0.03B	0.05C	0.01C
	45	NA	0.03B	0.02C	0.04B	0.03C	0.01C
	90	NA	0.13B	0.03BC	0.19B	0.04C	0.02C
	134	NA	0.97B	0.03BC	0.44B	0.16BC	0.02C
	179	0.91B	2.83A	0.10AB	1.34A	0.22B	0.06B
	224	1.70A	3.78A	0.17A	1.65A	0.49A	0.09A
	LSD (0.05)	0.5	1.16	0.07	0.47	0.17	0.03
APP*RATE		NS	<0.001	NS	<0.001	<0.001	<0.001
		Total Mean Loss kg NH <sub>3</sub> ha <sup>-1</sup>					
JD	0	0.06	0.05	0.06	0.09	0.15	0.04
	45	NA	0.09	0.11	0.15	0.11	0.03
	90	NA	0.48	0.09	1.13	0.15	0.11
	134	NA	4.86	0.12	2.01	0.90	0.09
	179	5.42	14.52	0.43	8.35	0.97	0.35
	224	10.03	22.26	0.97	9.84	2.88	0.57
Trad	0	0.05	0.09	0.03	0.09	0.18	0.04
	45	NA	0.12	0.08	0.10	0.15	0.03
	90	NA	0.34	0.07	0.17	0.13	0.03
	134	NA	0.98	0.06	0.98	0.22	0.02
	179	0.05	2.49	0.10	0.70	0.53	0.04
	224	0.22	0.45	0.10	1.26	0.46	0.04

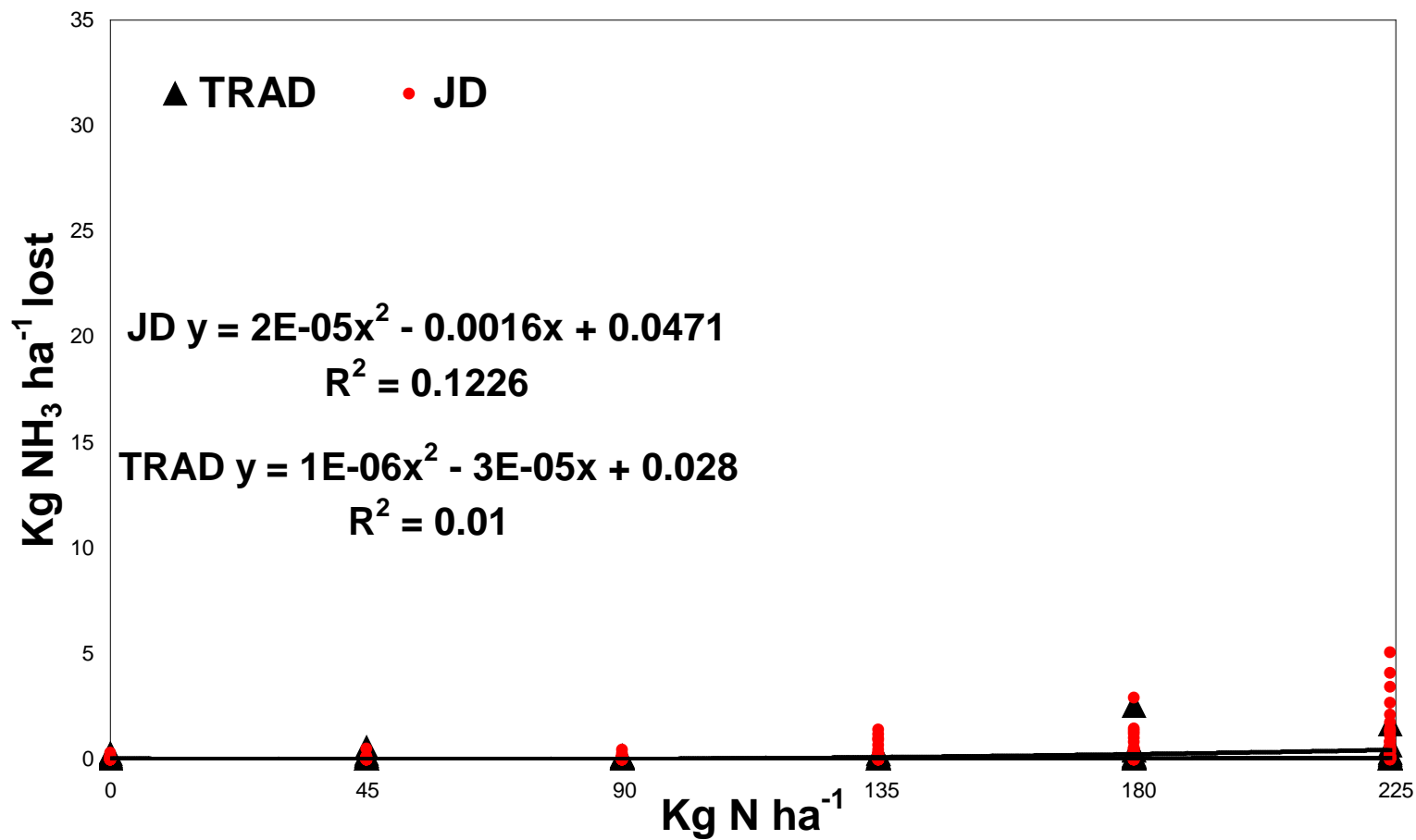


Figure 2.1 Levels of NH<sub>3</sub> lost at SD 08, Pre 09, and SD 09 between applicators at all collection times when soil moisture was above 0.16 cm<sup>3</sup>/cm<sup>3</sup>.

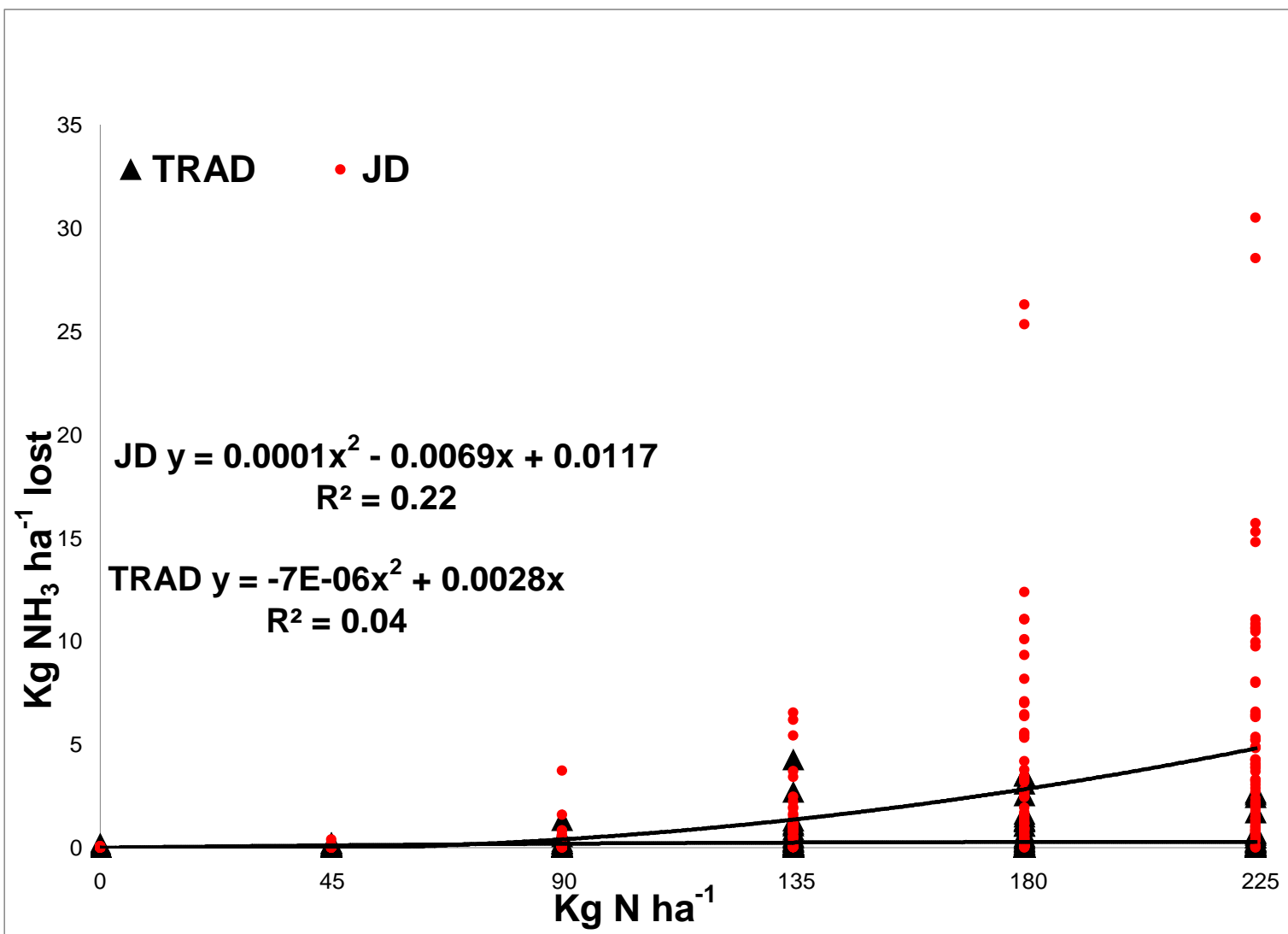
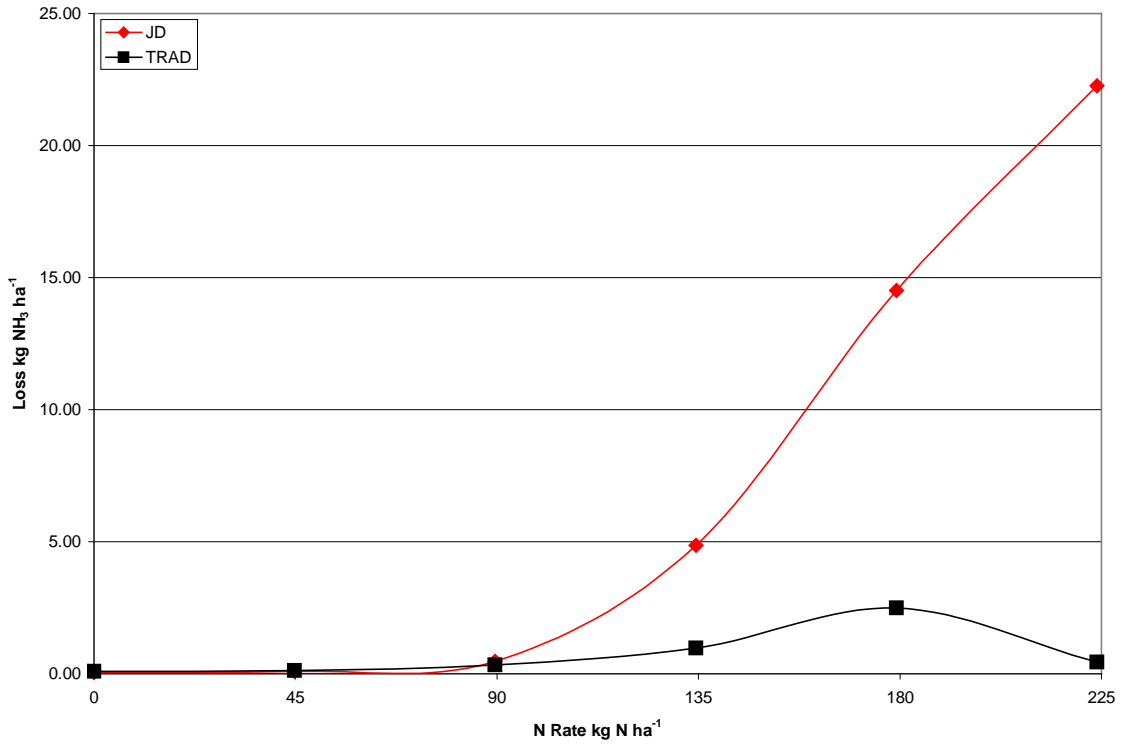


Figure 2.2 Levels of NH<sub>3</sub> lost at FALL 07, PRE 08, and Fall 08 between applicators at all collection times when soil moisture was below 0.16 cm<sup>3</sup>/cm<sup>3</sup>.

**Figure 2.3 Applicator\*N rate gaseous AA loss interaction means for PRE 08.**



**Figure 2.4 Applicator\*N rate gaseous AA loss interaction means for Fall 08.**

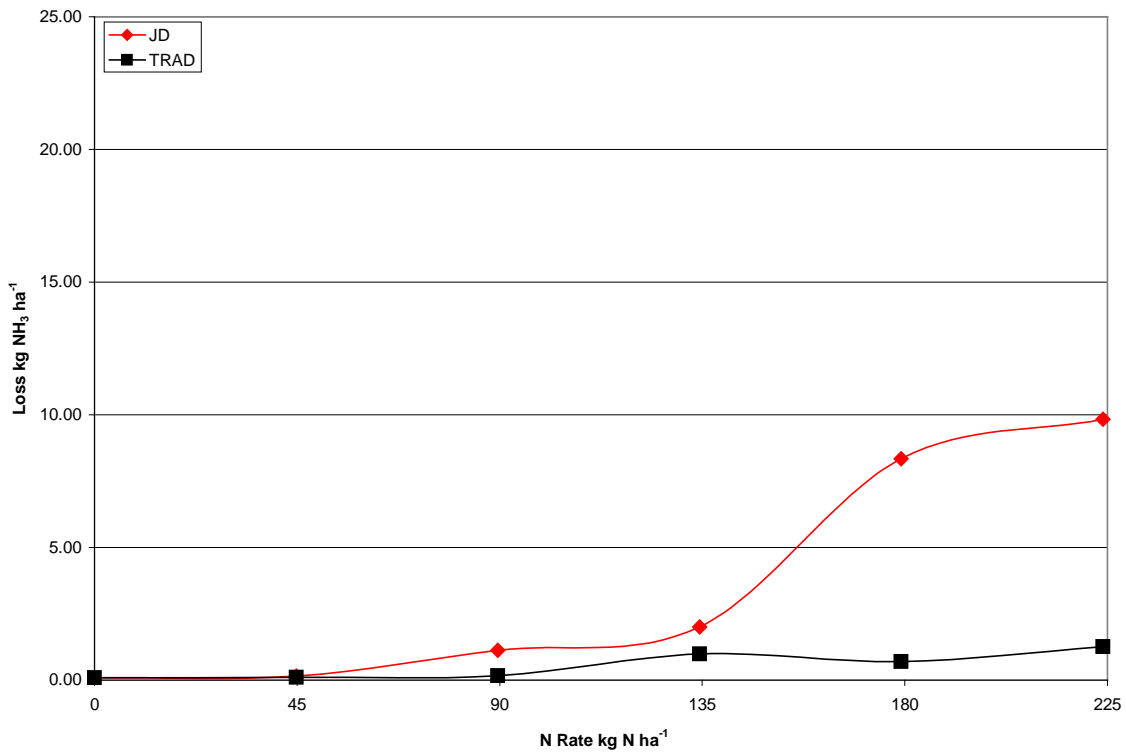


Figure 2.5 Applicator\*N rate gaseous AA loss interaction means for PRE 09.

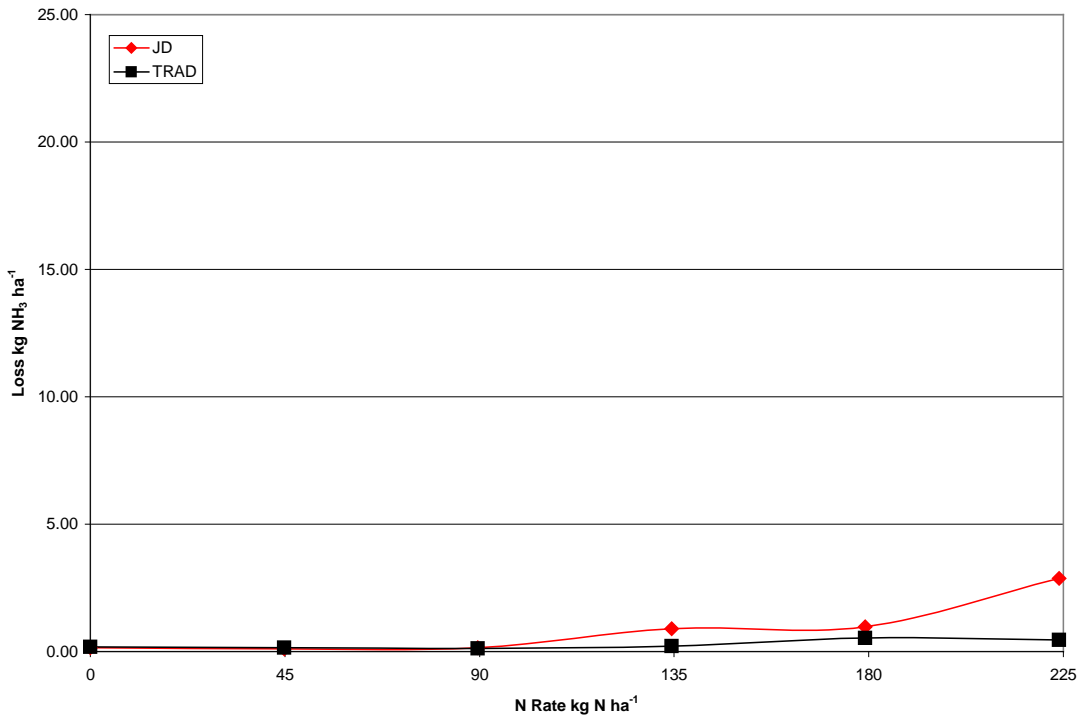
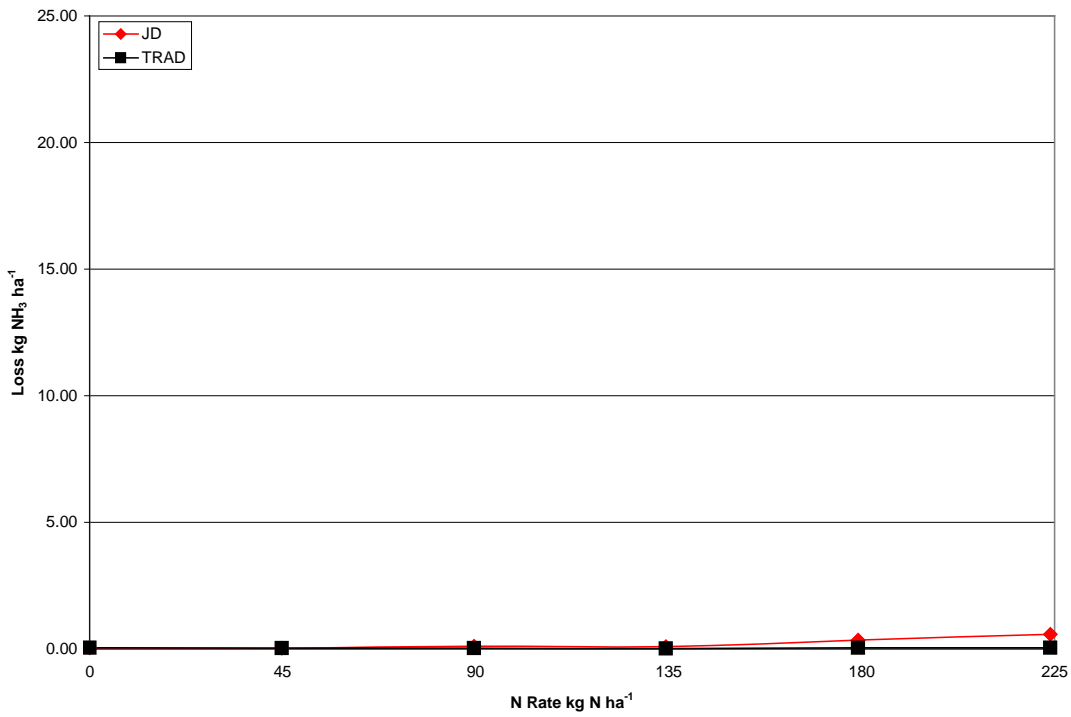


Figure 2.6 Applicator\*Nrate gaseous AA loss interaction means for SD 09.



