

Evaluation of Urea Ammonium-Nitrate Fertilizer Application Methods

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ABSTRACT

Increased nitrogen (N) costs and environmental concerns have created a need to reevaluate current sidedress N application recommendations for corn. Injection of Urea Ammonium-Nitrate (UAN) may reduce N-loss via ammonia (NH_3) volatilization compared to current surface application methods. This study evaluated injection and surface-banding application techniques of UAN in two ways: (1) by conducting a laboratory experiment where NH_3 -N loss was measured from UAN applied by both techniques across varying residue covers; and (2) by performing a field study where the application methods were compared by their effect on corn grain yield, ear leaf tissue N content, and stalk nitrate (NO_3). The laboratory system used to compare the NH_3 -N loss from the UAN application methods was evaluated and found to be capable of providing rapid, accurate, and precise measurements of N loss throughout a range of N rates and conditions. In the laboratory study, injection of UAN reduced NH_3 -N losses to <1% of applied N. Surface-banding of UAN resulted in NH_3 -N losses between 15.3 and 32.5% of applied N. Results from the field study suggest that differences between application methods were commonly seen in ear leaf tissue N, where injection of UAN was often found to increase tissue N compared to surface-banding. Also, injection of UAN reduced the optimal N rate by 25 kg N ha⁻¹ compared to surface-banding. The results suggest that injection of UAN reduces the potential of NH_3 -N losses and is a practice worth considering in developing an efficient N fertilizer program.

For the Family and Friends Unable to Share this Achievement with Me

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1 INTRODUCTION

1.1 PROBLEM, RATIONALE, AND SIGNIFICANCE

Nitrogen management is a growing concern among corn producers for two reasons: (1) the economic impact resulting from N-loss and subsequent unavailability of the nutrient for plant uptake; and (2) environmental concerns associated with the movement of N from agricultural systems into the surrounding environment. In the recent decade N prices in the U.S. have risen at a dramatic rate. Environmental effects associated with N movement into water and into the atmosphere are increasingly being studied and quantified, and has lead to increased government regulations and public pressure. This has created greater producer interest and investment into N application techniques, system management methods, and N products that may reduce N losses, increase crop N uptake, and/or decrease total N inputs while maintaining yield.

The loss of N as volatilized ammonia (NH_3) can be limited by specific management techniques or fertilizer additives. Any ammonium (NH_4^+)-forming fertilizer is subject to potential N losses via NH_3 volatilization; however urea and urea-containing fertilizers are more likely to have the greatest N losses (FAO/IFA, 2001). Synthetic fertilizer use is a major source of NH_3 in the atmosphere, contributing an estimated 9.0 Mt $\text{NH}_3\text{-N yr}^{-1}$ globally (Bouwman, 2002). The rate and extent of N loss as NH_3 depends on the fertilizer type and physical features, method of application, and environmental conditions during and post application. Soil pH, moisture content, texture, buffering capacity, cation exchange capacity (CEC), temperature, wind speed and duration, and precipitation/irrigation are environmental factors that affect NH_3 volatilization (Fenn and Hosner, 1985; Ferguson and Kissel, 1986). Many factors that contribute to increasing the rate of ammonia volatilization coincide when urea-containing fertilizers are surface applied to plant residues in no-tillage systems.

The increasing adoption of no-tillage management has prompted reevaluation of current and previous N application strategies. One N application strategy that has come under scrutiny is the surface application of urea-containing solutions to corn at growth stage V4-V6; typically known as sidedress. Urea Ammonium-Nitrate (UAN) is the primary N solution used during sidedress application in the Mid-Atlantic, and is commonly administered in a single band between corn rows onto the surface of the soil and plant residues. The primary concern for N loss

with this method is as $\text{NH}_3\text{-N}$. In conventional-tillage systems, which were the norm when previous sidedress recommendations were developed, volatilization rates and total $\text{NH}_3\text{-N}$ losses may be dramatically less compared to UAN surface applied to plant residues in no-tillage systems. To reduce $\text{NH}_3\text{-N}$ losses with minimal disturbance of these plant residues, placing the fertilizer in a band below surface residue into the mineral soil has been proposed; however, little research has been performed comparing surface-band application of UAN to subsurface banding (injection) in no-tillage systems. Furthermore, even less research has been conducted directly measuring $\text{NH}_3\text{-N}$ losses from both techniques, especially across residue types and ground cover. Ammonia-N losses and crop N use need to be evaluated under both methods of UAN application to determine if injection application is a viable practice for reducing N losses and potential yield reductions.

1.2 THESIS OBJECTIVES

1. Design and evaluate a laboratory system capable of measuring NH_3 volatilization losses from fertilizer treatments applied to an alkaline sand.
2. Evaluate $\text{NH}_3\text{-N}$ losses from surface applied and injected UAN from bare soil, corn residue, and small grain residue using the laboratory system evaluated in objective 1
3. Evaluate the influence of surface-banding and injection methods of UAN on corn grain yield, ear leaf tissue N content, and stalk NO_3 concentrations under field conditions.

1.3 PREVIOUS WORK

Urea-containing fertilizers have a greater potential for $\text{NH}_3\text{-N}$ losses compared to other $\text{NH}_4^+\text{-N}$ forming N fertilizers. This is due to urea hydrolysis, which converts urea $[(\text{NH}_2)_2\text{CO}]$ into NH_3 . Urea hydrolysis depletes H^+ from the soil system, subsequently increasing pH. In high pH conditions NH_3 formed from urea hydrolysis is less likely to be protonated into NH_4^+ , and

also, there is a higher potential for existing NH_4^+ to be deprotonated into NH_3 . Urea hydrolysis is driven by the urease enzyme that is naturally occurring in soils and plant residues. Expectedly, there are many environmental and fertilizer physical conditions that affect the rate of urea hydrolysis. A significant amount of studies have taken place evaluating many of the factors that contribute to urea hydrolysis and subsequent NH_3 volatilization from applied N fertilizers in agricultural systems.

1.3.1 Factors Affecting NH_3 Volatilization from Urea-Containing Fertilizers

The factors that affect the rate and sum of NH_3 volatilization include: (1) soil temperature; (2) soil pH; (3) soil moisture; (4) CEC and buffering capacity; (5) soil texture; (6) timing and amount of precipitation/irrigation; (7) urease activity; (8) wind speed and duration; (9) tillage practice and residue cover; and (10) fertilizer composition and physical features.