## **Corn Plant Populations**

There were no significant differences in plant population between applicators in any year. There were also no significant N Rate\*Applicator interactions in any year. In 2007 the populations were significantly lower at the 90 kg N ha<sup>-1</sup> rate with both applicators than with other N rates. No explanation for this observation is provided. Plant population effects of applicators, N rates, and years are summarized in Table 2.5.



**Table 2.5 Plant populations as affected by N rate and applicator.**

		2007	2008	2009
		Population 10000 plants ha <sup>-1</sup>		
JD	N Rate			
	0	5.28	7.84	7.91
	45		7.53	8.12
	90	4.99	7.66	8.07
	134	5.15	7.53	8.07
	179	5.24	7.71	8.00
Trad	N Rate			
	0	5.24	7.80	7.90
	45		7.63	7.98
	90	4.82	7.73	7.97
	134	5.09	7.72	8.00
	179	4.97	7.57	7.98
Rate	N Rate			
	0	5.26	7.8	7.9
	45		7.6	8.04
	90	4.9	7.7	8.01
	134	5.11	7.7	8.03
	179	5.1	7.6	7.99
LSD (.05)		NS	NS	NS
	Applicator			
	JD	5.13	7.7	8
	Trad	5.05	7.7	7.98
	LSD (.05)	NS	NS	NS
		Pr > F		
Time		0.0009	NS	NS
Applicator		NS	NS	NS
Rate		NS	NS	NS
Time*Nrate		NS	NS	NS
Applicator*Nrate		NS	NS	NS
Applicator*Time		NS	NS	NS
Time*Applicator*Nrate		NS	NS	NS

### Earleaf N Content

N applications significantly increased earleaf N content in all three years of the study, with earleaf N maximized at the 179 to 224 kg N rates (Table 2.6) There were no significant

differences in earleaf N content between applicator in any year. There were no significant N Rate\*Applicator interactions in any year. Interactions involving application timing are addressed in chapter 3.

**Table 2.6 Earleaf N content as affected by N rate and applicator**

		2007	2008	2009
N Rate		Earleaf N g kg <sup>-1</sup>		
JD	0	21.0	19.6	18.0
	45		21.5	21.1
	90	30.5	23.5	22.8
	134	31.6	24.0	24.5
	179	31.9	24.2	25.7
	224	33.0	24.5	25.7
	Trad	0	21.9	20.2
45			21.8	22.0
90		31.7	23.1	23.1
134		31.6	23.5	24.4
179		31.6	24.0	25.6
224		32.3	24.4	25.0
Rate		0	21.4C	19.9D
	45		21.6C	21.5D
	90	31.1B	23.3B	22.9C
	134	31.6AB	23.8AB	24.4A
	179	31.8AB	24.1AB	25.6A
	224	32.7A	24.4A	25.3A
	LSD (.05)	1.38	1.10	1.2
Applicator	JD	29.6	22.9	23
	Trad	29.8	22.8	22.8
	LSD (.05)	NS	NS	NS
		Pr > F		
Time		0.0047	0.002	0.0067
Applicator		NS	NS	NS
Rate		<.0001	<.0001	<.0001
Time*Nrate		NS	NS	<.0001
Applicator*Nrate		NS	NS	NS
Applicator*Time		NS	0.0219	NS
Time*Applicator*Nrate		NS	NS	NS

## Grain Yield

There were no significant differences in grain yield due to applicator in 2007 or in 2008. However, in 2009 there was a significant difference between applicators with the TRAD applicator producing higher yields than the JD applicator by 0.42 Mg grain ha<sup>-1</sup>. There were no significant N Rate\*Applicator interactions in 2007 or 2008, however there was a significant N Rate\*Applicator and N Rate\*Time\*Applicator interaction in 2009. In 2009 much of these interactions can be attributed to a reduction in yield at the highest N rate with the JD applicator at SD, as compared to the TRAD applicator. A significant amount of tissue damage occurred with the SD application with the JD applicator at the 224 kg N ha<sup>-1</sup> rate due to high levels of ammonia loss during application, but not during the time period following application. The impact of damage at high N rates with the JD SD compared to all other timings is shown in Figure 2.7. There was a significant response to N up to the 90, 179, and 134 kg N ha<sup>-1</sup> in 2007, 2008, and in 2009, respectively (Table 2.7). The yield and N response in 2007 was limited by low rainfall.

**Table 2.7 Grain yield as affected by N rate and applicator.**

		2007	2008	2009
		Grain Yield Mg ha <sup>-1</sup>		
	N Rate			
JD	0	6.28	9.44	9.69
	45		11.12	11.47
	90	8.46	12.61	12.80
	134	8.24	13.15	13.30
	179	8.46	13.39	12.35
	224	7.77	13.08	12.29
	Trad	0	6.91	9.31
45			11.34	11.53
90		8.58	11.75	12.88
134		8.55	13.01	13.41
179		8.12	13.71	13.30
224		8.20	13.33	13.74
Rate		0	6.59C	9.37E
	45		11.22D	11.50B
	90	8.52A	12.17C	12.84A
	134	8.39AB	13.08B	13.35A
	179	8.28AB	13.54A	12.82A
	224	7.98B	13.20AB	13.02A
	LSD (.05)	0.44	0.45	0.55
Applicator	JD	7.97	12.1	11.98B
	Trad	8.07	12.1	12.40A
	LSD (.05)	NS	NS	0.32
		Pr > F		
Time		NS	0.0121	NS
Applicator		NS	NS	0.0105
Rate		<.0001	<.0001	<.0001
Time*Nrate		NS	NS	NS
Applicator*Nrate		NS	NS	0.0346
Applicator*Time		NS	NS	NS
Time*Applicator*Nrate		NS	NS	0.0533

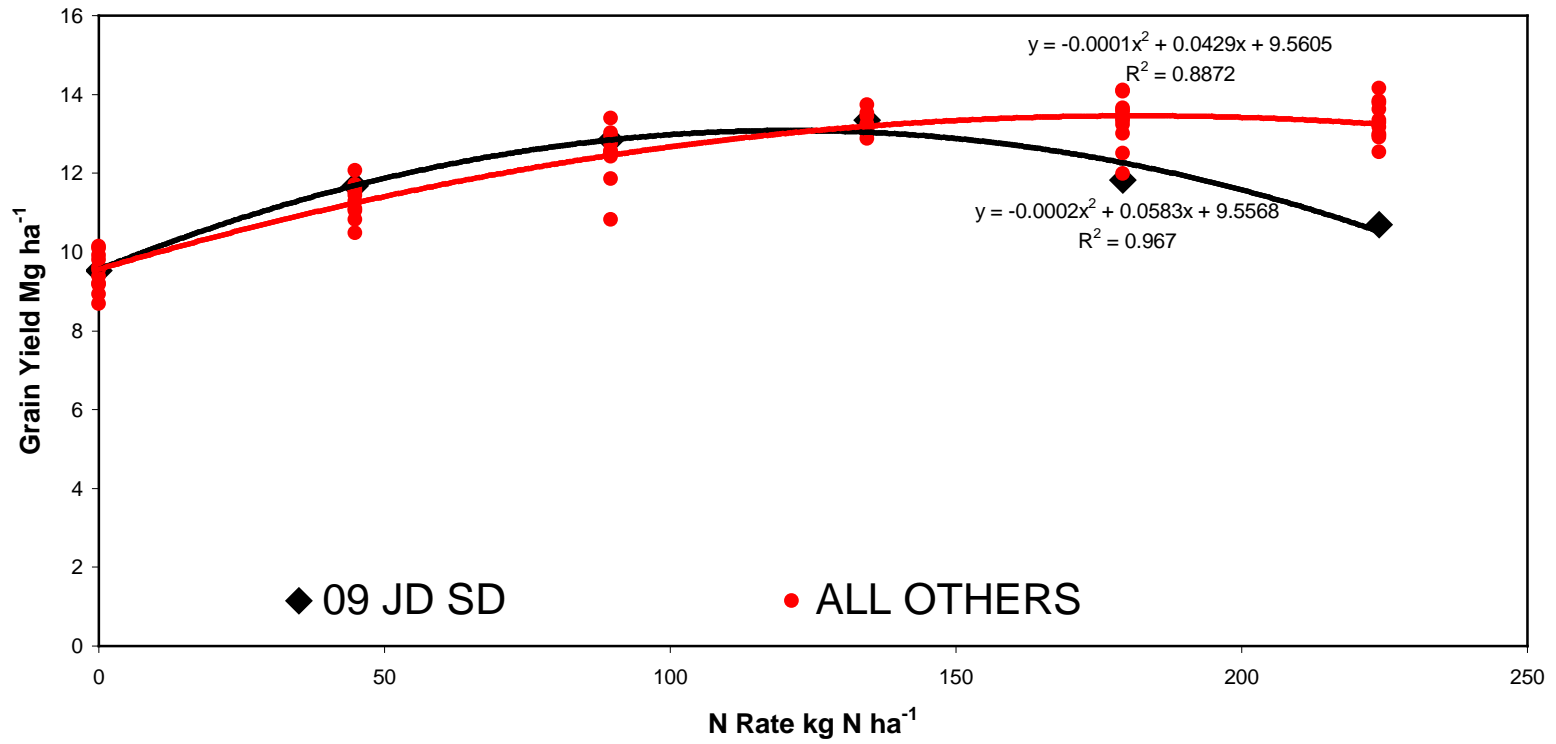


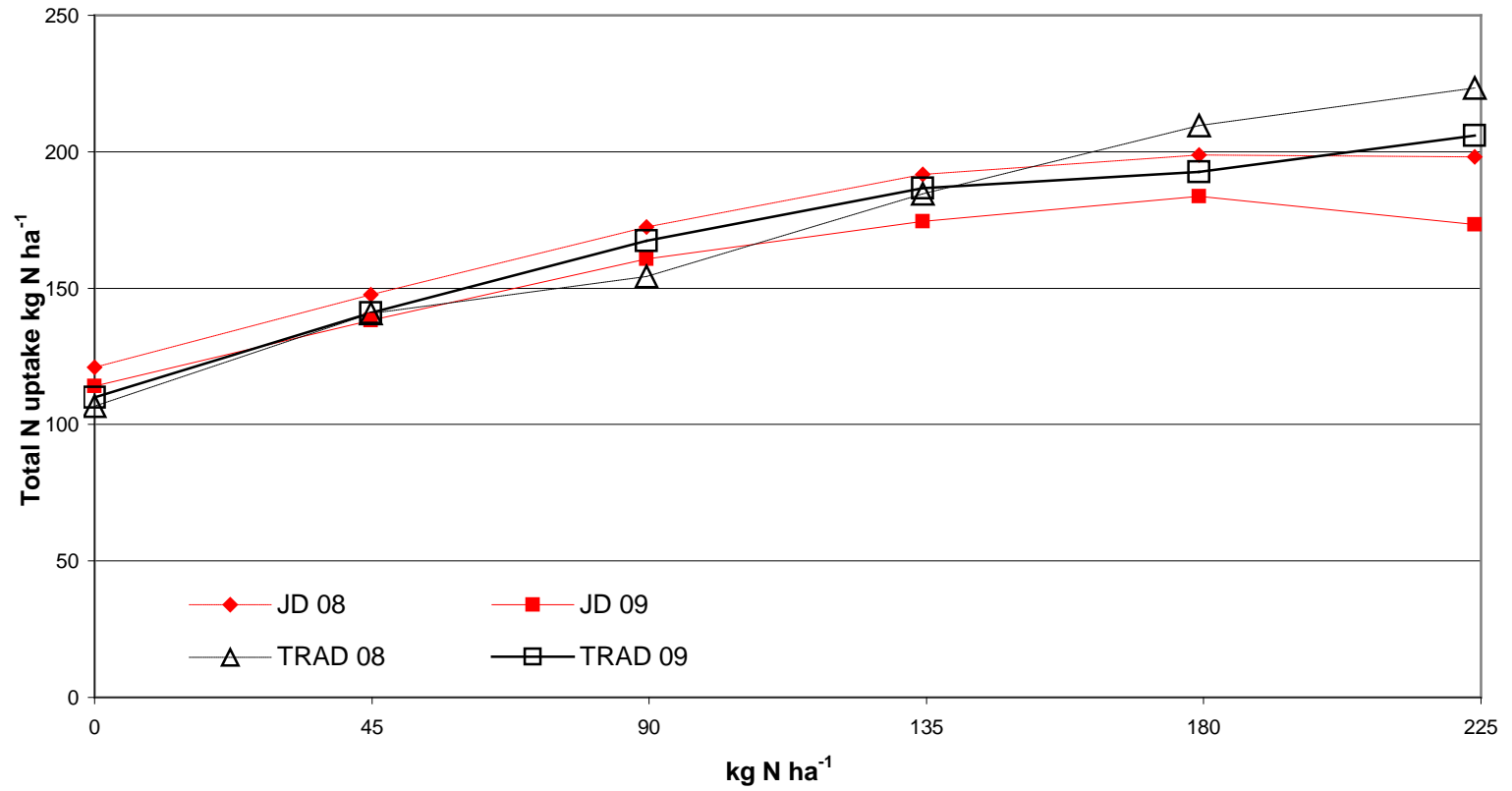
Figure 2.7 Grain yield effect of 2009 JD SD application AA losses.

## **Total N Uptake**

In 2007 the TRAD applicator resulted in significantly greater total N plant uptake than with the JD applicator. This was particularly noticeable at the lower N rates, though there was no N Rate\*Applicator interaction. This can be explained by the lower levels of N uptake at the lower N rates with the JD applicator in 2007. In 2008 there was no significant difference between applicators with regard to total N uptake, and a significant increase in total N uptake up to 224 kg N ha<sup>-1</sup>. However, in both 2008 and in 2009, there was a significant N rate\*applicator interaction since at 0 and 45 kg N ha<sup>-1</sup> rates the plots where the JD applicator had greater levels of N uptake, while at the 179 and 224 kg N ha<sup>-1</sup> rates the plots where the TRAD applicator had greater levels of N uptake as observed in Figure 2.8. In 2009 this interaction was primarily caused by the severe tissue damage from the SD application at high N rates with the JD applicator.

**Table 2.8 Total N uptake as affected by N rate and applicator.**

		2007	2008	2009
N Rate		Total N Uptake kg N ha <sup>-1</sup>		
JD	0	89.0	121.1	114.2
	45		147.7	138.1
	90	137.6	172.5	160.7
	134	135.3	191.7	174.5
	179	145.2	198.9	183.7
	224	134.6	198.1	173.3
	Trad	0	95.9	106.8
45			140.6	140.9
90		152.7	154.3	167.4
134		140.5	184.6	186.6
179		145.8	209.7	192.5
224		137.6	223.3	206
Rate		0	92.4C	113.9E
	45		144.2D	139.5C
	90	145.1A	163.4C	164.0B
	134	137.9B	188.2B	180.6A
	179	145.5A	204.3A	188.1A
	224	136.1B	210.7A	189.6A
	LSD (.05)	6.0	11.1	9.1
Applicator	JD	128.2B	171.7	157.2B
	Trad	134.5A	169.9	167.2A
	LSD (.05)	3.9	NS	5.3
		Pr > F		
Time		<.0001	0.0723	NS
Applicator		0.011	NS	0.0004
Rate		<.0001	<.0001	<.0001
Time*Nrate		NS	NS	NS
Applicator*Nrate		NS	0.0007	0.0004
Applicator*Time		NS	NS	NS
Time*Applicator*Nrate		NS	NS	0.0776



**Figure 2.8 Applicator\*N Rate interaction effects in 2008 and 2009.**



## Conclusion

Depth and method of placement significantly impacted AA loss. Applications made with the JD applicator had consistently greater post application emission losses at higher N rates than the TRAD applicator. However, the high level of N loss at high N rates did not correspond to significant differences in any plant growth parameters with the exception of total N uptake in 2007 and grain yield in 2009. The losses of AA over a 7-9 day period following application, while statistically significant, were not of agronomic significance, primarily because these losses occurred at N rates above optimum for yield. Post application N loss of applied ammonia was a product of application timing and the soil conditions at the time of application. The FALL 07, PRE 08 and FALL 08 timings which had greater levels of loss, were all periods of lower soil moisture. This would agree with the observations presented by Stanley and Smith (1958) and Blue and Eno (1954), regarding the importance of adequate depth of placement if soil moisture was less than optimal. The shallow application of AA with the JD applicator at the 179 and 224 kg N ha<sup>-1</sup> rate led to very high levels of loss compared to the TRAD applicator, which placed AA almost twice as deep in the soil.

The high levels of AA loss at high N rates did not result in yield reductions with the possible exceptions of in the 2009 JD SD application. This was due to the high post emerge losses occurring only at N rates above those needed to optimize yield. In the 2009 SD situation, the quantifiable post application emission losses were negligible during this period, however significant visual gassing, or AA loss was observed at application. This is possibly due to excessively high soil moisture content and smearing of the soil sidewall during application as hypothesized by Stanley and Smith (1956) and Blue and Eno (1956). These results clearly show the importance of soil moisture conditions at the time of application especially if application depth is less than 15 cm. If moisture conditions are such that a producer would not be comfortable planting due to sidewall compaction, then the producer may encounter application gassing loss with shallow placed ammonia which could result in tissue damage and yield reductions at SD time.