1.3.1.1 Soil Temperature

Typically, NH_3 volatilization increases linearly as the temperature of the soil increases within a range found in normal field conditions, assuming environmental conditions and urea and ammonium concentrations are held constant (Harper et al., 1983; Moyo et al., 1989; Sadeghi et al., 1988; Gould et al., 1973). In urea-containing fertilizers, this is primarily due to increased rates of urea hydrolysis, which is an enzymatic reaction (Sherlock and Goh, 1985; and Van Slyke and Cullen, 1914). Temperature-dependent equilibrium reactions $[\text{NH}_4^+(\text{sol}) \leftrightarrow \text{NH}_3(\text{sol}) \leftrightarrow \text{NH}_3(\text{g})]$ also affect NH_3 volatilization from urea fertilizers, where reaction rates increase with increasing temperature.

Van Slyke and Cullen (1914) found the temperature where the urea hydrolysis rate is at maximum to be approximately 55°C , outside of normal field conditions; however, the optimum temperature for NH_3 volatilization varies greatly depending on soil and environmental conditions at the time of application (Wagner and Smith, 1958). Ernst and Massey (1960) found ammonia loss from silty loam soil with a pH of 6 was 6, 10, 15, and 23% of N applied when soil temperature was 7, 16, 24, and 32°C , respectively. Kumar and Wagenet (1984) reported a linear increase in urease activity when soil temperature increased from 5 to 35°C . Fenn and Kissel

(1976) reported $\text{NH}_3\text{-N}$ loss increased 73% when temperature increased from 12 to 32°C. Most studies observing soil temperature effects on $\text{NH}_3\text{-N}$ volatilization have similar results, but a large number of the studies end observations within a 2 to 3 week period after application because most volatilization is believed to have occurred during this time.

Wagner and Smith (1958) reported NH_3 losses from surface applied urea at temperatures of 10°C and 25°C over a five month period. In the first two weeks after the addition of urea, NH_3 losses were higher at 25°C; after that period, total NH_3 losses were higher from the soil at 10°C. The lower temperature was thought to inhibit nitrification and maintain a higher NH_3 concentration in the soil over a longer period of time (Ernst and Massey, 1960). Results from numerous studies observing soil temperature effects on urease hydrolysis demonstrate a common increasing trend with increasing temperature (Bouwman et al., 2002). However, the rate and sum of $\text{NH}_3\text{-N}$ loss depends on a large number of environmental factors working in complex with each other.

1.3.1.2 Soil pH

Alkaline soil conditions are known to have increased NH_3 volatilization from the application of any NH_4^+ -forming fertilizer, due the increased potential of deprotonation of NH_4^+ and potential Ca-saturation on exchange sites limiting NH_4^+ adsorption (Ernst and Massey, 1960). When urea-containing fertilizers are applied in these conditions $\text{NH}_3\text{-N}$ losses may be even greater, due to the urea hydrolysis reaction further increasing pH. This is seen in a study reported by Clay et al. (1990), where an increase of soil pH from 6.5 to 9 within a period of 3 days after urea application was observed. Therefore, NH_3 volatilization from urea-containing fertilizers is commonly found to be proportional to soil pH, where $\text{NH}_3\text{-N}$ losses increases with increasing soil pH.

Volk (1959) was among the first researchers to identify a proportional increase of NH_3 volatilization from applied urea with increasing soil pH. Ernst and Massey (1960) quickly followed this study with markedly similar results. The researchers applied urea to soils adjusted to initial pH levels ranging from 5.0 to 7.5, and observed a 45% increase in $\text{NH}_3\text{-N}$ loss with a pH increase from 5.0 to 7.5. Several studies have observed similar results in that N losses, as a percentage of applied N, increased with increasing soil pH: loss increased from 7.4 to 12% with

a pH increase from 7 to 8.4 (Gangwar, 1976); loss increased from 0 to 59.2% for a pH increase from 5.50 to 7.03 (Ismail et al., 1991); and loss increased from 0 to 60% when soil pH increased from 5 to 9 (Reynolds and Wolf (1987). A global NH₃ emission estimate produced by Bouwman et al. (2002) summarized 1,667 individual measurements from 148 studies and also found similar results. The summary found a 61 percent increase in the NH₃ volatilization rate of soils with pH >8.5 as compared to soils with a pH range of 5.5 to 7.3. An 80% increase was observed when comparing to soils with a pH of <5.5. Volatilization from soils with a pH range of 7.3 to 8.5 exceeded the volatilization from soils with a pH range of 5.5 to 7.3 by 39%.

1.3.1.3 Soil Moisture

The relation of soil moisture to NH₃ volatilization rates is more dynamic than the relations expressed with soil pH and soil temperature. Observations from several studies are contradictory. Bouwmeester et al. (1985) found low initial soil moisture content reduced NH₃-N losses by an average of 7%; but, Overrein and Moe (1967) observed increasing NH₃-N loss with decreasing initial soil moisture. More and Varade (1978) report an increase of 2.25% N-loss (as a percentage of applied N) when soil moisture increased from 50 to 75% of water holding capacity.

The contradiction in reports may be explained by data developed by Stanley and Smith (1956) who found that NH₃-N loss decreased when soil moisture content increased to 5% (by weight); however, above 5% they found NH₃-N loss increased with increasing soil moisture. As soil moisture increases through the 0 to 5% moisture content range NH₄⁺ adsorption is increasing, while urea hydrolysis is inhibited. Above 5% moisture, NH₃ and NH₄⁺ produced from urea hydrolysis begins to exceed NH₄⁺ adsorption, and NH₃ volatilization begins to increase with increasing soil moisture. The specific soil moisture where NH₃ volatilization begins to increase is dependent on many soil and environmental conditions (Ismail et al., 1991).

McGarry et al., (1987) found increasing NH₃-N volatilization as soil moisture decreased below 60% field capacity; however, they observed a significant decrease in NH₃-N loss when soil moisture reached 85% field capacity. Also, reported by McGarry et al. (1987) was the significant interaction of soil type/texture and soil moisture content, which may indicate the influence of urease activity and cation exchange capacity on the effects of soil moisture on NH₃

volatilization rates. Based on previously mentioned studies, there seems to be a range of soil moisture where NH_3 volatilization rates may be at optimum, but at very low or very high moisture conditions NH_3 -N loss may be inhibited. However, defining specific soil moisture values for said range is dependent on soil and environmental conditions at the time of application.

Though evidence of initial soil moisture effects on NH_3 volatilization is contradictory, many studies find that rapid soil drying leads to reduced NH_3 -N loss compared to prolonged drying conditions (Chao and Kroontje, 1964; Ernst and Massey, 1960; Baligar and Patil, 1968; Volk, 1959; Kresge and Satchell, 1960; Simpson, 1968; Fenn and Escarzaga, 1976; Ferguson and Kissel, 1986; and Reynolds and Wolf, 1987). In urea-containing fertilizers this may be due to an inhibition of urea hydrolysis. Rapidly dried soils also may lead to drier soil surface conditions as compared to deeper portions of the soil. This may limit capillary water movement, which results in an inhibition of physical movement of NH_3 and NH_4^+ to the soil surface (Fenn and Kissel, 1976). This would explain decreased volatilization rates from ammonium-forming fertilizers not containing urea.