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## **CHAPTER 3 - Effect of Timing and Rate of Nitrogen Application on the Nitrogen Utilization and Yield of Maize.**

### **Abstract**

The timing of nitrogen (N) application is a very important component in the production of corn in the Midwest and Great Plains regions. Producers often find it necessary to apply N in the fall preceding a corn crop, rather than attempting to fertilize just prior to planting or at sidedress due to time constraints.

The objectives of this study were to: 1) Evaluate the effect of N rate on population, earleaf N content, whole plant N uptake and grain yield and 2) Compare the effects of when the fertilizer N is applied (fall, spring preplant or sidedress) on N recovery and utilization and yield. The fertilizer was applied as anhydrous ammonia, with two different types of applicators: a high speed, low draft prototype applicator that is currently marketed by The John Deere Company (Model 2510) and a traditional knife type applicator. Since few significant agronomic differences have been seen between the applicators, all data were grouped together without regard to applicator unless otherwise noted.

To evaluate the agronomic efficiency of Fall Preplant (FALL), Spring Preplant, (PRE), and Sidedress (SD) N application timings, six N rates ranging from 0 to 224 kg N ha were applied in dryland (2007) and irrigated (2008 and 2009) environments in the Kansas River Valley. FALL timing was delayed until soil temperatures were consistently below 10° C, in the last two weeks of November. PRE applications were scheduled 2 weeks prior to proposed planting date. SD application occurred between V4 and V8 growth stages.

In the rainfall limited year, 2007, response to N was maximized for grain yield and Total N uptake at the 90 kg N ha<sup>-1</sup> rate, and there was no difference between application timings. The optimum N rate was 179 and 134 kg N ha<sup>-1</sup> in 2008 and 2009 respectively. In 2008 the PRE application timing proved to be statistically greater than the FALL or SD in total N uptake, and greater than SD in grain yield. In 2009 there was no difference in application timings for grain yield.

## Introduction

Anhydrous ammonia is one of the primary sources of N fertilizer in the Midwest and the Great Plains due to its low cost and “self-inhibiting” behavior. The direct application of AA into agricultural soils and the resulting protonation of the ammonia, causes a spike in soil pH in the 10 cm immediately surrounding the application zone. Free ammonia that might not be converted to ammonium immediately is also highly toxic to soil dwelling organisms. This drastically restricts the activity of the microbial populations that are responsible for nitrification (McIntosh and Frederick, 1958; Nommick and Nilsson, 1963).

The ability to place fertilizer below the soil surface is especially important in NT production systems, due to the likelihood of immobilization and loss of surface applied N fertilizers in high residue situations through volatilization (Mengel et. al., 1982). In NT systems, there also exists the potential for greater levels of loss due to leaching and denitrification, due to increased soil water content (Thomas et al. 1973). This is of greater concern in areas with sandy soils or where precipitation exceeds crop water use.

Anhydrous ammonia is commonly used for fall N application to corn since nitrification and the potential for loss are reduced once soil temperatures are below 10° C (Keeney, 1982). There has been extensive research on the impact of the timing of N fertilization using AA. The general conclusion is that N should be applied when the crop is actively taking up N due to the risk of leaching and denitrification losses prior to crop uptake.

Most of this work has been done in the northern and eastern corn belt where spring precipitation creates cool, wet soil conditions around planting. Soil conditions in this region are often more favorable for N applications in the fall, and it allows producers to spread out workload away from the busy planting season (Bundy, 1986; Randall and Schmitt, 1998). Aldrich (1984) stated that FALL applied AA was generally 75 to 90% as effective as Spring applied AA. This observation also agrees with what several researchers found; that Fall application is an acceptable practice, if applied to medium to fine textured soils after soil temperatures have dropped below 10° C., thus minimizing nitrification (Keeney, 1982., Bundy, 1986.). The common method of compensating for the yield drag that is sometimes associated with the reduced performance of fall applied N is to increase the rate of N applied. In a compendium of timing comparisons, Bundy (1986) concluded that with above optimum N rates (>220 kg N ha<sup>-1</sup>) fall applications were as efficient as spring applied AA at optimum rates.

Randall and Vetsch (2005) observed large degrees of variability in the efficacy of N when comparing timing of AA fertilization and the effects of nitrification inhibitor, Nitrapyrin (2-chloro-6-(trichloromethyl)pyridine). Maddux et al. (1984) saw similar variable responses to Nitrapyrin that was characterized by above average May-June precipitation; however a significant response of grain yield to Nitrapyrin was only seen once. This typifies the high levels of year to year variability that affects the efficacy of preplant timing of AA.

However, Meisinger, et al. (2008) pointed out that optimizing N rate can have a greater impact on NUE than any other single practice. Nitrogen rates that exceed that of what the crop is capable of utilizing pose a greater risk of adverse environmental implications, than the effects of N source, timing or placement. This is due to the wide reaching variability in climate in cropping systems and the trend toward increasing N rates in grain production. In work by Schegel and Havlin (1995) N recommendations of 24 kg N Mg<sup>-1</sup> of 15.5% moisture grain were compared with 30 year irrigated corn economic optimum N rate (EONR). They found that when compared to the yield based N recommendations, the long term EONR for the location had a 15% greater NUE than the yield based recommendation (57% and 42% respectively).

Recovery of N applied has been evaluated in several different studies in recent years with limited advantages to spring applications of AA versus fall. Randall and Vetsch (2005) saw a significant advantage in N recovery to spring applications in 4 years of a 6 year study. However, in another project by Vetsch and Randall (2004), a significant advantage to spring application of AA was seen in only one out of three years. This level of year to year variability in N recovery was also seen in the earlier work of Chalk et al. (1975).

## **Materials an Methods**

The site was established in the spring of 2007 in Willard, Kansas (39° 5' 36" N, 95° 56' 27" W) on a dryland field that had been in soybeans the previous year and continued in Silver Lake, KS (39°5' 52"N, 95° 49' 33"W) in 2008 and 2009 on a center pivot irrigated field that was split east and west between corn and beans. Cultural practices, material and methods are found in Table 3.1. Soils present are listed in Table 3.2. Annual average yearly precipitation is 897mm (<http://countrystudies.us/united-states/weather/kansas/topeka.htm>, accessed 9/2009). Treatment structure consisted of three separate application timings, Fall (FALL), Spring preplant (PRE), and Sidedress (SD) in a randomized complete split-block design. Both applicators, described in

chapter 2, applied AA at six N rates of 0, 45, 90, 134, 179 and 224 kg N ha<sup>-1</sup> at each of the above timings. Plot size was 3.0 by 76 meters. All data was collected from the center two rows of the 45 to 60 meter area of the plot. This allowed application equipment to get up to speed and equilibrate. Plot areas were managed using no-till techniques. Weeds were effectively controlled each year with the use of pre-emergence and post emergence herbicides.

In 2007, at the Willard location, only Spring and SD treatments were applied. The previous fall, 12, 60, and 33 kg ha<sup>-1</sup> of N, P, and K were broadcast on the field. In 2008, there was a no starter fertilizer applied, and in 2009 13 and 45 kg ha<sup>-1</sup> of N and P in the form of ammonium polyphosphate, was surface dribble applied prior to planting. Nitrogen from these preplant applications were not accounted for in the six planned N rates.

**Table 3.1 Site Year information**

Year	2007	2008	2009
Location	Willard, KS	Silver Lake, KS	Silver Lake, KS
	LadySmith Silty	Rossville Silt	Rossville Silt
Soil Type	Clay Loam	Loam	Loam
Fall Application Date	NA	17-Nov	19-Nov
Spring Application Date	30-Apr	15-Apr	22-Apr
Planting Date	14-May	2-May	11-May
	Golden Harvest H-	Producers 7624	Producers 7624
Hybrid	9006 BT	VT3	VT3
Maturity	112 day	116 day	116 day
Sidedress Date	18-Jun	16-Jun	19-Jun
Supplemental Irrigation	NA	89mm	89mm
Harvest Date	12-Oct	30-Oct	17-Oct

**Table 3.2 Soil Information**

ID	Soil Series	Taxonomic Class	pH	OM g kg <sup>-1</sup>	Nitrate	P mg kg <sup>-1</sup>	K
2007	Silty Clay Loam	Fine, smectitic, mesic Udertic Argiustolls	6.1	12	15.2	15.0	200
2008	Rossville Silt Loam	Fine-silty, mixed, superactive, mesic Cumulic Hapludall	7.2	19	11.3	11.5	335
2009	Rossville Silt Loam	Fine-silty, mixed, superactive, mesic Cumulic Hapludall	6.9	19	9.5	12.5	397

## **Plant Populations, Tissue Sampling and Analysis**

Plant stands were measured at the three leaf stage. Fifteen ear leaves were collected for N analysis at green silk (R1). Shortly after black layer, 10 plants were collected from the first and fourth rows of each plot to estimate the amount of plant biomass and the N content of the stover just prior to physiological maturity. These samples were dried at 60°C and ground to pass through a 0.5 mm stainless steel sieve. Tissue samples were analyzed for total Kjeldahl N after digestion using H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O<sub>2</sub> (Linder and Harley, 1942; Thomas et al., 1967). Total N uptake of the above ground plant was determined by combining the N content in the stover and the N content in the grain. Concentrations in the digest sample were measured with a Rapid Flow Analyzer (Model RFA-300) using RFA methodology No. A303-S072 for Total Kjeldahl N (Alpkem Corporation, Clackamas, OR 97015).

## **Grain Yield and Analysis**

Yield was determined by mechanically harvesting the center 2 rows of the 45-60 meter area of the plots. Yields were adjusted to 155 g kg<sup>-1</sup> moisture content. A sub sample was collected and ground to pass through a 0.5 mm stainless steel sieve. Grain analytical methods were identical to tissue methods given above. Nitrogen use efficiency (NUE) was calculated as ((N uptake- N uptake of unfertilized check plot) / rate of N applied)\*100=NUE.

## **Statistical Analysis**

Data for gaseous losses, population, and yield were analyzed using the MIXED Procedure in SAS (SAS, 2004). Data was analyzed separately each year. All LSDs are calculated at probability level of 0.05 with the GLM Procedure.

## **Results and Discussion**

### **Populations**

Nitrogen rate did not appear to directly affect the plant population when AA is used as a N source. Time of N application had a significant effect on plant population in 2007, with lower populations found with preplant N than SD plots. This is likely the result of poor soil seed



contact in the disturbed application zone. No differences in population were seen in 2008 or 2009, and no significant interaction was seen in either year. Timing did not seem to play a consistent role in the main effects of population. There were no significant interactions in any year.

**Table 3.3 Effect of N rate and timing on population.**

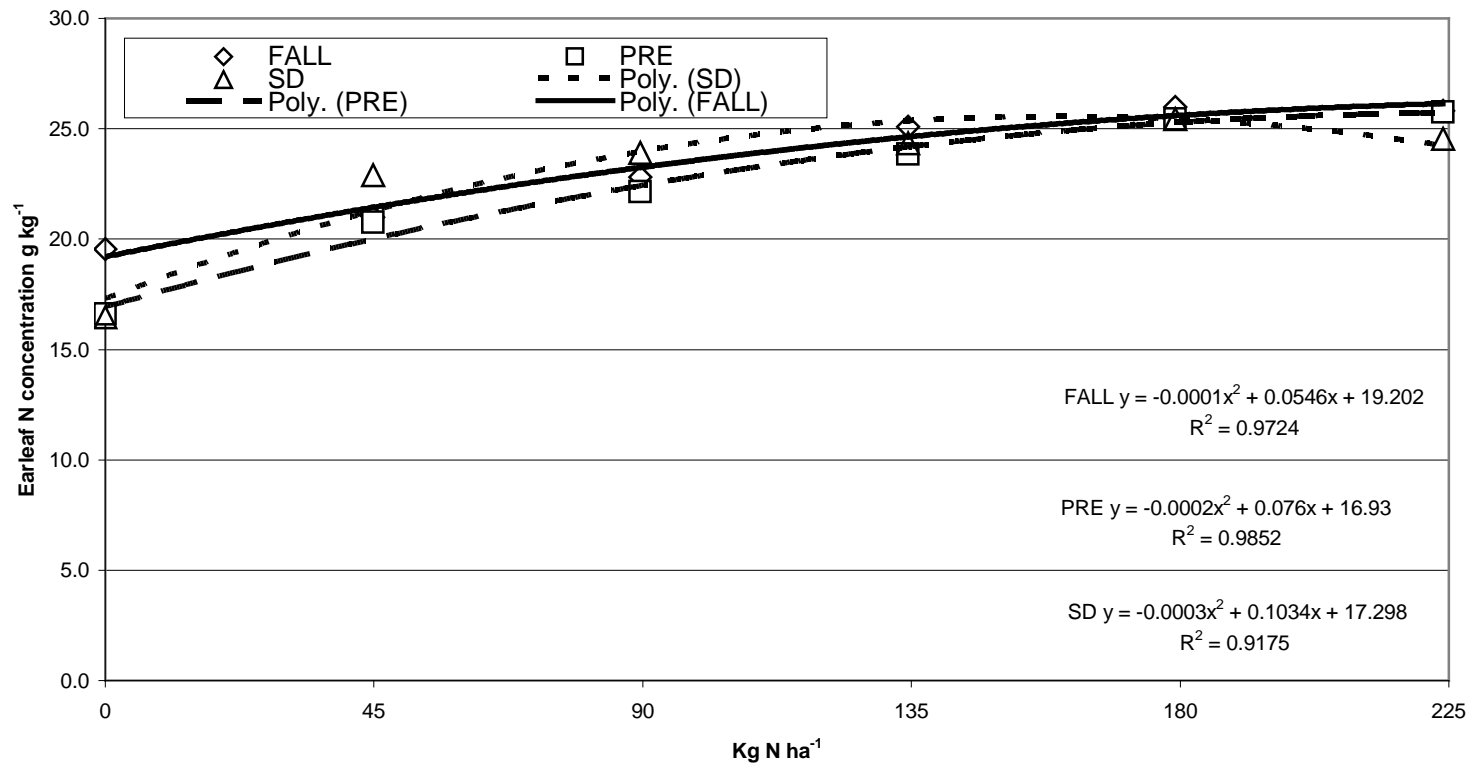
Timing	N Rate kg ha <sup>-1</sup>	2007	2008	2009
		Population 10000 plants ha <sup>-1</sup>		
FALL	0	NA	7.91	7.94
	45	NA	7.56	8.06
	90	NA	7.65	8.03
	134	NA	7.53	8.13
	179	NA	7.86	7.94
	224	NA	7.97	7.92
PRE	0	5.08	7.83	8.01
	45	NA	7.64	8.05
	90	4.69	7.79	8.03
	134	5.01	7.81	8.05
	179	5.01	7.64	8.02
	224	4.93	7.89	8.00
SD	0	5.45	7.72	7.77
	45	NA	7.56	8.05
	90	5.12	7.64	7.99
	134	5.23	7.52	7.93
	179	5.21	7.43	8.01
	224	5.19	7.66	8.02
Rate	0	5.26	7.81	7.9
	45		7.63	8.04
	90	4.90	7.66	8.01
	134	5.11	7.65	8.03
	179	5.10	7.62	7.99
	224	5.05	7.81	7.97
	LSD (.05)	NS	NS	NS
Timing	Fall		7.74	8.00
	Preplant	4.94B	7.74	8.02
	Sidedress	5.23A	7.58	7.96
	LSD (.05)	0.17	NS	NS
		Pr > F		
Time		0.0009	NS	NS
Applicator		NS	NS	NS
Rate		NS	NS	NS
Time*Nrate		NS	NS	NS
Applicator*Nrate		NS	NS	NS
Applicator*Time		NS	NS	NS
Time*Applicator*Nrate		NS	NS	NS

## **Earleaf N concentrations**

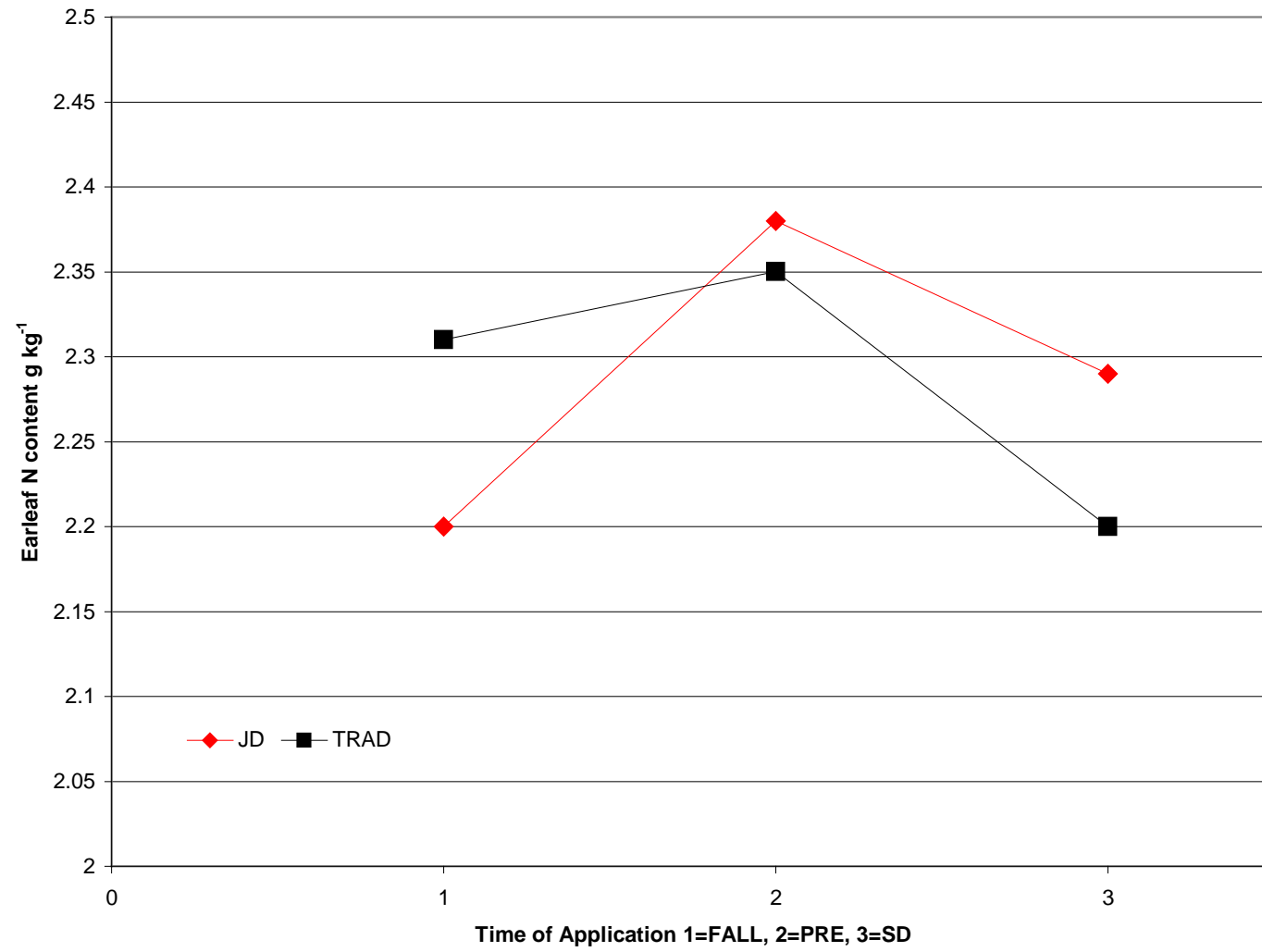
Earleaf N content increased significantly with N fertilization in all three years. In 2007 and in 2008 Earleaf N concentrations were maximized at the 224 kg N ha<sup>-1</sup> rate, and in 2009 Earleaf N concentration was maximized at 179 kg N ha<sup>-1</sup>. In both 2007 and in 2008 the PRE application resulted in greater earleaf N concentrations. In 2009 PRE applications were less than either FALL or SD applications. Interaction effects for timing and N rate interaction in 2009 are shown in figure 3.1. Interaction between applicators and timing in 2008 is seen in figure 3.2, and is the result of low earleaf N content in the FALL with the JD applicator.

**Table 3.4 Effect of N rate and timing on earleaf N concentration**

		2007	2008	2009
		Earleaf N		
		g kg <sup>-1</sup>		
FALL	0		19.7	19.6
	45		20.9	21.0
	90		22.8	22.8
	134		23.9	25.1
	179		23.9	26.0
	224		24.2	25.8
PRE	0	20.0	22.3	16.6
	45		22.2	20.8
	90	24.6	23.7	22.2
	134	23.1	24.5	23.9
	179	26.3	24.5	25.5
	224	26.3	24.8	25.8
SD	0	16.6	17.9	16.5
	45		21.9	22.9
	90	17.5	23.5	23.9
	134	17.5	23.1	24.4
	179	20.1	24.0	25.5
	224	20.9	24.4	24.6
Rate	0	21.4C	19.9D	17.5E
	45		21.6C	21.5D
	90	31.1B	23.3B	22.9C
	134	31.6AB	23.8AB	24.4B
	179	31.8AB	24.1AB	25.6A
	224	32.7A	24.4A	25.3A
	LSD (.05)	1.4	1.1	0.7
Timing	Fall		22.5B	23.3A
	Preplant	31.4A	23.6A	22.4B
	Sidedress	28.1B	22.4B	22.9A
	LSD (.05)	0.9	0.8	0.5
		Pr > F		
Time		0.0047	0.002	0.0067
Applicator		NS	NS	NS
Rate		<.0001	<.0001	<.0001
Time*Nrate		NS	NS	<.0001
Applicator*Nrate		NS	NS	NS
Applicator*Time		NS	0.0219	NS
Time*Applicator*Nrate		NS	NS	NS



**Figure 3.1 Interaction effects of timing and N rate on earleaf N content in 2009.**



**Figure 3.2 Applicator\*Timing interaction effects for earleaf N content in 2008.**

## Grain yield

In all years and at all timings a significant response to N was observed. Higher grain yields were observed in 2008 and in 2009 due to higher levels of growing season precipitation, lower temperatures and supplemental irrigation. The control plots ( $0 \text{ kg N ha}^{-1}$ ) in 2008 and 2009 out yielded the highest treatment means in 2007. In 2007 there were no appreciable precipitation events after the R1 growth stage (Figure 3.3) . In both years where FALL timing treatments were applied, there were no differences between FALL or spring PRE applications of AA (Table 3.5). In 2007 and in 2009 there were no significant differences between application timings. In 2008 however, grain yields were significantly lower when N was applied at the SD timing, than with either the FALL or PRE timings. The poor performance of SD treatments in 2008 could be explained by the fact that in the 2007 and 2009 seasons preplant phosphorus fertilizer sources were used that contained N, while in 2008 no ammoniated phosphorus products were applied preceding planting.

In 2009 there was a significant difference between applicators. This was the product of high levels of ammonia loss during SD application with the JD applicator that was noted by a visible cloud and strong pungent odor. See Figure 3.5 This high level of loss caused noticeable visual leaf damage, and resulted in greatly decreased yields in three of the four replications at the SD  $224 \text{ kg N ha}^{-1}$  rates applied with the JD applicator (13.54, 10.58, 8.39, and 10.39  $\text{Mg ha}^{-1}$  respectively). This also explains the significant levels of interaction between N rate, applicator, and timing from 2009 seen in Table 3.5 and graphically represented in figure 3.4.

**Table 3.5 Effect of N rate and timing on grain yield.**

		2007	2008	2009
		Grain Yield		
		Mg ha <sup>-1</sup>		
FALL	0		9.65	9.66
	45		11.75	11.41
	90		12.38	12.89
	134		13.03	13.30
	179		13.19	12.25
	224		13.39	13.71
PRE	0	6.71	9.67	9.88
	45		11.17	11.61
	90	8.62	12.49	12.52
	134	8.43	13.17	13.38
	179	7.98	13.83	13.28
	224	7.81	13.17	12.91
SD	0	6.48	8.81	9.35
	45		10.77	11.49
	90	8.43	11.65	13.12
	134	8.36	13.05	13.39
	179	8.60	13.63	12.95
	224	8.16	13.04	12.43
Rate	0	6.59C	9.37E	9.63C
	45		11.22D	11.50B
	90	8.52A	12.17C	12.84A
	134	8.39AB	13.08B	13.35A
	179	8.28AB	13.54A	12.82A
	224	7.98B	13.20AB	13.02A
	LSD (.05)	0.44	0.45	0.55
Timing	Fall		12.23A	12.2
	Preplant	7.91	12.25A	12.26
	Sidedress	7.88	11.82B	12.12
	LSD (.05)	NS	0.32	NS
Interaction		Pr > F		
Time		NS	0.0121	NS
Applicator		NS	NS	0.0105
Rate		<.0001	<.0001	<.0001
Time*Nrate		NS	NS	NS
Applicator*Nrate		NS	NS	0.0346
Applicator*Time		NS	NS	NS
Time*Applicator*Nrate		NS	NS	0.0533



Figure 3.3 Grain yield response to N rate across all timings

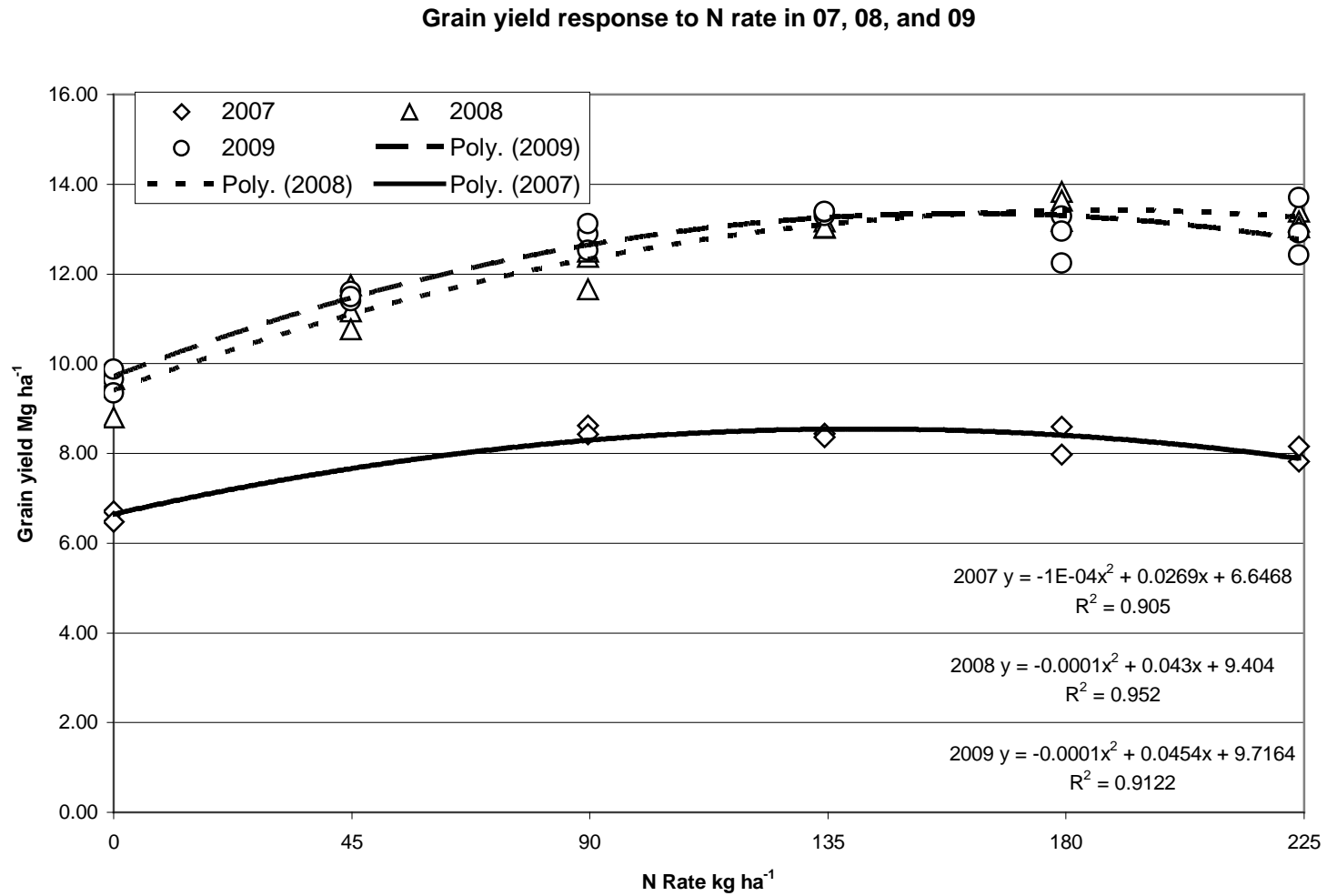
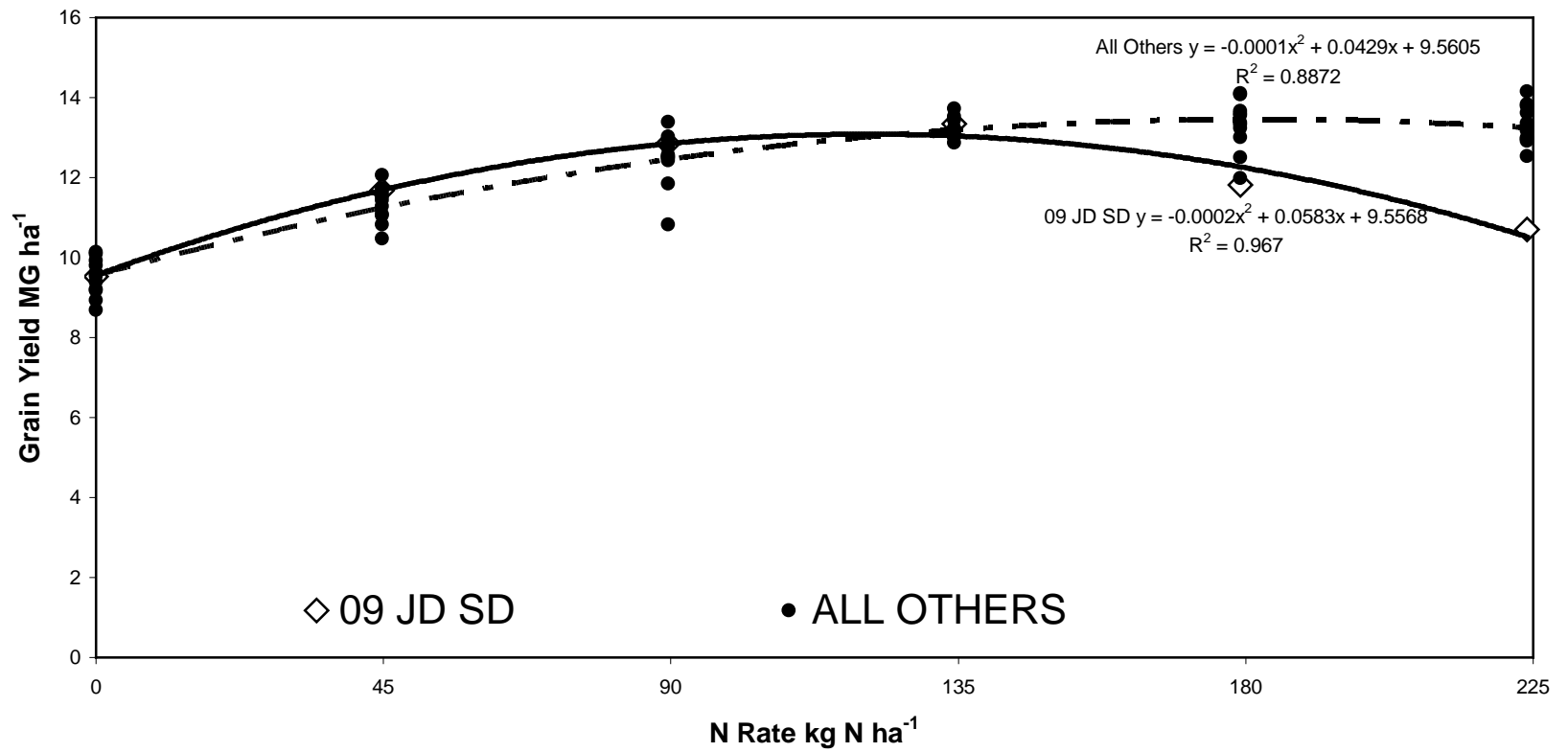


Figure 3.4 Difference in grain yield between JD SD 09 and all other application times



**Figure 3.5 Gaseous losses of AA in 2009 SD application with JD applicator at 224 kg N ha<sup>-1</sup> rate.**



### **Total N Uptake and Nitrogen Use Efficiency**

In 2008 and 2009 total N uptake was maximized at the 224 kg N ha<sup>-1</sup> rate, and in 2007 N uptake was maximized at the 179 Kg N ha<sup>-1</sup> rate. In all three years the PRE application timing resulted in the greatest levels of N uptake. There was no time\*N rate interaction in total N uptake in any year. However, in 2008 and 2009, applicators did cause some interaction with N rate. In 2009 this was directly tied to the high levels of leaf damage from the JD applicator at SD failing to seal at high N rates. The same trends for both grain yield and total N uptake were observed in the 2009 JD SD applications at high N rates.

Nitrogen use efficiency (NUE) tended to decrease as N rate increased. Recovery of applied N was statistically greater at SD in both years.

**Table 3.6 Total N uptake and Nitrogen use efficiency of N rates and timing.**

	N Rate kg ha <sup>-1</sup>	2007	2008	2009	2008	2009
		Total N Uptake kg ha <sup>-1</sup>			Nitrogen Use Efficiency %	
FALL	0		112.4	115.2		
	45		144.1	133.9	70.8	46.7
	90		168.3	169.0	62.4	67.3
	134		185.3	172.8	54.2	47.9
	179		188.6	176.5	42.5	38.4
	224		207.6	189.6	42.5	37.2
PRE	0	97.87	124.5	112.4		
	45		144.0	144.8	43.5	80.9
	90	151.78	166.9	157.9	47.3	56.9
	134	142.06	190.9	184.5	49.4	60
	179	151.40	216.5	201.2	51.3	55.5
	224	144.88	212.4	196.9	39.2	42.2
SD	0	86.95	104.9	108.7		
	45		144.4	139.8	88.3	77.7
	90	138.52	154.9	165.2	55.9	70.6
	134	133.76	188.3	184.5	62.1	63.2
	179	139.61	207.9	186.8	57.5	48.8
	224	127.33	212.0	182.6	47.9	36.9
Rate	0	92.4C	113.9E	112.1D		
	45		144.2D	139.5C	67.5A	68.4A
	90	145.15A	163.4C	164.0B	55.2AB	64.9A
	134	137.90B	188.2B	180.6A	55.3AB	57.1AB
	179	145.51A	204.3A	188.1A	50.4B	47.5BC
	224	136.10B	210.7A	189.6A	43.2B	38.8C
Timing	LSD (.05)	6.63	11.1	9.1	15.1	15.2
	Fall		167.74B	159.5B	54.7AB	47.5B
	Preplant	137.59A	175.9A	166.3A	46.1B	59.1AB
	Sidedress	125.23B	168.7AB	161.2AB	62.4A	59.5A
	LSD (.05)	4.2	7.8	6.5	11.7	11.8
		Pr > F				
Time		<.0001	0.0723	NS	0.0144	NS
Applicator		0.011	NS	0.0004	0.0311	0.0043
Rate		<.0001	<.0001	<.0001	0.0168	0.001
Time*Nrate		NS	NS	NS	NS	NS
Applicator*Nrate		NS	0.0007	0.0004	NS	NS
Applicator*Time		NS	NS	NS	NS	NS
Time*Applicator*Nrate		NS	NS	0.0776	NS	NS

## Conclusion

The use of AA as a N fertilizer did not appear to have any adverse effects on any of the yield components evaluated in this study with the exception of the JD SD 2009 application. While there were differences between application timings, there was no difference between FALL and PRE applied AA in grain yield. However, this is not to say that there is no loss of Fall applied AA to denitrification and leaching. If we look at the main effects of timing in Total N uptake there is a greater level of N uptake from N applied just prior to planting as opposed to FALL applications. This level of loss is not of the economic and environmental significance observed by Vetsch and Randall (2004), and was not of enough consequence to cause a significant decrease in yield. This is not to say that FALL applied AA is a risk free practice. For many producers that operate in today's world of large area and low manpower production, the loss of fall applied N is just as much a calculated risk as is trying to apply all of the N prior to planting when excess moisture may restrict field traffic. However, there was a consistent yield advantage to PRE applications in all three years of this study, although this was not always a statistically significant increase.