Overall, the effect of soil moisture on NH_3 volatilization is dynamic. Depending on soil features, NH_3 -N loss tends to decrease with increasing soil moisture until urea hydrolysis is no longer inhibited by lack of moisture. At this point NH_3 volatilization increases until conditions become saturated. Also, the rate of soil drying greatly impacts NH_3 -N loss. Conditions where rapid soil drying is discouraged increases the potential for NH_3 -N loss. Said conditions are commonly associated with no-tillage systems, where plant residues remaining on the soil surface may reduce evaporative losses and maintain higher soil moisture compared to conventionally tilled soils. Therefore, soil moisture conditions in no-tillage systems are probably an important factor when evaluating the potential of NH_3 volatilization.

1.3.1.4 Cation Exchange Capacity and Buffering Capacity

Buffering capacity is directly related to CEC; therefore, for the purposes of this review studies focusing on the effects of CEC on NH_3 volatilization will be used. Most research concerning the effect of cation exchange capacity (CEC) has indicated an inverse relationship NH_3 volatilization to CEC (Fenn and Kissel, 1976; Lyster et al., 1980; Volk, 1959; Bouwman et

al., 2002). This may be due to increased NH_4^+ adsorption sites in the soil; thus, removing NH_4^+ from soil solution resulting in less potential for conversion to NH_3 . Also, as CEC increases there is increased buffering of soil pH, which would reduce the effects of urea hydrolysis (Ferguson et al., 1984). Overall, the effect of CEC is based on the inhibition of the transformation of NH_4^+ to NH_3 .

Fenn and Kissel (1976) observed increased NH_3 -N volatilization when CEC was approximately less than 20 meq/100 g. Soils with CEC above 20 meq/100 g experienced little or no difference in NH_3 -N loss between soils with increasing CEC (Fenn and Kissel, 1976). Lyster et al. (1980) found negligible NH_3 -N loss when CEC was above 25 meq/100 g, but volatilization rates increased rapidly below the 25 meq/100 g threshold. Volk (1959) observed similar results with bare sandy soil at CEC 7.2 meq/100g experiencing NH_3 -N loss of between 17 to 58% of N applied. A review of literature performed by Bouwman et al. (2002) determined soils with a CEC $<32 \text{ cmol kg}^{-1}$ had significantly increased NH_3 volatilization compared to soils above $>32 \text{ cmol kg}^{-1}$.

Cation exchange capacity near the soil surface is commonly higher in no-tillage systems than in conventional-tillage systems; therefore, the potential for NH_3 volatilization, if all other environmental conditions have negligible effects, would be considered lower in no-tillage situations. However, when urea-containing fertilizers are surface applied in no-tillage systems, the actual placement of the fertilizer is typically onto plant residues where CEC may be dramatically less than at the surface of the mineral soil.

1.3.1.5 Soil Texture

The texture of soil affects soil temperature, soil moisture, CEC, and urease activity, all of which impact NH_3 volatilization in some way. Soils containing high clay contents are commonly associated with increased CEC, soil moisture, and urease activity and increased temperature buffering. Sandy soils have the opposite effect. Very few studies have directly compared the effects of soil texture on NH_3 volatilization from urea fertilizers, but rather focused on said properties affecting NH_3 -N. Based on a review of many of these studies by Bouwman et al. (2002), soils with greater clay contents significantly reduced NH_3 -N loss from both urea-containing and NH_4^+ -forming fertilizers compared to soils predominately sandy in texture. In no-

tillage systems where urea-containing fertilizers are surface applied onto plant residues, soil texture may have a negligible effect on NH_3 volatilization unless the temperature and moisture of the residue is dramatically influenced by the underlying soil.

1.3.1.6 Timing and Amount of Precipitation

Rainfall following the application of urea-containing and NH_4^+ -forming fertilizers may reduce NH_3 volatilization through multiple actions: (1) reducing the concentration of NH_3 and NH_4^+ in the immediate vicinity of the fertilizer, (2) dissolving and dispersing granular fertilizers, and (3) transporting dissolved fertilizers deeper into the soil profile, therefore, increasing the potential for NH_4^+ adsorption (Harper et al. 1983; and Keller and Mengel, 1986). However, if the amount of precipitation that is experienced is insufficient at performing the previously stated actions then NH_3 volatilization may be increased significantly (Oberle and Bundy, 1987). Also, timing of the rainfall event is critical; for example, a rainfall event at an adequate amount to reduce NH_3 volatilization may have little to no effect on the total $\text{NH}_3\text{-N}$ loss if most of the volatilization has occurred before the event. Quantification of exact rainfall amounts and timing after application to reduce $\text{NH}_3\text{-N}$ loss is site and climate dependent due to the complex of other environmental factors affecting NH_3 volatilization; however, many studies have been performed, and general rainfall figures and recommendations have been created.

Black et al. (1987) found misting 0, 4, and 16 mm of water on to soil at field capacity within 3 h of the application of 10 g N m^{-2} urea to pasture produced $\text{NH}_3\text{-N}$ losses of 28.1, 9.2, and 1.8% of applied N, respectively. However, delaying the watering until 48 h after application only produced an $\text{NH}_3\text{-N}$ loss reduction of 0.24 g N m^{-2} with the addition of 16 mm of water. The study also found that repeated additions of 2 mm of water produced bursts of hydrolysis and $\text{NH}_3\text{-N}$ loss until hydrolysis was complete. The total $\text{NH}_3\text{-N}$ loss of this treatment was 3.94 g N m^{-2} , significantly greater than the treatment with no additions of water (2.81 g N m^{-2}). Based on the results in this study, a significant portion of NH_3 volatilization occurred within 48 h of application, and water added at an amount of at least 4 mm soon after the fertilizer application significantly reduced $\text{NH}_3\text{-N}$ loss. However, the addition of water beyond the 48 h interval had little effect on total $\text{NH}_3\text{-N}$ loss, and the addition of water at 2 mm throughout the trial significantly increased $\text{NH}_3\text{-N}$ loss. Bouwmeester et al. (1985) found contradictory results in that

the addition of 8 mm of water every 3 d after urea application maintained urea hydrolysis without inducing leaching; therefore, exaggerating $\text{NH}_3\text{-N}$ loss. The study also found that volatilization could be reduced from 40% to 13% with an addition of 4 cm of water immediately after urea application.