It is also important to recognize the importance of preplant fertilizer if the majority of N is going to be applied at SD. Since most of the N is taken up by tasseling, if a developing plant operates in a N deficit in the early vegetative growth stages it will not be able to compensate later, as was observed in 2008.

In years when water was not a limiting factor, a response to increasing N rates was observed up to 179 and 134 kg N ha<sup>-1</sup> in 2008 and 2009. These responses very closely match the current K-State Soil test and fertilizer recommendations.

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## **CHAPTER 4 - Summary and General Conclusions**

The ability to utilize economical sources of nitrogen fertilizers is an important component of managing risk for agricultural producers. An equally important aspect of managing risk is the timing of N applications to maximize production and minimize environmental impact from off-site movement of nutrients. Anhydrous ammonia accounts for a very large portion of the N that is applied in the Midwest and Great Plains, and the general public's perception of AA has also changed over the past 10 years as AA is now more often associated with methamphetamine production than crop production. If AA is to remain a viable and economic source of N fertilizer, perceptions of how, when, where and why AA is used in the agronomic community must be addressed.

Application of AA is a common practice in KS and across the Midwest, and can be utilized with adequate safeguards against environmental degradation if several key points are kept in mind.

### **Timing of N Application**

In Kansas the use of preplant applications of AA is considered a low risk endeavor, however the risk of loss increases when fall applications for spring crops are used. The results of this project very clearly show that AA applied at least 2 weeks prior to planting or in the fall once soil temperatures were consistently under 10° C (50° F) produced similar levels of grain yield. Traditionally in the northern corn belt states, the "50° F" rule meant that once soils reached the 50° F point, it would not be long until soil temperatures were under the 4.5° C (40° F), the point at which nitrification is truly restricted. As was observed, this "50° F rule" works well for the northern portions of Kansas, but more southern areas of the state would be well advised to wait until soil temperatures are consistently below 4.5° C (40° F) or perhaps delay AA application until the spring.

Levels of precipitation and soil texture, coupled with spring time soil temperatures are another factor to consider when planning preplant applications of AA. Yearly rainfall increases to over 1100 mm (45 inches) towards the southeastern corner of the state. These high levels of precipitation combined with warm soil temperatures create very high risk of loss from AA that was not applied close enough to actual crop uptake. These conditions may warrant the use of

nitrification inhibitors such as nitrapyrin. If SD applications are to be utilized, it is also very important to use some form of starter N fertilizer.

### **Application Issues**

The ability to effectively utilize AA as a N source depends directly on a soils ability to adsorb a high pressure gas. The more soil that AA comes into contact with the less likely it will be lost. High speed, shallow draft applicators are very effective method for applying AA if a few things are kept in mind regarding application conditions.

- Not enough soil moisture: Think of it as you would planting. If things are dry you tend to place the seed a little deeper to utilize moisture in the soil profile. The same is true for AA applications, in that if there is not enough soil moisture to chemically adsorb the ammonia, then it must be placed deeper in the soil to restrict loss. Especially in courser textured soils. Adequate soil moisture, as a component of chemical retention is the primary factor that influences a soils ability to retain AA. If adequate soil moisture is not present, then increased application depths will reduce the risk of loss or applications must be delayed until rain or irrigation corrects the problem.
- Too much moisture can also cause excessive levels of loss through sidewall compaction and failure to seal the application lot. If these losses are present while a crop is actively growing, then significant levels of tissue damage can impact yield as seen in 2009 with the SD application.

### **Nitrogen Rate**

Current N recommendations place an emphasis on the importance of using soil test information like profile nitrate tests to accurately predict N needs. The current KSU recommendations are based off of realistic yield goals, and take into account soil organic matter, profile nitrate tests, and previous crop adjustments. In both 2008 and in 2009 the KSU recommendations, as defined below (Leikam et al., 2003), very closely matched the actual yields and corresponding N rates from this study, and should be considered a excellent tool for determining N rates for corn production in KS where all N, in the form of AA, is applied in a single application.



$$N_{\text{rec}} = 28.6 Y_{\text{grain}} - N_{\text{OM}} - N_{\text{r}} - N_{\text{m}} - N_{\text{o}} + C$$

where

$N_{\text{rec}}$  = recommended N rate ( $\text{kg ha}^{-1}$ )

$Y_{\text{grain}}$  = expected grain yield ( $\text{Mg ha}^{-1}$ )

28.6 = N requirement of the corn crop ( $\text{kg ha}^{-1}$ ) per unit of grain yield ( $\text{kg ha}^{-1}$ )

$N_{\text{OM}}$  = N adjustment from the mineralization of soil organic matter ( $\text{kg ha}^{-1}$ ), determined as  $2.24 \times$  soil organic matter content ( $\text{g kg}^{-1}$ ).

$N_{\text{r}}$  = available preseason profile nitrate ( $\text{kg N ha}^{-1}$ ), determined as  $0.12 \times$  sampling depth (cm)  $\times$  soil  $\text{NO}_3\text{-N}$  ( $\text{mg kg}^{-1}$ )

$N_{\text{m}}$  = inorganic N available from manure application ( $\text{kg N ha}^{-1}$ )

$N_{\text{o}}$  = inorganic N from irrigation water ( $\text{kg N ha}^{-1}$ )

C = previous crop adjustment ( $\text{kg N ha}^{-1}$ )

In both 2008 and 2009 maximum yields were achieved with 179 and 134  $\text{kg N ha}^{-1}$  respectively. Using the Crop Nutrient Response Tool (IPNI, <http://nane.ipni.net/articles/NANE0001-EN>) mean optimum economic N rates (OENR) were calculated for each application timing in 2008 and 2009. Cost of AA was assumed to be \$0.67 per kg N, and corn prices were set at the current price of \$148.80 per Mg of grain. In 2008 the OENR for FALL, PRE and SD was 177, 181, and 191  $\text{kg N ha}^{-1}$ . In 2009 the EONR for FALL, PRE, and SD was 167, 166, and 142  $\text{kg N ha}^{-1}$ . The 2009 SD OENR was skewed due to the low yields at high N rates with the JD applicator. Again proving the importance of application depth when soil conditions are not optimal.

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**Appendix A - Gaseous Anhydrous Ammonia losses from 2008 and  
2009**

**Table A.1 Gaseous AA emissions following 2008 FALL application**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				48	96	144
				Ammonia Loss kg AA ha <sup>-1</sup>		
Fall 07	126	Trad	0	0.01	0.01	0.01
Fall 07	126	Trad	0	0.01	0.01	0.01
Fall 07	128	JD	0	0.01	0.01	0.01
Fall 07	128	JD	0	0.01	0.01	0.00
Fall 07	129	Trad	160	0.04	0.08	0.01
Fall 07	129	Trad	160	0.01	0.01	0.01
Fall 07	131	JD	200	0.09	6.38	1.56
Fall 07	131	JD	200	0.09	6.59	5.20
Fall 07	133	Trad	200	0.01	0.14	0.04
Fall 07	133	Trad	200	0.05	0.05	0.05
Fall 07	134	JD	160	0.65	5.55	2.70
Fall 07	134	JD	160	0.86	6.99	0.90
Fall 07	202	JD	0	0.01	0.02	0.01
Fall 07	202	JD	0	0.01	0.01	0.01
Fall 07	204	JD	200	0.03	4.83	2.23
Fall 07	204	JD	200	2.14	9.75	1.32
Fall 07	205	Trad	160	0.01	0.01	0.05
Fall 07	205	Trad	160	0.02	0.03	0.02
Fall 07	208	JD	160	0.17	0.13	0.05
Fall 07	208	JD	160	0.08	3.19	0.41
Fall 07	209	Trad	0	0.01	0.01	0.01
Fall 07	209	Trad	0	0.01	0.01	0.02
Fall 07	212	Trad	200	0.01	0.23	0.01
Fall 07	212	Trad	200	0.03	0.02	0.07
Fall 07	326	JD	200	0.01	11.04	1.39
Fall 07	326	JD	200	4.27	4.87	1.41
Fall 07	327	Trad	0	0.01	0.01	0.04
Fall 07	327	Trad	0	0.02	0.01	0.02
Fall 07	328	JD	0	0.01	0.08	0.03
Fall 07	328	JD	0	0.01	0.01	0.03
Fall 07	329	Trad	200	0.02	0.48	0.02
Fall 07	329	Trad	200	0.05	0.05	0.07
Fall 07	331	JD	160	0.12	1.21	0.26
Fall 07	331	JD	160	0.01	1.42	0.11
Fall 07	336	Trad	160	0.01	0.04	0.02
Fall 07	336	Trad	160	0.01	0.02	0.01
Fall 07	402	Trad	160	0.01	0.01	0.01
Fall 07	402	Trad	160	0.01	0.01	0.01
Fall 07	404	Trad	200	0.02	0.33	0.00
Fall 07	404	Trad	200	0.01	0.01	0.02
Fall 07	405	JD	200	1.24	0.75	1.41
Fall 07	405	JD	200	0.34	10.59	2.70

**Table A.1 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				48	96	144
Fall 07	406	JD	0	0.01	0.07	0.05
Fall 07	406	JD	0	0.01	0.03	0.01
Fall 07	407	Trad	0	0.01	0.01	0.03
Fall 07	407	Trad	0	0.01	0.05	0.01
Fall 07	411	JD	160	0.04	6.36	1.53
Fall 07	411	JD	160	0.03	9.33	1.31

**Table A.2 Gaseous AA ammonia loss following PRE 08 application.**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	120	168
				Ammonia Loss kg AA ha <sup>-1</sup>		
Pre 08	101	trad	120	0.16	0.12	0.04
Pre 08	101	trad	120	0.45	0.09	0.07
Pre 08	102	JD	40	0.03	0.01	0.01
Pre 08	102	JD	40	0.02	0.01	0.01
Pre 08	103	trad	0	0.03	0.01	0.01
Pre 08	103	trad	0	0.01	0.01	0.00
Pre 08	104	trad	200	0.02	0.02	0.01
Pre 08	104	trad	200	0.14	0.01	0.02
Pre 08	105	JD	0	0.02	0.01	0.01
Pre 08	105	JD	0	0.03	0.01	0.01
Pre 08	106	JD	160	10.09	0.05	2.46
Pre 08	106	JD	160	0.12	2.45	0.04
Pre 08	107	trad	80	0.04	0.01	0.03
Pre 08	107	trad	80	0.18	0.01	0.01
Pre 08	108	JD	120	3.43	1.63	1.36
Pre 08	108	JD	120	2.23	1.17	1.54
Pre 08	109	trad	40	0.04	0.02	0.01
Pre 08	109	trad	40	0.02	0.01	0.01
Pre 08	110	JD	80	0.04	0.25	0.10
Pre 08	110	JD	80	0.45	0.00	0.02
Pre 08	111	JD	200	10.82	1.89	3.29
Pre 08	111	JD	200	15.29	4.03	3.30
Pre 08	112	trad	160	1.61	0.01	0.01
Pre 08	112	trad	160	0.15	0.39	1.05
Pre 08	225	JD	40	0.01	0.01	0.03
Pre 08	225	JD	40	0.01	0.01	0.03
Pre 08	226	trad	200	0.03	0.01	0.01
Pre 08	226	trad	200	2.41	0.26	0.01
Pre 08	227	JD	0	0.02	0.01	0.01
Pre 08	227	JD	0	0.03	0.01	0.01
Pre 08	228	trad	80	0.04	0.01	0.01
Pre 08	228	trad	80	0.03	0.01	0.01
Pre 08	229	JD	120	0.75	1.05	0.85
Pre 08	229	JD	120	6.19	1.22	0.81
Pre 08	230	JD	160	25.35	5.45	2.59
Pre 08	230	JD	160	26.31	2.79	6.44
Pre 08	231	trad	160	0.03	0.02	0.02
Pre 08	231	trad	160	0.03	0.03	0.01
Pre 08	232	trad	40	0.20	0.06	0.01
Pre 08	232	trad	40	0.03	0.01	0.07
Pre 08	233	JD	80	0.61	0.01	0.18
Pre 08	233	JD	80	0.02	0.20	0.01

**Table A.2 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	120	168
Pre 08	234	trad	120	0.07	0.01	0.01
Pre 08	234	trad	120	0.04	0.02	0.01
Pre 08	235	trad	0	0.11	0.02	0.01
Pre 08	235	trad	0	0.10	0.02	0.01
Pre 08	236	JD	200	0.69	0.35	3.85
Pre 08	236	JD	200	4.88	1.74	3.91
Pre 08	313	trad	80	1.30	0.01	0.29
Pre 08	313	trad	80	0.05	0.16	0.01
Pre 08	314	trad	200	0.02	0.01	0.01
Pre 08	314	trad	200	0.07	0.02	0.01
Pre 08	315	trad	0	0.05	0.01	0.01
Pre 08	315	trad	0	0.01	0.01	0.01
Pre 08	316	trad	160	3.47	0.45	0.52
Pre 08	316	trad	160	3.08	1.03	2.51
Pre 08	317	JD	120	0.08	1.19	0.72
Pre 08	317	JD	120	3.70	0.02	0.03
Pre 08	318	JD	40	0.03	0.02	0.01
Pre 08	318	JD	40	0.07	0.01	0.01
Pre 08	319	trad	40	0.23	0.01	0.01
Pre 08	319	trad	40	0.01	0.01	0.01
Pre 08	320	trad	120	0.73	1.28	0.27
Pre 08	320	trad	120	2.69	0.14	0.86
Pre 08	321	JD	80	0.02	0.02	0.04
Pre 08	321	JD	80	0.06	0.01	0.01
Pre 08	322	JD	200	10.45	15.71	9.97
Pre 08	322	JD	200	2.10	0.84	1.99
Pre 08	323	JD	0	0.02	0.01	0.02
Pre 08	323	JD	0	0.03	0.01	0.02
Pre 08	324	JD	160	1.19	7.07	4.19
Pre 08	324	JD	160	11.07	0.43	0.73
Pre 08	413	JD	200	28.55	10.66	3.69
Pre 08	413	JD	200	30.50	5.36	4.25
Pre 08	414	JD	120	5.44	0.52	0.51
Pre 08	414	JD	120	2.46	1.00	1.00
Pre 08	415	trad	80	0.20	0.04	0.02
Pre 08	415	trad	80	0.17	0.04	0.03
Pre 08	416	JD	80	0.82	0.26	0.26
Pre 08	416	JD	80	0.23	0.10	0.10
Pre 08	417	JD	0	0.05	0.01	0.01
Pre 08	417	JD	0	0.04	0.01	0.01
Pre 08	418	trad	40	0.02	0.02	0.01
Pre 08	418	trad	40	0.12	0.01	0.04

**Table A.2 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	120	168
Pre 08	419	trad	120	0.02	0.01	0.13
Pre 08	419	trad	120	0.34	0.31	0.01
Pre 08	420	trad	160	3.46	0.69	0.01
Pre 08	420	trad	160	0.03	0.01	1.32
Pre 08	421	trad	0	0.06	0.01	0.01
Pre 08	421	trad	0	0.19	0.01	0.03
Pre 08	422	JD	40	0.09	0.14	0.10
Pre 08	422	JD	40	0.01	0.00	0.01
Pre 08	423	JD	160	0.22	0.16	0.60
Pre 08	423	JD	160	5.32	0.93	0.10
Pre 08	424	trad	200	0.11	0.01	0.02
Pre 08	424	trad	200	0.28	0.03	0.05

**Table A.3 Gaseous AA emission following SD 08 application.**

Application Plot		Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	48	192
				Ammonia Loss kg AA ha <sup>-1</sup>		
SD 08	305B	JD	40	0.06	0.01	0.01
SD 08	305C	JD	40	0.52	0.00	0.00
SD 08	306A	JD	200	0.15	0.02	0.01
SD 08	306B	JD	200	0.60	0.15	0.06
SD 08	306C	JD	200	0.06	0.07	0.03
SD 08	307A	trad	0	0.05	0.00	0.00
SD 08	307B	trad	0	0.02	0.01	0.01
SD 08	307C	trad	0	0.02	0.00	0.00
SD 08	308A	JD	0	0.04	0.00	0.00
SD 08	308B	JD	0	0.10	0.01	0.00
SD 08	308C	JD	0	0.02	0.00	0.00
SD 08	309A	JD	160	0.06	0.02	0.01
SD 08	309B	JD	160	0.31	0.02	0.02
SD 08	309C	JD	160	0.40	0.04	0.02
SD 08	310A	JD	80	0.01	0.00	0.00
SD 08	310B	JD	80	0.47	0.04	0.00
SD 08	310C	JD	80	0.09	0.01	0.01
SD 08	311A	JD	120	0.04	0.01	0.00
SD 08	311B	JD	120	0.04	0.01	0.01
SD 08	311C	JD	120	0.02	0.02	0.01
SD 08	312A	trad	160	0.45	0.00	0.00
SD 08	312B	trad	160	0.09	0.00	0.00
SD 08	312C	trad	160	0.08	0.01	0.01
SD 08	425A	JD	80	0.02	0.01	0.00
SD 08	425B	JD	80	0.01	0.01	0.00
SD 08	426A	JD	160	0.02	0.00	0.00
SD 08	426B	JD	160	0.54	0.04	0.02
SD 08	426C	JD	160	0.09	0.07	0.04
SD 08	428A	JD	0	0.00	0.03	0.03
SD 08	428B	JD	0	0.00	0.00	0.00
SD 08	428C	JD	0	0.02	0.00	0.00
SD 08	429A	JD	200	0.17	0.00	0.00
SD 08	429B	JD	200	0.46	0.04	0.03
SD 08	429C	JD	200	1.12	0.16	0.07
SD 08	434A	JD	40	0.02	0.16	0.09
SD 08	434B	JD	40	0.01	0.01	0.01
SD 08	434C	JD	40	0.06	0.00	0.00
SD 08	435A	JD	120	0.17	0.00	0.00
SD 08	435B	JD	120	0.09	0.00	0.00