Kissel et al. (2004) found similar results to the Black et al. (1987) study in that the addition of 4 and 11 mm of water added 4 days after urea application to pine needles resulted in significant difference in $\text{NH}_3\text{-N}$ loss compared to no addition of water. The study also found $\text{NH}_3\text{-N}$ loss was increased or not affected by the addition of rainfall unless the urea granules were dissolved by the morning dew. This was attributed to inefficient downward leaching of urea due to the pine needles found on the surface of the mineral soil and the increase in water content.

Though this study used pine needles as the residue cover, it may be comparable to no-tillage situations where plant residues are undisturbed on the soil surface and may impede downward leaching thus increasing the amount of rainfall needed to reduce $\text{NH}_3\text{-N}$ loss compared to soils with no surface residues. Fox et al. (1986) found $\text{NH}_3\text{-N}$ losses were strongly influenced by the number of days after application until a total of 10 mm of rain fell in no-tillage systems. In this study, the apparent $\text{NH}_3\text{-N}$ loss ranged from 5.0% of applied N with 10 mm of rainfall within 2-3 days after application to >30% of applied N with 5-7 days of dry weather after application. By comparing this study to the Black et al. (1987) study, we can observe a reduced rainfall amount needed to inhibit NH_3 volatilization in situations where surface residue is not present compared to situations where it is. This further supports the theory that no-tillage systems have an increased potential for NH_3 volatilization from surface applied urea fertilizers due to the conditions created by plant residues at the surface.

1.3.1.7 Urease Activity

Ammonia volatilization from urea-containing fertilizers is dependent on urease activity, since urea hydrolysis is mediated by the urease enzyme. Therefore, greater urease activity generally produces increased NH_3 volatilization. Urease activity is dependent on various environmental conditions including, but not limited to: soil temperature, urea concentration, and plant residue.

Temperature is commonly known to affect enzyme activity. Urease activity increases with increasing temperatures until the point at which the urease enzyme is denatured. Optimum temperature for urease activity varies greatly between studies, ranging from 45 to 70°C; however, these temperatures are well beyond observed temperatures in field conditions (Gould et al., 1973; Kumar and Wagenet, 1984; Moyo et al., 1989; and Bhupinderpal et al., 1992).

Urea concentration in the soil solution can vary widely after application due to the rate and method of application, soil water content, and movement of urea away from the application site (Kissel et al., 2008). Concentrations around 1 M urea N may be present within 48 h of application, but in most cases soil solution concentrations of urea may be closer to 0.2 M urea N (Kissel et al., 2008). Numerous studies suggest the effect of urea concentration on urease activity can be best described by Michaelis-Menten enzyme kinetics when urea concentrations are below 1.0 M urea N (Paulson and Kurtz, 1969; Dalal, 1975; and Pettit et al., 1976). However, in situations where urea concentration above 1.0 M urea N, urease activity may be described by the sum of two Michaelis-Menten equations; one without inhibition by urea and one with uncompetitive inhibition by urea (Kissel et al., 2008; Singh and Nye, 1984). Singh and Nye (1984) found using this method the maximum rate of urea hydrolysis, which is assumed as an indicator for urease activity, to be between 4 to 6 M urea N. However, actual optimum urea concentrations for urease activity vary depending on soil type and pH (Cabrera et al., 1991). For example, Cabrera et al. (1991) found that urea hydrolysis increased as urea-N concentration increased from 0.01 to 10 M at pH levels from 5.5 to 8.5, but at a pH of 9.5 urea hydrolysis was inhibited at 6 M urea-N on a Cumulic Hapludoll and at 8 M urea-N on a Typic Argiudoll.

Plant residues also have a major impact on urease activity. Crop residues can be actively colonized by saprophytic microorganisms, which in turn, enhance the urease activity of the crop residue (Goos, 1985b; and Lal et al., 1993). However, studies suggest there is a difference in urease activity between the residues of plant species. Frankenberger and Tabatabai (1982) found graminaceous plants exhibited the highest urease activity of 21 plant species; whereas, Cruciferae and Tilliaceae plant families had no urease activity. McInnes et al. (1986) observed urease activity 20 times higher in wheat residue than in the surface 10 mm of soil beneath it. Barreto and Westerman (1989) reported similar results, where urease activity of wheat residue was found to be 28 times higher than the surface 10 mm of soil. Dick (1984) reported cropping rotations in no-tillage management resulted in differences in urease activity. A continuous corn

rotation was found to have less urease activity than a corn-oats-alfalfa rotation in the upper 7.5 cm. These studies suggest typically high urease activity at the soil surface in no-tillage systems. However, very few, if any, studies have directly compared small grain and corn residues' urease activity or impact on NH_3 volatilization.

1.3.1.8 Wind Speed and Duration

The effect of wind speed and duration can have complex effects on NH_3 volatilization. Harper (1995) reported increasing wind speed would promote more rapid transport of NH_3 from the soil surface; therefore, if NH_3 is in steady supply, higher wind speeds would increase NH_3 -N loss. This is primarily due to increased gas exchange from a lower partial pressure at the ground surface (Overrein and Moe, 1967; and Harper, 1995). However, increased wind speed dries soil. Depending on the speed and extent of drying at the soil surface, an increase in wind speed could either increase or decrease NH_3 volatilization. Nathan and Malzer (1994) found that increased wind speed produced higher solution concentrations of NH_3 due to the drying effect. Contrarily, Bouwmeester et al (1985) concluded that the drying effect would impede NH_3 movement upward; therefore, reducing total NH_3 -N loss. They also found this effect was dependent on the humidity of the air, and that conditions where humidity was high higher wind speeds would actually increase NH_3 -N loss.

1.3.1.9 Tillage Practice and Residue Cover

There are many studies evaluating the effect of tillage practice and urea fertilizer placement on NH_3 volatilization and there are conflicting reports on the effect of plant residues on NH_3 -N loss from surface applied urea-containing fertilizers in no-tillage systems. Clay et al. (1990) found that plant residues on the soil surface reduced NH_3 volatilization by reducing the maximum soil temperature and increasing the soil water content. It has also been suggested that old residues, those exposed to long periods of sunlight, high temperatures, and moisture fluctuations, may have significantly reduced urease activity; therefore, reduced NH_3 volatilization may be observed from surface applied urea fertilizers onto these residues (Schilke-Gartley and Sims, 1993).

Most studies, however, report an increase in NH_3 volatilization from surface application of urea fertilizers in no-tillage systems. Crop residues may increase $\text{NH}_3\text{-N}$ losses in numerous ways: (1) higher urease activity compared to the soil; (2) increased surface area for urease activity and volatilization to occur; (3) promotion of slow drying periods compared to soil surface; and (4) formation of a physical barrier between the N source and the soil (Al-Kanani and Mackenzie, 1992; Dick, 1984; Hargrove, 1988; Francis et al., 2008; and Whitehead and Raistrick, 1990). These factors would suggest that regardless of urease activity of the residue, $\text{NH}_3\text{-N}$ losses from surface applications of urea fertilizers would generally be expected to remain higher than for fertilizer applications to bare soil.