**Table A.3 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	48	192
SD 08	215B	trad	80	0.10	0.01	0.10
SD 08	215C	trad	80	0.02	0.01	0.02
SD 08	216A	JD	0	0.04	0.01	0.02
SD 08	216B	JD	0	0.01	0.00	0.04
SD 08	216C	JD	0	0.02	0.01	0.04
SD 08	217A	trad	120	0.05	0.02	0.01
SD 08	217B	trad	120	0.03	0.02	0.02
SD 08	217C	trad	120	0.02	0.01	0.01
SD 08	218A	trad	40	0.02	0.01	0.02
SD 08	218B	trad	40	0.01	0.04	0.15
SD 08	218C	trad	40	0.01	0.01	0.03
SD 08	219A	JD	160	1.33	0.31	0.28
SD 08	219B	JD	160	0.05	0.02	0.48
SD 08	219C	JD	160	0.11	0.02	0.05
SD 08	220A	trad	160	0.02	0.00	0.03
SD 08	220B	trad	160	0.07	0.01	0.02
SD 08	220C	trad	160	0.02	0.01	0.02
SD 08	221A	JD	40	0.02	0.01	0.05
SD 08	221B	JD	40	0.02	0.03	0.03
SD 08	221C	JD	40	0.09	0.01	0.02
SD 08	222A	JD	80	0.02	0.00	0.02
SD 08	222B	JD	80	0.01	0.00	0.03
SD 08	222C	JD	80	0.02	0.00	0.03
SD 08	223A	trad	0	0.02	0.01	0.02
SD 08	223B	trad	0	0.01	0.00	0.01
SD 08	223C	trad	0	0.01	0.01	0.02
SD 08	224A	JD	120	0.04	0.02	0.03
SD 08	224B	JD	120	0.24	0.02	0.05
SD 08	224C	JD	120	0.09	0.01	0.01
SD 08	301A	trad	120	0.02	0.01	0.01
SD 08	301B	trad	120	0.01	0.00	0.01
SD 08	301C	trad	120	0.02	0.02	0.01
SD 08	302A	trad	200	0.02	0.05	0.00
SD 08	302B	trad	200	0.02	0.05	0.00
SD 08	302C	trad	200	0.06	0.04	0.01
SD 08	303A	trad	40	0.01	0.00	0.00
SD 08	303B	trad	40	0.02	0.00	0.00
SD 08	303C	trad	40	0.01	0.00	0.00
SD 08	304A	trad	80	0.07	0.01	0.01
SD 08	304B	trad	80	0.12	0.01	0.00
SD 08	304C	trad	80	0.06	0.00	0.00
SD 08	305A	JD	40	0.16	0.02	0.00

**Table A.4 Gaseous AA loss following FALL 09 application.**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	96	168
				Ammonia Loss kg AA ha <sup>-1</sup>		
09Fall	101	TRAD	160	0.03	0.03	0.03
09Fall	101	TRAD	160	0.03	0.02	0.02
09Fall	102	JD	120	1.09	0.08	0.08
09Fall	102	JD	120	0.04	0.50	0.56
09Fall	103	TRAD	80	0.03	0.01	0.01
09Fall	103	TRAD	80	0.03	0.09	0.10
09Fall	104	TRAD	40	0.04	0.03	0.04
09Fall	104	TRAD	40	0.01	0.02	0.02
09Fall	105	JD	0	0.02	0.02	0.02
09Fall	105	JD	0	0.03	0.02	0.03
09Fall	106	TRAD	200	0.03	0.59	0.66
09Fall	106	TRAD	200	0.28	0.46	0.51
09Fall	107	JD	200	1.09	2.87	3.21
09Fall	107	JD	200	4.26	4.05	4.54
09Fall	108	TRAD	120	0.03	0.02	0.02
09Fall	108	TRAD	120	0.02	0.03	0.03
09Fall	109	JD	160	7.01	3.27	3.67
09Fall	109	JD	160	12.37	3.48	3.89
09Fall	110	TRAD	0	0.02	0.07	0.07
09Fall	110	TRAD	0	0.03	0.03	0.04
09Fall	111	JD	80	0.05	0.02	0.03
09Fall	111	JD	80	0.59	0.12	0.14
09Fall	112	JD	40	0.01	0.07	0.08
09Fall	112	JD	40	0.06	0.02	0.02
09Fall	225	JD	200	3.05	7.98	8.94
09Fall	225	JD	200	14.81	5.23	5.86
09Fall	226	TRAD	40	0.02	0.07	0.08
09Fall	226	TRAD	40	0.03	0.03	0.03
09Fall	227	TRAD	160	0.01	0.06	0.07
09Fall	227	TRAD	160	0.03	0.01	0.01
09Fall	228	JD	0	0.03	0.04	0.04
09Fall	228	JD	0	0.01	0.04	0.05
09Fall	229	JD	40	0.12	0.03	0.03
09Fall	229	JD	40	0.39	0.02	0.02
09Fall	230	TRAD	120	4.25	1.13	1.26
09Fall	230	TRAD	120	0.01	0.03	0.04
09Fall	231	TRAD	80	0.05	0.05	0.06
09Fall	231	TRAD	80	0.01	0.05	0.05
09Fall	232	JD	120	0.03	0.05	0.05
09Fall	232	JD	120	0.09	0.02	0.02
09Fall	233	TRAD	0	0.06	0.04	0.05
09Fall	233	TRAD	0	0.04	0.06	0.07
09Fall	234	JD	80	1.59	0.06	0.07
09Fall	234	JD	80	0.04	0.52	0.59
09Fall	235	TRAD	200	0.02	0.06	0.07

**Table A.4 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	96	168
				Ammonia Loss kg AA ha <sup>-1</sup>		
09Fall	235	TRAD	200	2.55	2.64	2.96
09Fall	236	JD	160	11.05	1.13	1.27
09Fall	236	JD	160	3.78	1.58	1.77
09Fall	301	TRAD	200	1.67	0.69	0.77
09Fall	301	TRAD	200	0.01	0.01	0.01
09Fall	302	JD	120	1.04	0.02	0.02
09Fall	302	JD	120	0.05	0.56	0.62
09Fall	303	TRAD	40	0.03	0.02	0.02
09Fall	303	TRAD	40	0.18	0.05	0.05
09Fall	304	TRAD	120	0.01	0.06	0.06
09Fall	304	TRAD	120	0.09	0.02	0.02
09Fall	305	TRAD	80	0.01	0.01	0.01
09Fall	305	TRAD	80	0.01	0.02	0.02
09Fall	306	JD	0	0.01	0.02	0.03
09Fall	306	JD	0	0.02	0.01	0.01
09Fall	307	TRAD	160	1.25	1.48	1.66
09Fall	307	TRAD	160	0.03	0.04	0.05
09Fall	308	JD	160	0.16	3.35	3.75
09Fall	308	JD	160	8.18	0.15	0.17
09Fall	309	TRAD	0	0.04	0.01	0.01
09Fall	309	TRAD	0	0.05	0.03	0.03
09Fall	310	JD	80	0.03	0.03	0.04
09Fall	310	JD	80	0.02	0.04	0.04
09Fall	311	JD	200	0.57	3.21	3.60
09Fall	311	JD	200	8.04	1.23	1.38
09Fall	312	JD	40	0.04	0.03	0.04
09Fall	312	JD	40	0.01	0.04	0.05
09Fall	413	JD	200	6.32	0.99	1.11
09Fall	413	JD	200	2.40	6.45	7.23
09Fall	414	TRAD	40	0.03	0.01	0.01
09Fall	414	TRAD	40	0.01	0.01	0.01
09Fall	415	JD	160	2.78	0.95	1.07
09Fall	415	JD	160	1.93	1.71	1.91
09Fall	416	TRAD	80	0.53	0.18	0.20
09Fall	416	TRAD	80	0.03	0.02	0.02
09Fall	417	TRAD	200	0.01	0.02	0.02
09Fall	417	TRAD	200	0.03	0.01	0.01
09Fall	418	TRAD	120	1.05	0.53	0.59
09Fall	418	TRAD	120	0.03	0.01	0.01
09Fall	419	TRAD	0	0.03	0.02	0.02
09Fall	419	TRAD	0	0.02	0.01	0.01
09Fall	420	JD	80	3.72	0.84	0.94
09Fall	420	JD	80	0.58	0.25	0.28
09Fall	421	TRAD	160	1.32	0.15	0.17
09Fall	421	TRAD	160	0.23	0.29	0.33
09Fall	422	JD	40	0.02	0.04	0.04
09Fall	422	JD	40	0.07	0.02	0.03

**Table A.4 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				24	96	168
09Fall	423	JD	0	0.03	0.03	0.03
09Fall	423	JD	0	0.03	0.02	0.03
09Fall	424	JD	120	6.53	0.94	1.05
09Fall	424	JD	120	1.96	1.90	2.12

**Table A.5 Gaseous AA loss following PRE 09 application.**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				48	96	144
				Ammonia Loss kg AA ha <sup>-1</sup>		
09PRE	113	TRAD	80	0.08	0.02	0.00
09PRE	113	TRAD	80	0.04	0.06	0.01
09PRE	114	TRAD	40	0.02	0.04	0.00
09PRE	114	TRAD	40	0.01	0.12	0.00
09PRE	115	JD	80	0.09	0.07	0.00
09PRE	115	JD	80	0.18	0.03	0.00
09PRE	116	TRAD	0	0.11	0.05	0.00
09PRE	116	TRAD	0	0.09	0.02	0.00
09PRE	117	JD	0	0.09	0.02	0.00
09PRE	117	JD	0	0.09	0.01	0.02
09PRE	118	TRAD	120	0.25	0.01	0.02
09PRE	118	TRAD	120	0.03	0.03	0.03
09PRE	119	TRAD	160	0.13	0.06	0.01
09PRE	119	TRAD	160	2.25	0.37	0.09
09PRE	120	JD	40	0.12	0.02	0.00
09PRE	120	JD	40	0.09	0.02	0.01
09PRE	121	JD	120	0.07	0.83	0.03
09PRE	121	JD	120	1.07	0.04	0.00
09PRE	122	JD	200	4.53	3.66	0.13
09PRE	122	JD	200	3.07	1.12	0.28
09PRE	123	TRAD	200	0.10	0.08	0.00
09PRE	123	TRAD	200	0.11	0.02	0.00
09PRE	124	JD	160	2.61	0.14	0.00
09PRE	124	JD	160	0.10	1.31	0.11
09PRE	213	JD	200	1.56	1.88	0.12
09PRE	213	JD	200	0.08	0.06	0.01
09PRE	214	TRAD	200	0.04	0.27	0.01
09PRE	214	TRAD	200	0.59	0.04	0.01
09PRE	215	TRAD	40	0.04	0.01	0.00
09PRE	215	TRAD	40	0.01	0.02	0.00
09PRE	216	JD	80	0.12	0.03	0.00
09PRE	216	JD	80	0.06	0.03	0.01
09PRE	217	JD	160	0.10	0.03	0.01
09PRE	217	JD	160	0.03	0.01	0.01
09PRE	218	TRAD	160	0.10	0.02	0.01
09PRE	218	TRAD	160	0.12	0.02	0.00
09PRE	219	TRAD	80	0.03	0.04	0.01
09PRE	219	TRAD	80	0.09	0.03	0.00
09PRE	220	JD	40	0.02	0.01	0.03
09PRE	220	JD	40	0.01	0.01	0.03
09PRE	221	TRAD	0	0.01	0.04	0.00
09PRE	221	TRAD	0	0.15	0.01	0.02
09PRE	222	JD	0	0.04	0.03	0.00
09PRE	222	JD	0	0.07	0.01	0.00

**Table A.5 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				48	96	144
				Ammonia Loss kg AA ha <sup>-1</sup>		
09PRE	223	TRAD	120	0.08	0.22	0.00
09PRE	223	TRAD	120	0.13	0.09	0.00
09PRE	224	JD	120	0.08	0.03	0.02
09PRE	224	JD	120	0.60	0.27	0.02
09PRE	325	TRAD	120	0.04	0.02	0.01
09PRE	325	TRAD	120	0.03	0.23	0.00
09PRE	326	JD	200	0.18	0.50	0.02
09PRE	326	JD	200	0.49	0.13	0.00
09PRE	327	JD	80	0.11	0.03	0.01
09PRE	327	JD	80	0.01	0.01	0.01
09PRE	328	TRAD	160	0.16	0.04	0.00
09PRE	328	TRAD	160	0.09	0.03	0.01
09PRE	329	TRAD	40	0.09	0.23	0.01
09PRE	329	TRAD	40	0.14	0.15	0.01
09PRE	330	JD	160	0.14	0.04	0.01
09PRE	330	JD	160	0.21	0.01	0.01
09PRE	331	TRAD	80	0.16	0.02	0.01
09PRE	331	TRAD	80	0.02	0.01	0.01
09PRE	332	JD	40	0.08	0.10	0.01
09PRE	332	JD	40	0.04	0.01	0.01
09PRE	333	TRAD	200	0.18	0.03	0.01
09PRE	333	TRAD	200	0.04	0.01	0.00
09PRE	334	TRAD	0	0.23	0.01	0.00
09PRE	334	TRAD	0	0.22	0.02	0.01
09PRE	335	JD	0	0.06	0.05	0.00
09PRE	335	JD	0	0.27	0.01	0.00
09PRE	336	JD	120	0.42	0.89	0.02
09PRE	336	JD	120	1.25	0.27	0.03
09PRE	401	JD	160	0.26	0.91	0.04
09PRE	401	JD	160	0.75	0.08	0.02
09PRE	402	TRAD	200	0.07	0.20	0.02
09PRE	402	TRAD	200	1.48	0.01	0.01
09PRE	403	JD	200	1.31	0.77	0.03
09PRE	403	JD	200	0.17	0.42	0.02
09PRE	404	JD	120	0.05	0.02	0.03
09PRE	404	JD	120	0.18	0.21	0.01
09PRE	405	JD	40	0.03	0.01	0.01
09PRE	405	JD	40	0.06	0.01	0.01
09PRE	406	TRAD	160	0.08	0.03	0.02
09PRE	406	TRAD	160	0.06	0.10	0.02
09PRE	407	TRAD	120	0.04	0.10	0.04
09PRE	407	TRAD	120	0.11	0.01	0.02
09PRE	408	JD	0	0.13	0.01	0.02
09PRE	408	JD	0	0.11	0.02	0.02

**Table A.5 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				48	96	144
09PRE	409	TRAD	0	0.03	0.04	0.02
09PRE	409	TRAD	0	0.15	0.02	0.03
09PRE	410	JD	80	0.10	0.02	0.09
09PRE	410	JD	80	0.04	0.04	0.02
09PRE	411	TRAD	40	0.07	0.01	0.00
09PRE	411	TRAD	40	0.04	0.02	0.01
09PRE	412	TRAD	80	0.10	0.03	0.00
09PRE	412	TRAD	80	0.09	0.03	0.01

**Table A.6 Gaseous AA losses following SD 09 application.**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				72	120	216
				Ammonia Loss kg AA ha <sup>-1</sup>		
09SD	125	JD	0	0.05	0.00	0.01
09SD	125	JD	0	0.02	0.00	0.01
09SD	126	JD	200	0.86	0.08	0.01
09SD	126	JD	200	0.36	0.10	0.03
09SD	127	JD	80	0.29	0.01	0.01
09SD	127	JD	80	0.02	0.01	0.01
09SD	128	TRAD	200	0.01	0.00	0.02
09SD	128	TRAD	200	0.02	0.00	0.01
09SD	129	JD	120	0.05	0.00	0.00
09SD	129	JD	120	0.02	0.01	0.01
09SD	130	JD	40	0.04	0.01	0.00
09SD	130	JD	40	0.04	0.00	0.00
09SD	131	TRAD	40	0.00	0.02	0.00
09SD	131	TRAD	40	0.01	0.00	0.01
09SD	132	TRAD	80	0.01	0.01	0.01
09SD	132	TRAD	80	0.01	0.00	0.01
09SD	133	JD	160	0.03	0.02	0.02
09SD	133	JD	160	0.54	0.01	0.02
09SD	134	TRAD	0	0.01	0.01	0.01
09SD	134	TRAD	0	0.01	0.01	0.01
09SD	135	TRAD	160	0.00	0.01	0.02
09SD	135	TRAD	160	0.00	0.02	0.00
09SD	136	TRAD	120	0.01	0.01	0.00
09SD	136	TRAD	120	0.01	0.02	0.01
09SD	201	TRAD	40	0.00	0.01	0.00
09SD	201	TRAD	40	0.01	0.02	0.02
09SD	202	TRAD	0	0.01	0.01	0.04
09SD	202	TRAD	0	0.00	0.02	0.01
09SD	203	JD	200	0.58	0.07	0.03
09SD	203	JD	200	0.51	0.08	0.03
09SD	204	JD	0	0.00	0.01	0.02
09SD	204	JD	0	0.00	0.01	0.00
09SD	205	TRAD	160	0.00	0.00	0.01
09SD	205	TRAD	160	0.00	0.00	0.01
09SD	206	TRAD	80	0.00	0.00	0.02
09SD	206	TRAD	80	0.00	0.00	0.02
09SD	207	JD	40	0.00	0.00	0.01
09SD	207	JD	40	0.00	0.00	0.02
09SD	208	JD	120	0.08	0.00	0.00
09SD	208	JD	120	0.03	0.00	0.03
09SD	209	TRAD	120	0.00	0.01	0.01
09SD	209	TRAD	120	0.00	0.00	0.00
09SD	210	JD	160	0.33	0.07	0.01



**Table A.6 Continued**

Application	Plot	Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				72	120	216
				Ammonia Loss kg AA ha <sup>-1</sup>		
09SD	210	JD	160	1.23	0.10	0.05
09SD	211	TRAD	200	0.00	0.04	0.02
09SD	211	TRAD	200	0.00	0.00	0.00
09SD	212	JD	80	0.03	0.03	0.00
09SD	212	JD	80	0.07	0.02	0.02
09SD	313	JD	0	0.16	0.00	0.01
09SD	313	JD	0	0.01	0.01	0.00
09SD	314	TRAD	80	0.01	0.02	0.00
09SD	314	TRAD	80	0.05	0.01	0.01
09SD	315	JD	40	0.01	0.02	0.00
09SD	315	JD	40	0.02	0.01	0.03
09SD	316	TRAD	120	0.02	0.01	0.01
09SD	316	TRAD	120	0.01	0.01	0.01
09SD	317	JD	200	0.42	0.01	0.02
09SD	317	JD	200	0.08	0.03	0.00
09SD	318	TRAD	160	0.02	0.01	0.09
09SD	318	TRAD	160	0.02	0.01	0.02
09SD	319	JD	160	0.02	0.01	0.01
09SD	319	JD	160	0.16	0.00	0.00
09SD	320	TRAD	0	0.00	0.00	0.00
09SD	320	TRAD	0	0.12	0.01	0.00
09SD	321	TRAD	200	0.09	0.00	0.01
09SD	321	TRAD	200	0.00	0.01	0.01
09SD	322	JD	80	0.04	0.01	0.02
09SD	322	JD	80	0.03	0.00	0.00
09SD	323	TRAD	40	0.01	0.02	0.01
09SD	323	TRAD	40	0.02	0.01	0.05
09SD	324	JD	120	0.02	0.01	0.01
09SD	324	JD	120	0.04	0.00	0.01
09SD	425	JD	0	0.02	0.00	0.00
09SD	425	JD	0	0.01	0.01	0.00
09SD	426	JD	80	0.14	0.00	0.00
09SD	426	JD	80	0.12	0.00	0.01
09SD	427	JD	120	0.09	0.00	0.01
09SD	427	JD	120	0.24	0.01	0.01
09SD	428	TRAD	40	0.01	0.01	0.00
09SD	428	TRAD	40	0.01	0.00	0.00
09SD	429	JD	160	0.14	0.01	0.00
09SD	429	JD	160	0.05	0.01	0.00
09SD	430	TRAD	160	0.02	0.04	0.01
09SD	430	TRAD	160	0.01	0.01	0.01
09SD	431	JD	200	0.03	0.03	0.01