1.3.1.10 Fertilizer Properties

Though all NH_4^+ -forming fertilizers have the potential for N losses via NH_3 volatilization, certain fertilizers have a greater potential for loss than others. Typically, urea and urea-containing fertilizers have greater $\text{NH}_3\text{-N}$ losses compared to other N fertilizers (Bandel et al., 1980; Botha, 1987; Fox and Hoffman, 1981; and Oberle and Bundy, 1987). This has a profound effect globally since urea-based fertilizers are the most common N source in agricultural settings worldwide. Extensive research has been performed comparing the effects of fertilizers types on NH_3 volatilization, and urea fertilizers are considered to have the greatest potential for $\text{NH}_3\text{-N}$ losses due to urea hydrolysis, the chemical reaction that transforms urea into NH_4^+ . Therefore, for the purpose of this thesis, the effects of specific chemical and physical properties of urea-containing fertilizers, as well as application method, on NH_3 volatilization will be considered in this review.

Alterations to urea fertilizer compositions and certain physical properties of the fertilizers can have a major effect on NH_3 volatilization. Solid urea fertilizers are considered to have a higher potential of NH_3 volatilization than UAN solution fertilizers (Francis et al., 2008). A study by Reynolds and Wolf (1987) found the form of urea, either prilled, granular, and solution urea, had no significant difference on NH_3 volatilization. Al-Kanani and MacKenzie (1992) found UAN at a ratio of 1:1 urea to ammonium nitrate resulted in substantially more $\text{NH}_3\text{-N}$ loss compared to UAN at a ratio of 1:2 urea to ammonium nitrate. This study confirmed that the urea component of the fertilizer solution is largely responsible for NH_3 volatilization, and that there

may also be a pH buffering effect from the AN portion. This could relate in less NH_3 loss from the urea component of UAN compared to urea-only fertilizer.

There are two main strategies available to producers to limit the potential of NH_3 -N loss via volatilization: chemical fertilizer additives and application/management techniques. Fertilizer additives have three potential modes of action for limiting NH_3 volatilization: (1) limiting urease activity in the proximity of the fertilizer; (2) providing a physical coating on solid urea that inhibits the dissolution of the fertilizer until a general volume of rainfall is met; and (3) chemical coatings on solid urea forms that alter the chemical properties of the soil near the fertilizer.

Clay et al. (1990) observed a 100 fold decrease in NH_3 -N loss with urea coated with N-(butyl)thiophosphoric triamide (NBPT) compared to urea alone. NBPT is a urease inhibitor; therefore, delaying the transformation of urea to NH_4^+ and reducing the potential of NH_3 -N loss. The study also observed an increase in pH of 6.5 to 7.2 from the urea-NBPT treatment, which was considerably less compared to the 6.5 to 9.0 increase in the urea only treatment. Fox and Piekielek (1993) observed similar results with the addition of NBPT to UAN, noting a significant increase in yield and N uptake compared to UAN alone.

Goos (1985a) studied the effects on NH_3 volatilization from the addition of ammonium thiosulfate (ATS) and ammonium polyphosphate (APP) to liquid UAN. The addition of ATS was found to retard urea hydrolysis and reduced NH_3 -N loss by 45% compared to UAN alone. However, the addition of APP had no effect on volatilization until the droplet size of the fertilizer increased to beyond 0.5 ml, which may be due to a pH-buffering effect. Ambily et al. (2003) found surface applied urea, coated with neem and nimin, significantly reduced NH_3 -N loss.

Matocha (1976) found urea granules coated with elemental sulfur substantially reduced NH_3 -N loss compared to uncoated urea, and N recovery by corn was significantly higher with the coated urea. Lightner et al. (1990) found that urea in solution mixed with CaCl_2 significantly lowered volatilization compared to urea alone on a silt loam soil. The study also found that KCl mixed with urea in solution did not reduce NH_3 volatilization compared to urea alone. This could have been due to too little KCl present in the solution, since previous studies investigating KCl-urea solutions have found significant NH_3 -N loss reductions compared to urea alone.

There is a large selection of chemical additives for N fertilizers that have been proven to reduce NH_3 volatilization, such as NBPT, ATS, Sulfur-coatings, and organic-coatings; however,

additives currently available to crop producers in the Mid-Atlantic region are typically costly. There are application techniques known to reduce NH_3 volatilization as well as, if not better, than chemical fertilizer additives. For example, incorporation of urea fertilizers and injection of urea solutions into the soil are methods proven to reduce NH_3 volatilization, but these methods may be restricted due to management practices or costs associated with equipment and labor. Costs and management goals need to be considered when adopting the use of fertilizer additives or new application methods.

1.3.2 Urea Ammonium-Nitrate Application Methods

There are two primary methods of application for UAN solution fertilizers, surface-banding and injection. Surface-banding, as the name implies, dribbles the fertilizer along the surface of the soil or residue in a band. This method is the most commonly used method of UAN application for corn sidedress in the Mid-Atlantic region. However, NH_3 -N losses are potentially significant from this method of application, especially in no-tillage systems. Injection application places the fertilizer solution below crop residue into the mineral soil, where the potential of NH_3 volatilization is greatly reduced.

1.3.2.1 Comparison of Application Methods by NH_3 -N Loss

Reported NH_3 -N losses from surface-banded UAN varies greatly, which is primarily due to varying environmental conditions between studies. Keller and Mengel (1986) observed NH_3 -N losses of 9.2 and 14.6 kg N ha⁻¹ from UAN surface applied to no-tillage corn after 5 days. Al-kanani et al (1990) reported an NH_3 -N loss of 21.3% of applied N from surface application onto bare soil after 10 days. Al-kanani et al. (1991) reported an NH_3 -N loss of 19% of applied N under similar situations. The following year they reported NH_3 -N losses between 0.8 and 9.5% of applied N after 9 days from UAN surface applied to conventionally tilled and no-tillage soil, respectively (Al-kanani and Mackenzie, 1992). Oberle and Bundy (1987) found NH_3 -N losses from surface applied UAN onto conventionally tilled soils ranged from 0 to 12% of applied N. From aforementioned studies, NH_3 -N loss from surface applied UAN varies from 0 to >20% of applied N with greatest losses observed in no-tillage conditions.