**Table A.6 Continued**

Application Plot		Applicator	N Rate kg N ha <sup>-1</sup>	Hours after application		
				72	120	216
09SD	431	JD	200	0.84	0.03	0.37
09SD	432	TRAD	200	0.03	0.01	0.01
09SD	432	TRAD	200	0.03	0.01	0.01
09SD	433	JD	40	0.02	0.00	0.01
09SD	433	JD	40	0.01	0.00	0.02
09SD	434	TRAD	80	0.01	0.01	0.01
09SD	434	TRAD	80	0.02	0.01	0.00
09SD	435	TRAD	0	0.02	0.00	0.00
09SD	435	TRAD	0	0.03	0.02	0.01
09SD	436	TRAD	120	0.01	0.02	0.00
09SD	436	TRAD	120	0.01	0.01	0.00

## **Appendix B - Components of Yield from 2007-2009**

**Table B.1 Data for yield components in 2007**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2007	101	PRE	JD	80	37027	5073	3.43	2.64	8.32	1.44
2007	102	PRE	TRAD	160	45638	5898	3.70	2.69	6.35	1.54
2007	103	PRE	JD	120	49082	5101	3.34	2.57	7.38	1.43
2007	104	PRE	JD	160	55110	5447	3.47	2.89	8.98	1.39
2007	105	PRE	JD	0	53388	6486	2.27	1.89	6.18	1.10
2007	106	PRE	TRAD	80	50805	5775	3.43	2.40	8.97	1.45
2007	108	PRE	TRAD	120	54249	5483	3.42	2.51	8.90	1.36
2007	109	PRE	TRAD	200	49082	5689	3.25	2.80	8.93	1.43
2007	111	PRE	JD	200	52527	4515	3.40	2.58	8.09	1.44
2007	112	PRE	TRAD	0	50805	7265	2.13	2.27	6.48	1.19
2007	113	SD	TRAD	0	52527	4977	2.40	2.05	6.53	1.16
2007	114	SD	JD	200	52527	5370	3.06	2.01	8.46	1.39
2007	115	SD	JD	160	54249	6248	3.08	2.08	7.90	1.38
2007	116	SD	JD	0	47360	4444	1.87	1.98	5.73	1.16
2007	118	SD	JD	80	52527	5119	2.95	2.03	8.75	1.33
2007	119	SD	TRAD	120	50805	4848	2.80	2.05	8.25	1.34
2007	120	SD	JD	120	56832	4433	2.69	1.64	8.30	1.38
2007	122	SD	TRAD	160	55110	4659	3.11	1.95	8.85	1.41
2007	123	SD	TRAD	200	50805	4575	3.15	2.21	8.53	1.44
2007	124	SD	TRAD	80	49082	6860	2.91	2.09	8.94	1.42
2007	201	SD	JD	0	55971	3911	1.84	1.40	6.17	1.15
2007	202	SD	JD	200	46499	4912	3.42	2.24	6.48	1.38
2007	203	SD	JD	80	50805	5579	2.80	1.44	7.39	1.30
2007	204	SD	JD	120	45638	4268	3.04	1.57	8.54	1.29
2007	206	SD	TRAD	120	51666	4592	2.95	1.56	7.93	1.34
2007	207	SD	TRAD	200	59415	5357	3.12	1.83	8.00	1.27
2007	208	SD	TRAD	0	54249	4380	1.99	1.27	5.25	1.07
2007	210	SD	TRAD	160	45638	5830	2.65	1.44	7.81	1.46
2007	211	SD	TRAD	80	49943	6107	2.88	1.42	8.69	1.49
2007	212	SD	JD	160	50805	5390	3.02	2.12	8.61	1.41
2007	213	PRE	TRAD	200	51666	4609	3.66	2.44	7.83	1.46

**Table B.1 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2007	214	PRE	TRAD	80	43055	6262	3.32	2.84	9.15	1.41
2007	215	PRE	JD	0	50805	5992	2.33	1.93	6.10	1.16
2007	216	PRE	JD	200	49082	4780	3.77	2.32	6.95	1.58
2007	217	PRE	TRAD	0	44777	6711	2.06	2.09	6.89	1.24
2007	218	PRE	JD	160	45638	4451	3.25	2.72	7.94	1.62
2007	219	PRE	TRAD	120	49943	4423	3.39	2.33	8.60	1.49
2007	220	PRE	TRAD	160	48221	5874	3.30	2.36	8.39	1.50
2007	221	PRE	JD	80	52527	5091	2.97	2.03	8.61	1.40
2007	223	PRE	JD	120	49943	4739	3.29	1.55	8.31	1.43
2007	301	SD	JD	120	55110	4031	3.21	2.43	8.23	1.47
2007	302	SD	TRAD	120	51666	5116	3.10	1.58	8.48	1.37
2007	303	SD	TRAD	200	52527	3386	3.11	2.09	8.32	1.28
2007	305	SD	JD	0	55971	4408	2.19	1.78	6.44	1.17
2007	307	SD	TRAD	80	56832	5267	3.13	2.02	8.32	1.37
2007	308	SD	TRAD	0	60277	4937	1.57	1.97	6.34	1.13
2007	309	SD	JD	80	53388	4172	3.01	1.87	8.37	1.50
2007	310	SD	JD	200	49082	3877	3.07	2.28	8.41	1.46
2007	311	SD	JD	160	51666	4765	3.01	2.53	9.82	1.39
2007	312	SD	TRAD	160	54249	4568	2.85	2.66	8.49	1.37
2007	313	PRE	TRAD	120	53388	5727	3.37	2.72	9.10	1.37
2007	315	PRE	JD	0	52527	5191	2.35	2.48	6.45	1.20
2007	317	PRE	JD	80	50805	4706	3.29	2.91	8.71	1.49
2007	318	PRE	TRAD	0	49943	5814	2.75	2.08	7.50	1.16
2007	319	PRE	TRAD	200	47360	6031	3.15	2.53	7.82	1.57
2007	320	PRE	JD	120	49943	6628	3.39	2.67	7.63	1.46
2007	321	PRE	JD	160	55110	5232	3.32	2.37	7.65	1.43
2007	322	PRE	TRAD	160	49943	5392	3.25	3.18	8.91	1.44
2007	323	PRE	TRAD	80	49082	5526	3.24	2.35	7.95	1.47
2007	324	PRE	JD	200	52527	5911	3.46	3.33	7.59	1.42
2007	401	PRE	TRAD	160	49082	5189	3.57	2.35	7.67	1.51
2007	402	PRE	TRAD	200	49082	4362	3.25	2.33	7.60	1.52
2007	405	PRE	JD	160	51666	4490	3.28	2.46	7.73	1.49

**Table B.1 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2007	406	PRE	TRAD	120	44777	4552	3.37	2.52	8.07	1.54
2007	407	PRE	TRAD	0	53388	4830	2.18	1.72	7.79	1.18
2007	408	PRE	JD	80	51666	5050	2.96	2.16	8.94	1.37
2007	409	PRE	JD	200	43055	5854	3.31	2.70	7.49	1.54
2007	410	PRE	TRAD	80	40471	4569	3.34	2.27	8.08	1.52
2007	411	PRE	JD	120	49082	5214	3.49	2.40	9.27	1.43
2007	412	PRE	JD	0	50805	4312	1.99	1.49	6.07	1.15
2007	413	SD	TRAD	120	50805	4799	2.90	1.75	8.86	1.48
2007	414	SD	TRAD	200	49943	4735	3.22	2.26	8.39	1.38
2007	415	SD	JD	200	54249	3995	2.95	1.74	8.49	1.32
2007	416	SD	JD	80	50805	4397	3.02	1.88	8.42	1.45
2007	417	SD	TRAD	160	49943	5388	2.92	1.50	8.25	1.45
2007	418	SD	JD	160	55110	4513	3.16	1.55	8.83	1.38
2007	420	SD	JD	120	55971	4103	2.83	1.14	8.05	1.38
2007	421	SD	JD	0	55971	4986	1.97	1.46	6.92	1.18
2007	423	SD	TRAD	0	53388	5585	2.45	1.36	8.29	1.17
2007	424	SD	TRAD	80	46499	6264	3.13	1.23	8.35	1.48

**Table B.2 Data for yield components in 2008.**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2008	101	PRE	TRAD	120	83515	10195.1	2.47	0.45	13.07	1.29
2008	102	PRE	JD	40	78349	10833.6	2.15	0.47	10.74	1.04
2008	103	PRE	TRAD	0	79210	8494.3	2.06	0.41	9.67	0.97
2008	104	PRE	TRAD	200	79210	12793.1	2.45	0.76	11.13	1.23
2008	105	PRE	JD	0	81793	9205.2	1.89	0.52	8.76	0.94
2008	106	PRE	JD	160	78349	11476.0	2.57	0.56	14.61	1.18
2008	107	PRE	TRAD	80	76627	7987.1	2.19	0.44	13.07	1.11
2008	108	PRE	JD	120	78349	9884.2	2.36	0.39	13.69	1.22
2008	109	PRE	TRAD	40	79210	8605.9	2.05	0.36	11.07	1.02
2008	110	PRE	JD	80	76627	11209.1	2.38	0.38	12.76	1.16
2008	111	PRE	JD	200	76627	8802.4	1.94	0.79	14.17	1.22
2008	112	PRE	TRAD	160	79210	10654.3	2.08	0.58	14.39	1.24
2008	113	SD	TRAD	40	80071	6870.1	1.79	0.35	10.95	1.05
2008	114	SD	TRAD	200	74905	11644.5	2.27	0.80	13.68	1.28
2008	115	SD	JD	120	85237	6528.9	2.28	0.57	13.42	1.16
2008	116	SD	TRAD	160	69739	8109.0	2.31	0.79	13.91	1.23
2008	117	SD	JD	200	80932	7271.5	2.50	0.60	12.35	1.28
2008	118	SD	TRAD	120	77488	8245.8	2.27	0.58	13.84	1.26
2008	119	SD	JD	0	77488	7051.5	1.64	0.33	8.05	1.18
2008	120	SD	JD	160	72322	7578.0	2.44	0.63	12.84	1.00
2008	121	SD	TRAD	0	79210	8065.9	1.77	0.33	8.99	1.03
2008	122	SD	JD	40	75766	10022.0	2.35	0.40	9.54	1.20
2008	123	SD	JD	80	75766	6357.4	2.45	0.47	12.37	1.22
2008	124	SD	TRAD	80	75766	11884.4	2.25	0.46	10.11	0.85
2008	125	FALL	TRAD	120	81793	8335.5	2.28	0.44	11.87	1.19
2008	126	FALL	TRAD	0	80932	8192.0	2.12	0.42	9.19	0.89
2008	127	FALL	TRAD	80	76627	10575.3	2.26	0.39	10.69	1.09
2008	128	FALL	JD	0	80932	8330.3	2.08	0.46	10.06	0.98
2008	129	FALL	TRAD	160	88680	5194.8	2.39	0.46	12.83	1.22
2008	130	FALL	JD	40	80932	11005.1	2.06	0.46	11.57	1.04
2008	131	FALL	JD	200	81793	7956.8	2.19	0.51	11.24	1.17

**Table B.2 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2008	132	FALL	JD	80	80071	9949.8	2.17	0.43	11.11	1.18
2008	133	FALL	TRAD	200	85237	12216.5	2.61	0.61	12.77	1.23
2008	134	FALL	JD	160	83515	5848.1	2.51	0.51	12.45	1.22
2008	135	FALL	JD	120	76627	6873.3	2.42	0.54	12.43	1.28
2008	136	FALL	TRAD	40	75766	8558.6	2.09	0.34	11.38	1.05
2008	201	FALL	JD	120	73183	12929.9	2.21	0.37	12.26	1.19
2008	202	FALL	JD	0	83515	8465.7	1.97	0.38	8.90	0.99
2008	203	FALL	TRAD	120	79210	7862.4	2.34	0.42	13.29	1.27
2008	204	FALL	JD	200	75766	9449.8	2.08	0.56	13.19	1.29
2008	205	FALL	TRAD	160	68878	9819.5	2.23	0.49	12.09	1.18
2008	206	FALL	TRAD	80	78349	10053.7	2.36	0.32	11.98	1.14
2008	207	FALL	JD	80	75766	10083.3	2.19	0.56	13.05	1.22
2008	208	FALL	JD	160	74905	8726.9	2.37	0.49	13.02	1.24
2008	209	FALL	TRAD	0	74044	9877.1	1.95	0.27	9.57	1.00
2008	210	FALL	TRAD	40	72322	9955.3	1.93	0.36	11.62	1.01
2008	211	FALL	JD	40	78349	8347.2	1.95	0.29	12.33	1.09
2008	212	FALL	TRAD	200	75766	10153.0	2.64	0.55	14.58	1.26
2008	213	SD	TRAD	200	74044	7650.9	2.20	0.58	12.66	1.29
2008	214	SD	JD	200	80932	7498.5	2.54	0.58	12.49	1.34
2008	215	SD	TRAD	80	75766	8146.5	2.15	0.28	8.40	0.91
2008	216	SD	JD	0	74044	9524.3	1.70	0.28	8.12	0.97
2008	217	SD	TRAD	120	74044	7591.4	2.28	0.47	12.82	1.25
2008	218	SD	TRAD	40	75766	7478.4	2.09	0.47	10.53	1.00
2008	219	SD	JD	160	80932	8036.8	2.45	0.61	13.43	1.22
2008	220	SD	TRAD	160	71461	7971.7	2.20	0.65	13.16	1.29
2008	221	SD	JD	40	78349	7914.8	2.34	0.45	10.16	0.95
2008	222	SD	JD	80	76627	7875.0	2.39	0.47	11.56	1.15
2008	223	SD	TRAD	0	76627	8778.3	1.67	0.32	9.45	0.92
2008	224	SD	JD	120	60268	10214.1	2.11	0.72	13.04	1.21
2008	225	PRE	JD	40	80071	10209.9	2.22	0.44	11.78	0.96
2008	226	PRE	TRAD	200	80071	9550.2	2.25	0.58	13.94	1.26
2008	227	PRE	JD	0	76627	8969.0	1.98	0.57	9.68	1.02



**Table B.2 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2008	228	PRE	TRAD	80	78349	10242.5	2.15	0.66	12.50	1.09
2008	229	PRE	JD	120	76627	9715.1	2.45	0.58	13.13	1.18
2008	230	PRE	JD	160	74044	9142.1	2.62	0.69	13.70	1.22
2008	231	PRE	TRAD	160	82654	9549.8	2.72	0.65	14.06	1.26
2008	232	PRE	TRAD	40	75766	9805.6	2.59	0.72	11.53	0.99
2008	233	PRE	JD	80	74905	10033.1	2.46	0.62	12.72	1.03
2008	234	PRE	TRAD	120	83515	10313.2	2.42	0.53	13.59	1.10
2008	235	PRE	TRAD	0	80932	7593.7	2.37	0.34	10.73	0.98
2008	236	PRE	JD	200	77488	7716.7	2.74	0.45	13.99	1.30
2008	301	SD	TRAD	120	75766	8133.2	2.26	0.36	11.96	1.29
2008	302	SD	TRAD	200	78349	11519.3	2.46	0.95	13.18	1.33
2008	303	SD	TRAD	40	75766	9384.5	2.22	0.39	11.13	1.04
2008	304	SD	TRAD	80	76627	8366.9	2.34	0.47	12.46	1.26
2008	305	SD	JD	40	73183	8401.4	2.49	0.45	10.92	1.27
2008	306	SD	JD	200	78349	8895.6	2.62	0.74	13.53	1.11
2008	307	SD	TRAD	0	79210	8038.3	1.73	0.23	8.30	0.87
2008	308	SD	JD	0	77488	9756.7	1.90	0.41	8.75	0.84
2008	309	SD	JD	160	74905	9493.6	2.27	0.46	13.47	1.22
2008	310	SD	JD	80	74905	8777.8	2.45	0.48	12.60	1.15
2008	311	SD	JD	120	76627	8021.1	2.84	0.56	13.22	1.26
2008	312	SD	TRAD	160	76627	9101.8	2.67	0.86	14.25	1.26
2008	313	PRE	TRAD	80	78349	9343.5	2.41	0.37	12.35	1.08
2008	314	PRE	TRAD	200	76627	8806.2	2.40	0.65	12.60	1.21
2008	315	PRE	TRAD	0	76627	9421.9	2.56	0.52	9.45	0.90
2008	316	PRE	TRAD	160	70600	9518.9	2.17	0.48	13.86	1.21
2008	317	PRE	JD	120	76627	8242.3	2.50	0.52	13.02	1.07
2008	318	PRE	JD	40	78349	9473.2	2.38	0.39	11.06	0.95
2008	319	PRE	TRAD	40	77488	9087.4	2.23	0.40	11.95	0.98
2008	320	PRE	TRAD	120	78349	10129.3	2.56	0.52	12.52	1.16
2008	321	PRE	JD	80	75766	8340.8	2.56	0.47	11.77	1.05
2008	322	PRE	JD	200	72322	10236.0	2.68	0.56	12.63	1.23
2008	323	PRE	JD	0	80071	9061.0	2.46	0.57	10.13	1.04