Injection of UAN has been shown to essentially eliminate $\text{NH}_3\text{-N}$ loss (Mengel et al., 1982; Touchton and Hargrove, 1982; Fox et al., 1986). This is expected since the solution is placed into the mineral soil where there is increased pH buffering and NH_4^+ adsorption, and decreased gas exchange due to the physical barrier created by the residue, and potentially decreased urease activity, which is dependent on the condition of the residue. Also, since plant residues decrease evaporative losses from the soil, moisture content is also generally higher in the soil than in the plant residues. This would decrease the concentration of NH_3 and NH_4^+ in solution and provide increased opportunities for NH_4^+ adsorption and NH_3 protonation.

Injection application of UAN is considered to reduce $\text{NH}_3\text{-N}$ losses considerably compared to surface-banding, especially in no-tillage systems. However, very few studies have compared these two methods across different residue types and N rates. It is also apparent that surface application of UAN can result in very low or negligible $\text{NH}_3\text{-N}$ losses. In these situations, the injection method would be similar to surface-banding application, in terms of $\text{NH}_3\text{-N}$ loss. This would explain the variability in results from studies evaluating the two application methods by observing grain yield, tissue N, and N uptake.

1.3.2.2 Comparison of Application Methods through Grain Yield and N Uptake

Numerous studies found surface-banding and injection application of UAN produced higher yields and N uptake than broadcast spraying of UAN (Bandel et al., 1984; Eckert, 1987; Fox and Bandel, 1986; Mengel et al., 1982; and Touchton and Hargrove, 1982). However, many studies report no difference between surface-banding and injection applications of UAN (Bandel et al. 1984; Eckert, 1987; Fox and Bandel, 1986; Fox et al., 1986). Some studies found injection of UAN produced higher yields or N uptake, but also reported this effect was inconsistent across sites or seasons (Eckert, 1987; Touchton and Hargrove, 1982) Fox et al. (1986) proposes there are two possible causes for lack of difference between methods: (1) there was no NH_3 volatilization loss from the surface-applied UAN; or (2) the injection technique failed to prevent $\text{NH}_3\text{-N}$ loss or caused a comparable loss by some other pathway.

From the studies and considerations presented in section 1.3.2.1, we can infer that the lack of difference between application methods in most cases is probably due to negligible $\text{NH}_3\text{-N}$ losses from the surface application of UAN. However, there may have also been situations

where NH_3 volatilization was significantly greater from surface-banding than injection of UAN, but any effect on grain yield, crop tissue N, or N uptake could have been masked by variation within the studies. Either way, results from studies evaluating surface-banding and injection of UAN are variable. Injection of UAN, though considered to be the most efficient method of application by reducing the potential for N-loss, does not always equate to increased grain yield or decreased crop N needs.

1.4 SUMMARY AND CONCLUSION

Urea-containing fertilizers are the most common N source in the United States, but have the greatest potential for NH_3 volatilization N losses of all available N sources (Bandel et al., 1980; FAO/IFA, 2001). Therefore, there is continual pressure to develop management strategies that eliminate the potential for N loss. In order to evaluate an application method or other technique for reducing NH_3 -N losses, there needs to be an appreciation for the factors that affect NH_3 volatilization

Increases in soil temperature, pH, urease activity, and wind speed/duration generally increase NH_3 volatilization from urea-containing fertilizers. Soil temperature affects urea hydrolysis rates and some equilibrium reactions. Increased soil pH reduces the potential for NH_3 , formed from urea hydrolysis, to be protonated into NH_4^+ , and also increases the potential for existing NH_4^+ to be converted into NH_3 . Urease activity is directly related to the rate of urea hydrolysis; therefore, it can have a major impact on NH_3 volatilization. The effect of wind on NH_3 volatilization is dynamic. Typically, increased wind speed and duration increases gas exchange between the soil and atmosphere; therefore increasing NH_3 -N loss. However, in certain situations windy conditions can lead to the soil and residue surface drying rapidly, which could decrease the total NH_3 -N loss experienced. Increased CEC and pH buffering capacity of the soil tends to decrease the potential of NH_3 volatilization.

Soil moisture and rainfall amounts and timing have dynamic and often variable, effects on NH_3 volatilization. Generally, there is a low range of soil moisture where NH_3 -N loss decreases as moisture increases, but at some soil moisture level this effect switches until the soil becomes saturated. Gradual evaporative losses also may increase NH_3 -N losses; whereas, rapid drying of the soil tends to decrease NH_3 volatilization. Rainfall is generally thought to reduce

NH₃ volatilization by leaching of surface applied fertilizer into the soil, but in situations where there is an inadequate rainfall amount to leach the fertilizer, NH₃-N losses may be increased. It also should be noted that a significant portion of NH₃ volatilization occurs within 48 h after application; therefore, even adequate rainfall beyond this time may not have a major effect in reducing total NH₃-N loss.

Findings from studies evaluating NH₃ volatilization from urea fertilizers surface applied onto plant residues in no-tillage systems are variable. However, the presence of plant residues is generally considered to increase the potential of NH₃ volatilization due to increased urease activity and the promotion of slower soil drying or prolonged evaporative losses. Surface residues also may increase the amount of rainfall necessary to leach the fertilizer into the soil. It should be acknowledged that weathered plant residue may have reduced urease activity compared to the mineral soil, which in this case would reduce the potential for NH₃-N losses.

When evaluating methods for UAN application the above factors need to be considered. Broadcast-spray application was a common method of UAN application at one time. However, this method encourages significant NH₃-N losses by increasing the surface area onto which the fertilizer is applied. This would lead to rapid urea hydrolysis and enhanced effects on NH₃ volatilization from evaporative losses and wind. Surface-banding UAN was proposed as an alternative method to broadcast-spraying. Studies soon proved NH₃-N losses were significantly less with surface-banding method, and adoption of this method increased. Injection of UAN was then proposed as an alternative to both broadcast-spraying and surface-banding in no-tillage systems where incorporation of the fertilizer was restricted. Again, studies soon proved that injection of UAN essentially eliminated NH₃-N losses. However, studies evaluating the grain yield and N uptake from surface-banding and injection application of UAN reported variable results. It was quickly realized that in many situations NH₃-N loss from surface-banding was small enough that the injection method would not produce increased grain yields or N uptake.

Corn producers are seeking ways to limit N input due to increased N costs and public pressure. Injection application of UAN may be a method that further minimizes the potential for N loss. Though results from many studies suggest injection application of UAN is inconsistent in comparison to surface-banding, intuitively there may be a long-term benefit in the reduction of NH₃ volatilization potential.

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2 DESIGN AND VALIDATION OF A LABORATORY SYSTEM FOR MEASUREMENT OF VOLATILIZED AMMONIA

2.1 ABSTRACT

The design of laboratory systems for studying ammonia (NH₃) released from fertilizers varies widely, and few designs have been tested to determine the accuracy and precision in measuring ammonia loss. A standard volatilization system design is needed for reliable and comparable studies of ammonia volatilization from nitrogen fertilizer. The objectives of this study are: (i) to describe the design of a system capable of controlling air flow rate and temperature for laboratory measurement of NH₃ volatilized from N fertilizers; and (ii) assess the system's efficiency and variation in recovering NH₃ lost from NH₄Cl applied to an alkaline sand media. The system is comprised of individual chambers for soil and fertilizer, where temperature can be varied from room temperature to ~32° C; humidity is maintained near saturation, air flow rate can be varied, and acid traps are used to capture volatilized NH₃. Two initial trials (I and II) were conducted at an N rate of 90 kg N ha⁻¹ using air flow rates of 2.00 and 1.00 L min⁻¹ and trapping acid volumes of 50 and 100 ml, respectively. A third trial was conducted at 30 °C. A fourth trial (IV) was performed using a range of N application rates (25 to 250 kg N ha⁻¹). The system recovered 89.3% to 97.1% of the N applied over all four trials and provided accurate and repeatable results under the conditions tested. Rapid, precise comparisons of NH₃ volatilization losses from N fertilizers under laboratory conditions can be made with this system.

2.2 INTRODUCTION

Volatilization of NH₃ from N fertilizers is one of many processes where N is lost from the soil environment. Volatilization of NH₃ after fertilizer application did not receive substantial attention as a possible source for N loss until the 1950's (Freney et al., 1983). NH₃ volatilization reduces N-use efficiency (defined as N yield per unit of applied N) and creates uncertainty in the management of N at the farm level. The study of NH₃ volatilization requires equipment and practices that limit direct and indirect influences of factors that affect the volatilization of NH₃. Developing models to accurately predict NH₃ volatilization amounts in cropping systems, pastures or forests is difficult given the complexity of these biological systems.

Methods of measuring NH_3 volatilization from N sources, organic amendments or inorganic fertilizers, can be divided into two general classes: i) in-situ and ii) in-lab or controlled environment experiments. All in-situ NH_3 volatilization methods are disadvantaged by the inability to control climatic factors (e.g. rainfall timing and amount, humidity, and temperature) that directly influence NH_3 volatilization rates. These studies typically monitor these factors, but are unable to replicate exactly the factors across multiple studies or treatments unless all are performed during the same period and on the same site. Also, seasonal fluctuations limit the period in which reliable in-situ studies can be performed.

In-lab controlled studies can maintain environmental factors affecting NH_3 volatilization across multiple treatments and multiple treatment periods. Also, in-lab studies can be performed year-round with limited time needed for set-up between treatment periods. Reduced sample sizes allow for a larger number of treatments and replications. Results obtained from well-designed systems can provide reliable comparisons between treatments.

The primary method to measure NH_3 volatilization in laboratory studies utilizes a closed chamber, containing soil and N fertilizer amendments to be evaluated, and forced air flow across the treatment surface with an acid trap to capture the volatilized NH_3 (Hargrove and Kissel, 1979; Terman, 1979; Shi et al., 2001; Kissel et al., 2004; Portejoie et al., 2004; Todd et al., 2006, Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009). Many in-lab systems have incorporated humidification features, temperature controls, acid traps to scrub NH_3 from air being drawn into the system, and air flow controls. The design of in-lab systems is inconsistent, but performance of several laboratory systems used to measure ammonia volatilization have been studied and NH_3 recovery values have varied from 72.9 % to 103% with varying levels of consistency in the measurements (Table 2-1). Currently, in-lab volatilization systems are primarily being used to measure NH_3 released from manures (Cole et al., 2005; Miles et al., 2008; Portejoie, 2004; Shi et al., 2001; and Todd et al., 2006). Inorganic fertilizer studies using in-lab systems are less common, but are increasingly being performed (Knight, 2007; Rochette et al., 2009; and Susilawati et al., 2009). The detailed construction and operation of in-lab systems vary among studies, and again, few experiments have examined factors affecting NH_3 recovery within the specific system (Miles et al., 2008 and Ndegwa et al., 2009). These factors include: air flow rate, trapping acid (source, concentration, and volume), temperature and humidity conditions. In order to ascertain the validity of data from controlled environment systems, newly

designed in-lab systems need to be tested to determine the system's NH_3 recovery efficiency within an estimated range of potential NH_3 volatilization rates.

2.3 OBJECTIVES

- 1) To describe a controlled-environment volatilization system used for laboratory studies of NH_3 volatilization
- 2) To assess the system's efficiency and variation in recovering NH_3 lost from NH_4Cl applied to an alkaline sand media

2.4 MATERIALS AND METHODS

2.4.1 System Design

The NH_3 volatility measurement system as tested consists of three temperature-controlled enclosed cabinets that house six chambers each to which treatments are applied to soil or other media. Humidified (near 100%) air is passed through each chamber above the soil media of each chamber at a constant flow rate and temperature. Air exiting the chamber is collected by acid traps to recover ammonia lost by volatilization. Soil temperature within each chamber is monitored using thermocouples to ensure accurate and even temperatures within and across each chamber (Brooks Whitehurst Associates Inc., New Bern, NC). A materials list and prices are in Table 2-2 and the schematic for the system is shown in Fig. 2-1.

The enclosed cabinets are constructed using 9.5 mm thick plywood with the internal dimensions of 61 cm in width, 61 cm in length, and 46 cm in depth. The lid of the cabinets lifts off and was constructed to overhang the outside edge of the cabinet. The lid has a rim that fits securely within the internal dimensions and was insulated using 13 mm thick Styrofoam® sheath insulation (R value = 3). The temperature within the cabinets is controlled using a 1/32 Din programmable controller (CN7533, Omega Engineering Inc., Stamford, CN). The air temperature sensor (RTD-805, Omega Engineering Inc., Stamford, CN) used by the temperature controller is mounted on the opposite side of the cabinet from the heating element. The heating element was fabricated by attaching a silicone rubber heat strip (2.5 cm x 20 cm, 80 watts total, SRFG-108/10-P, Omega Engineering Inc., Stamford CN) to an angular aluminum strip