**Table B.2 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2008	324	PRE	JD	160	70600	11372.9	2.52	0.69	13.10	1.26
2008	325	FALL	TRAD	40	66295	9556.9	2.10	0.29	10.73	1.02
2008	326	FALL	JD	200	81793	9204.5	2.38	0.53	13.89	1.27
2008	327	FALL	TRAD	0	77488	9254.8	2.15	0.36	9.68	0.87
2008	328	FALL	JD	0	76627	10950.2	1.91	0.45	11.63	0.99
2008	329	FALL	TRAD	200	77488	10706.9	2.58	0.56	13.80	1.22
2008	330	FALL	TRAD	80	78349	10570.7	2.37	0.38	12.92	1.04
2008	331	FALL	JD	160	78349	8886.1	2.40	0.37	13.56	1.22
2008	332	FALL	JD	40	71461	9837.7	2.00	0.41	12.72	1.06
2008	333	FALL	JD	120	76627	10417.1	2.36	0.38	13.83	1.17
2008	334	FALL	JD	80	74905	9003.3	2.51	0.41	13.79	1.21
2008	335	FALL	TRAD	120	61990	9344.2	2.41	0.46	13.14	1.24
2008	336	FALL	TRAD	160	78349	9245.9	2.45	0.48	13.86	1.34
2008	401	FALL	JD	80	71461	9020.8	1.93	0.36	13.55	1.30
2008	402	FALL	TRAD	160	77488	12015.9	2.49	0.60	14.55	1.33
2008	403	FALL	TRAD	120	76627	10562.9	2.63	0.52	13.74	1.20
2008	404	FALL	TRAD	200	77488	10843.8	2.51	0.68	13.98	1.28
2008	405	FALL	JD	200	82654	9557.9	2.37	0.63	13.37	1.31
2008	406	FALL	JD	0	79210	8429.4	1.87	0.32	9.68	0.87
2008	407	FALL	TRAD	0	80071	9755.3	1.72	0.20	8.24	0.84
2008	408	FALL	JD	120	76627	9620.7	2.46	0.59	13.32	1.27
2008	409	FALL	TRAD	80	76627	8496.2	2.42	0.48	11.66	1.12
2008	410	FALL	JD	40	75766	8769.1	2.18	0.37	11.49	1.08
2008	411	FALL	JD	160	78349	9142.2	2.30	0.52	12.82	1.22
2008	412	FALL	TRAD	40	83515	10691.9	2.44	0.46	11.85	0.95
2008	413	PRE	JD	200	80071	9523.3	2.76	0.53	12.46	1.21
2008	414	PRE	JD	120	78349	11431.7	2.54	0.75	12.97	1.18
2008	415	PRE	TRAD	80	80071	10709.4	2.44	0.50	12.20	1.07
2008	416	PRE	JD	80	76627	10619.1	2.38	0.41	12.29	1.06
2008	417	PRE	JD	0	77488	9669.6	2.35	0.33	9.46	0.93
2008	418	PRE	TRAD	40	74905	10456.3	2.14	0.43	11.40	1.02

**Table B.2 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2008	419	PRE	TRAD	120	77488	10622.9	2.30	0.49	13.07	1.19
2008	420	PRE	TRAD	160	72322	11143.9	2.67	0.59	13.91	1.23
2008	421	PRE	TRAD	0	73183	10764.8	2.15	0.45	9.22	0.85
2008	422	PRE	JD	40	79210	13043.6	2.02	0.42	9.57	0.92
2008	423	PRE	JD	160	79210	11372.2	2.23	0.65	12.64	1.34
2008	424	PRE	TRAD	200	82654	12313.3	2.63	0.91	14.13	1.30
2008	425	SD	JD	80	79210	10127.7	2.35	0.55	13.24	1.13
2008	426	SD	JD	160	75766	11086.9	2.46	0.73	14.51	1.27
2008	427	SD	TRAD	0	77488	7410.7	2.08	0.27	8.87	0.93
2008	428	SD	JD	0	75766	13356.3	1.80	0.45	9.69	0.88
2008	429	SD	JD	200	74905	9327.9	2.62	0.74	13.11	1.26
2008	430	SD	TRAD	40	79210	9279.3	2.50	0.47	11.48	1.06
2008	431	SD	TRAD	80	76627	8379.3	2.43	0.49	12.18	1.09
2008	432	SD	TRAD	160	72322	9077.6	2.43	0.74	13.14	1.27
2008	433	SD	TRAD	200	70600	9016.4	2.34	0.66	13.01	1.21
2008	434	SD	JD	40	66295	11731.0	1.70	0.66	11.15	1.06
2008	435	SD	JD	120	75766	9656.1	2.35	0.71	13.03	1.14
2008	436	SD	TRAD	120	76627	8032.9	2.09	0.48	12.71	1.22

**Table B.3 Data for yield components in 2009.**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2009	101	FALL	TRAD	160	78359.6	7992.1	2.59	0.46	10.03	1.28
2009	102	FALL	JD	120	79651.2	7328.2	2.35	0.39	13.39	1.14
2009	103	FALL	TRAD	80	76637.4	10175.9	2.35	0.64	12.87	1.07
2009	104	FALL	TRAD	40	78790.1	8969.7	2.16	0.48	12.66	0.92
2009	105	FALL	JD	0	80942.8	8970.0	2.07	0.41	10.39	0.82
2009	106	FALL	TRAD	200	85248.3	9162.7	2.31	0.44	13.59	1.11
2009	107	FALL	JD	200	76637.4	7165.4	2.55	0.35	13.00	1.15
2009	108	FALL	TRAD	120	85248.3	10207.1	2.47	0.48	12.14	1.15
2009	109	FALL	JD	160	82665.0	9660.7	2.43	0.54	12.48	1.14
2009	110	FALL	TRAD	0	83095.6	9177.6	1.99	0.56	11.53	0.88
2009	111	FALL	JD	80	82234.5	9346.4	2.10	0.63	13.32	0.96
2009	112	FALL	JD	40	80081.7	9144.9	2.02	0.62	13.04	0.90
2009	113	PRE	TRAD	80	79651.2	9475.1	2.28	0.48	12.74	1.02
2009	114	PRE	TRAD	40	80512.3	9380.3	2.10	0.50	13.07	1.03
2009	115	PRE	JD	80	80942.8	9758.0	2.40	0.56	12.25	0.96
2009	116	PRE	TRAD	0	81373.4	10188.4	1.93	0.53	10.77	0.90
2009	117	PRE	JD	0	82665.0	9696.7	1.94	0.69	10.83	0.87
2009	118	PRE	TRAD	120	82665.0	10117.4	2.48	0.91	13.64	1.07
2009	119	PRE	TRAD	160	80081.7	10269.1	2.70	0.66	13.42	1.15
2009	120	PRE	JD	40	81373.4	7924.2	2.25	0.55	11.59	0.82
2009	121	PRE	JD	120	80081.7	9058.4	2.48	0.43	12.68	1.12
2009	122	PRE	JD	200	76206.8	8934.2	2.54	0.54	11.75	1.21
2009	123	PRE	TRAD	200	81803.9	9591.7	2.48	0.70	14.25	1.20
2009	124	PRE	JD	160	78790.1	9633.2	2.60	0.73	13.46	1.17
2009	125	SD	JD	0	79220.7	8628.7	1.72	0.59	10.21	0.83
2009	126	SD	JD	200	76637.4	9250.2	2.44	0.48	13.53	1.11
2009	127	SD	JD	80	79220.7	9703.4	2.49	0.47	13.03	1.12
2009	128	SD	TRAD	200	81803.9	7237.2	2.41	0.78	13.90	1.20
2009	129	SD	JD	120	82665.0	9040.1	2.48	0.54	13.36	1.18
2009	130	SD	JD	40	82665.0	8891.2	2.50	0.68	11.53	0.95
2009	131	SD	TRAD	40	83095.6	8113.1	2.28	0.67	11.45	0.97

**Table B.3 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2009	132	SD	TRAD	80	82665.0	8127.4	2.55	0.51	14.13	1.12
2009	133	SD	JD	160	81373.4	9448.2	2.54	0.51	11.82	1.23
2009	134	SD	TRAD	0	79651.2	7066.6	2.04	0.56	10.41	0.90
2009	135	SD	TRAD	160	80512.3	9044.4	2.60	0.75	13.76	1.17
2009	136	SD	TRAD	120	73193.0	9179.0	2.41	0.55	12.43	1.10
2009	201	SD	TRAD	40	76206.8	6707.6	2.04	0.40	10.84	0.88
2009	202	SD	TRAD	0	73193.0	6092.7	1.40	0.37	6.62	0.75
2009	203	SD	JD	200	77498.5	8633.6	2.43	0.47	10.58	0.97
2009	204	SD	JD	0	77929.0	9032.9	1.76	0.53	8.57	0.83
2009	205	SD	TRAD	160	78359.6	7475.3	2.31	0.45	13.26	1.03
2009	206	SD	TRAD	80	77929.0	9883.4	2.38	0.67	12.49	0.98
2009	207	SD	JD	40	78790.1	8677.8	2.32	0.54	11.04	0.88
2009	208	SD	JD	120	79651.2	7364.2	2.39	0.56	12.60	1.04
2009	209	SD	TRAD	120	79220.7	8846.4	2.31	0.81	13.78	1.06
2009	210	SD	JD	160	81803.9	9495.3	2.65	0.59	12.56	1.07
2009	211	SD	TRAD	200	83956.7	8905.5	2.41	0.76	13.85	1.09
2009	212	SD	JD	80	77929.0	7717.2	2.31	0.51	11.97	0.89
2009	213	PRE	JD	200	78359.6	8767.4	2.68	0.64	13.09	1.06
2009	214	PRE	TRAD	200	85678.9	9535.3	2.61	0.67	12.78	1.13
2009	215	PRE	TRAD	40	80081.7	9378.6	2.17	0.51	11.87	0.86
2009	216	PRE	JD	80	84387.2	8138.7	1.89	0.50	12.83	0.92
2009	217	PRE	JD	160	78359.6	9050.0	2.19	0.69	13.03	1.13
2009	218	PRE	TRAD	160	84387.2	9215.4	2.39	0.70	12.66	1.12
2009	219	PRE	TRAD	80	79220.7	9781.2	2.19	0.44	13.56	0.98
2009	220	PRE	JD	40	83526.1	8975.7	1.70	0.53	11.96	0.92
2009	221	PRE	TRAD	0	81803.9	7196.7	1.45	0.26	9.84	0.77
2009	222	PRE	JD	0	77067.9	6820.2	1.63	0.32	9.49	0.82
2009	223	PRE	TRAD	120	80081.7	9844.8	2.20	0.47	14.31	1.04
2009	224	PRE	JD	120	84817.8	9951.8	2.45	0.55	14.18	1.07
2009	225	FALL	JD	200	77929.0	10437.8	2.75	0.65	14.03	1.10
2009	226	FALL	TRAD	40	84817.8	9473.9	2.52	0.58	13.14	0.98
2009	227	FALL	TRAD	160	80512.3	8221.0	2.80	0.41	12.93	1.16

**Table B.3 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2009	228	FALL	JD	0	83526.1	8555.2	2.06	0.62	8.85	0.87
2009	229	FALL	JD	40	79651.2	7453.2	2.23	0.45	11.69	0.92
2009	230	FALL	TRAD	120	82234.5	8302.1	2.72	0.55	13.15	1.08
2009	231	FALL	TRAD	80	82665.0	9258.9	2.47	0.54	12.96	1.04
2009	232	FALL	JD	120	83956.7	8942.1	2.55	0.55	13.24	0.97
2009	233	FALL	TRAD	0	82234.5	8606.4	2.01	0.38	10.27	0.87
2009	234	FALL	JD	80	80512.3	9393.1	2.34	0.56	12.99	0.96
2009	235	FALL	TRAD	200	82234.5	9725.5	2.63	0.61	14.64	1.12
2009	236	FALL	JD	160	79220.7	11028.5	2.77	0.61	11.53	1.09
2009	301	FALL	TRAD	200	78359.6	9532.4	2.71	0.75	13.14	1.11
2009	302	FALL	JD	120	82234.5	8907.2	2.51	0.68	13.95	1.02
2009	303	FALL	TRAD	40	80942.8	8912.0	2.37	0.57	10.77	0.87
2009	304	FALL	TRAD	120	80081.7	8820.7	2.46	0.65	13.97	0.99
2009	305	FALL	TRAD	80	82665.0	9826.8	2.05	0.58	13.10	0.96
2009	306	FALL	JD	0	80081.7	8545.5	2.08	0.54	9.17	0.85
2009	307	FALL	TRAD	160	80081.7	8442.1	2.69	0.68	12.84	1.06
2009	308	FALL	JD	160	81803.9	9264.5	2.46	0.66	13.49	1.19
2009	309	FALL	TRAD	0	70609.7	7103.0	1.89	0.59	8.70	0.98
2009	310	FALL	JD	80	84387.2	8607.3	2.58	0.68	13.05	0.95
2009	311	FALL	JD	200	81803.9	8295.1	2.50	0.66	14.04	1.08
2009	312	FALL	JD	40	80512.3	8116.2	1.96	0.50	10.76	0.85
2009	313	SD	JD	0	74915.2	7874.4	1.44	0.47	9.24	0.78
2009	314	SD	TRAD	80	80512.3	8424.8	2.31	0.53	12.85	0.98
2009	315	SD	JD	40	83526.1	8563.4	2.33	0.58	11.83	0.87
2009	316	SD	TRAD	120	80081.7	10127.8	2.49	0.80	15.19	1.04
2009	317	SD	JD	200	81803.9	7431.6	2.58	0.83	8.39	1.09
2009	318	SD	TRAD	160	78790.1	9438.9	2.57	0.92	14.92	1.16
2009	319	SD	JD	160	79220.7	6785.6	2.67	0.75	10.84	1.08
2009	320	SD	TRAD	0	82234.5	7862.7	1.49	0.59	9.95	0.84
2009	321	SD	TRAD	200	78790.1	8781.5	2.20	0.94	14.07	1.09
2009	322	SD	JD	80	80512.3	7268.4	2.34	0.73	12.70	0.99
2009	323	SD	TRAD	40	80942.8	7971.9	2.16	0.60	11.73	0.89

**Table B.3 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2009	324	SD	JD	120	81803.9	8736.0	2.55	0.66	13.90	1.08
2009	325	PRE	TRAD	120	83095.6	9405.3	2.49	0.66	13.97	1.02
2009	326	PRE	JD	200	80942.8	10188.8	2.73	0.69	11.89	1.17
2009	327	PRE	JD	80	80081.7	7814.0	2.56	0.90	13.38	1.07
2009	328	PRE	TRAD	160	77498.5	8947.8	2.69	0.66	13.88	1.17
2009	329	PRE	TRAD	40	81803.9	10544.7	2.38	0.66	10.59	0.97
2009	330	PRE	JD	160	81803.9	10598.2	2.81	0.75	14.43	1.13
2009	331	PRE	TRAD	80	78359.6	9837.0	2.39	0.65	11.71	1.00
2009	332	PRE	JD	40	82234.5	9279.8	2.34	0.72	12.44	1.02
2009	333	PRE	TRAD	200	82665.0	10129.1	2.47	1.01	12.35	1.22
2009	334	PRE	TRAD	0	76206.8	8558.4	1.70	0.49	10.12	0.86
2009	335	PRE	JD	0	80081.7	7956.3	1.81	0.56	11.16	0.83
2009	336	PRE	JD	120	80081.7	10063.2	2.48	0.74	13.05	0.93
2009	401	PRE	JD	160	80942.8	9534.2	2.56	0.71	12.03	1.00
2009	402	PRE	TRAD	200	77067.9	8457.7	2.53	0.73	13.77	1.10
2009	403	PRE	JD	200	77067.9	8643.6	2.58	0.66	13.46	1.03
2009	404	PRE	JD	120	76206.8	9009.1	2.22	0.59	12.18	1.03
2009	405	PRE	JD	40	79220.7	7680.3	1.79	0.55	10.64	0.81
2009	406	PRE	TRAD	160	80081.7	9702.5	2.45	0.75	13.38	1.12
2009	407	PRE	TRAD	120	76637.4	10214.5	2.32	0.66	13.02	0.98
2009	408	PRE	JD	0	79220.7	7396.7	1.51	0.47	9.10	0.80
2009	409	PRE	TRAD	0	82665.0	7327.9	1.32	0.44	7.72	0.73
2009	410	PRE	JD	80	80942.8	9281.1	1.94	0.40	11.72	0.83
2009	411	PRE	TRAD	40	74915.2	8539.6	1.88	0.51	10.78	0.79
2009	412	PRE	TRAD	80	78790.1	9372.1	2.12	0.52	12.00	0.92
2009	413	FALL	JD	200	76206.8	9428.8	2.52	0.67	13.70	1.01
2009	414	FALL	TRAD	40	80512.3	7509.5	1.91	0.53	10.32	0.77
2009	415	FALL	JD	160	73193.0	9494.3	2.60	0.67	10.46	1.01
2009	416	FALL	TRAD	80	76637.4	9480.7	2.22	0.62	12.08	0.94
2009	417	FALL	TRAD	200	75345.7	10010.6	2.46	0.65	13.79	1.08
2009	418	FALL	TRAD	120	76206.8	9627.8	2.51	0.60	13.02	1.02

**Table B.3 Continued**

Year	Plot	Timing	Method	N-Rate	Population plants ha <sup>-1</sup>	Biomass kg ha <sup>-1</sup>	Earleaf%N	WP % N	Grain yield Mg ha <sup>-1</sup>	Grain %N
2009	419	FALL	TRAD	0	74915.2	7276.7	1.64	0.47	9.20	0.85
2009	420	FALL	JD	80	76637.4	9306.5	2.15	0.61	12.72	0.92
2009	421	FALL	TRAD	160	79651.2	9439.8	2.49	0.72	14.21	1.02
2009	422	FALL	JD	40	79220.7	7539.9	1.65	0.46	8.87	0.78
2009	423	FALL	JD	0	79651.2	7039.2	1.94	0.52	9.17	0.74
2009	424	FALL	JD	120	80942.8	9362.0	2.52	0.55	13.54	0.94
2009	425	SD	JD	0	74054.1	7965.1	1.75	0.47	10.12	0.86
2009	426	SD	JD	80	80512.3	8006.0	2.28	0.60	13.71	0.92
2009	427	SD	JD	120	76637.4	8471.8	2.44	0.55	13.53	1.05
2009	428	SD	TRAD	40	74915.2	7766.6	2.45	0.60	11.15	0.91
2009	429	SD	JD	160	81373.4	7796.6	2.58	0.75	12.07	1.07
2009	430	SD	TRAD	160	79651.2	7379.6	2.47	0.85	14.38	1.11
2009	431	SD	JD	200	80942.8	7421.2	2.58	0.82	10.31	1.07
2009	432	SD	TRAD	200	80081.7	8751.5	2.64	0.74	14.81	1.19
2009	433	SD	JD	40	83526.1	7373.2	2.28	0.51	12.33	0.95
2009	434	SD	TRAD	80	80081.7	7156.2	2.49	0.57	14.12	1.04
2009	435	SD	TRAD	0	80512.3	7393.0	1.60	0.46	9.71	0.81
2009	436	SD	TRAD	120	80942.8	9571.1	2.45	0.60	12.37	1.02