mounted on a rectangular block (4.1 cm x 4.1 cm x 20 cm long - 90°). An electric fan (2000 rpm, 120x120x25mm, 115 V, 60 Hz, 0.10 A) (BT12025B1L, CoolerGuys.com, Kirkland, WA) was placed above the heating element to disperse heat and circulate air inside the cabinet. A wooden baffle (19 mm wide, 30.8 cm long, 28 cm tall) with ends that angle (20-30°) towards the chambers (14 cm long outside and 13cm long inside) (Fig. 2-1). A raised platform for the chambers are used to insure uniform heat dispersal around the chambers (Fig. 2-1). The air supply to the entire system is provided by a oil-less linear air pump (DDL80-101, Gast Manufacturing Inc., Benton Harbor, MI) that pressurizes and fills a supply tank. This pump has a max power output of 93 watts, air flow rates range from 111-120 L min⁻¹ from 50-60 Hz, and maximum pressure of .48 bars. The lines carrying the air from pump to the supply block are 16 mm OD and 13 mm ID vinyl lines. The air pressure is monitored and regulated for the system at the supply tank. Air exiting the supply tank is supplied to three distribution manifolds via the same size vinyl line entering the supply tank. All fittings and connections for the 16 mm vinyl lines are secured by plastic hose clamps (SNP-2, Cole-Parmer Instrument Co. 95613-03). Each distribution manifold is used to supply air to six flow meters (0.4-5.0 L min⁻¹ flow meters – EW22461-50, Cole-Parmer Instrument Co., Vernon Hills, IL). Air exiting the distribution manifold flows through 6.4 mm OD and 4.3 mm ID vinyl hose. This size vinyl hose is what carries the air throughout the rest of the system. All fittings and connections for this size vinyl hose are secured with SNP-1 plastic hose clamps (Cole-Parmer Instrument Co. 06832-01). Air from the flow meters is then sparged through air stones (Coarse Bubbles, Kordon LLC., Hayward, CA) to reduce the bubble size inside a set of closed cylinders (external humistats) containing water purified by reverse osmosis (RO). This step saturates the air prior to entering the temperature controlled cabinet. Air exiting the external humistats is sparged through a second set of air stones inside a second set of closed cylinders containing RO water (internal humistats) within the controlled-temperature cabinets. This ensures no decrease in humidity due to the change in temperature between outside and inside the cabinet. Also, the second humidification step ensures the air temperature is brought to the temperature within the cabinets. The system was designed to increase the humidity of the air entering the chambers to a level that approaches 100% humidity and levels cannot be varied with the current system. Air from the internal humistats is routed into the individual chambers and then into an acid trap specific to each chamber. Since this is a laboratory system and based on the assumption that ambient NH₃

concentrations are below our capacity to detect, the humistats are for humidity purposes only and do not act as NH₃ scrubbers.

The chambers consist of threaded 100 mm by 150mm beakers (21650 B, Kimble Chase Life Science and Research Products LLC, Vineland, N.J.) and three-hole plastic caps (21650 C3, Kimble Chase Life Science and Research Products LLC, Vineland, N.J.). Two 9.5 mm holes with threaded fittings (threaded on top surface) are used in the cap for the air entry and exit ports, and a third 3.2 mm threaded hole is used to position the thermocouple into the soil media. The air entry port uses a portion of a small PVC pipe, same size as the incoming vinyl tubing, allowing the air to enter 6.4 mm above the soil surface. The air exit port extends 6.4 mm below the bottom face of the lid. The design allows for the air to move across the soil surface collecting ammonia, before being forced up exiting the chamber. Once filled the head space above the sand is 0.527 ± 0.005 L, and at an air flow rate of 1.00 L/min the air within each chamber is replaced every 32 seconds.

Temperature data from the soil media chambers were collected by type T thermocouples (TT36-18U-6-SB, Omega Engineering Inc., Stamford, CN) inserted through a 1/8 hole in the cap of each chamber. Analog signals from the thermocouples were converted to digital temperature readings using a 22 bit A/D converter (DAQ-56, Omega Engineering Inc., Stamford, CN). Temperature data from type T thermocouples and temperature control equipment were calibrated against a NIST Traceable™ digital thermistor (90080-12, Cole-Parmer Instrument Co., Vernon Hills, IL). Software provided with the A/D converter enables temperature data storage on the linked computer.

The acid traps were 125 ml plastic bottles (PCR8DB, Specialty Bottles, Seattle, WA) filled with 50 or 100 ml of acid solution. An air stone is used in each acid trap to reduce the bubble size passing through the 0.02 M phosphoric acid solution.

2.4.2 System Validation

To validate the laboratory system, four loss-and-recovery trials (I, II, III and IV) were conducted to determine the recovery efficiency and variability of NH₃ volatilization between each individual chamber. We used a similar method outlined by Cabrera et al. (2001) in that we applied ammonium chloride (NH₄Cl) to an alkaline sand media. The sand media was a mixture of CaCO₃ and sand, purchased at a local hardware store. Trials I and II tested the accuracy and

precision of the system to measure NH_3 loss at different air flow rates and acid trap volumes at a standard N rate of 20 mg N per chamber (90 kg N ha^{-1}) and a temperature of 26°C . Nitrogen rates were based on a weight basis, using 2.245 million kg soil per ha furrow slice, then calculating the 90 kg N ha^{-1} rate. Nitrogen was applied as an ammonium chloride solution to deliver the required N rate by dripping five milliliters of solution on the surface of the sand- CaCO_3 mixture. Trial III evaluated accuracy and precision of the system at 30°C . Trial IV tested the system over multiple N rates using the most accurate and precise air flow and acid trap volumes determined from trials I and II.

The duration of trial I was three weeks (504 h). We limited the run length of trials II, III, and IV to two weeks as volatilization losses were minimal after two weeks. The air flow rates were 2.00 L min^{-1} and 1.00 L min^{-1} for trials I and II, respectively. The volume of acid in the acid traps for trials I and II were 50 and 100 ml, respectively. Trial II air flow rate and acid volume were found to produce more precise NH_3 loss measurements; therefore, an air flow rate of 1.00 L min^{-1} and an acid volume of 100 ml were used for trial III, at a temperature of 30°C , and trial IV with multiple N rates. N rates for trial IV were 0, 25, 50, 150, 200, and 250 kg N ha^{-1} replicated three times. The temperature during trials I, II and IV was $26.0 \pm 0.5^\circ \text{C}$ and $30.0 \pm 0.3^\circ \text{C}$ for trial III.

The set-up of the system prior to commencing a trial consisted of making the alkaline sand media by adding calcium carbonate (CaCO_3) to oven dried (60°C) sand at a rate of $12.5 \text{ g CaCO}_3 \text{ kg}^{-1}$ dry sand. The mixture was brought to 20% moisture and oven dried overnight at 60°C . The wetting-drying step was repeated three times to ensure the pH of the mixture equilibrated (pH 7.8-8.1). Five-hundred grams of the oven dried mixture were placed into each chamber and the chambers placed inside the cabinets. Air flow was then calibrated using an NIST Traceable™ digital flow meter (FMA 1700/1800, Omega Engineering Inc., Stamford, CN) at the inlet to each chamber. The external and internal humistats were filled with 900 and 450 ml of reverse osmosis (RO) purified water, respectively. The internal humistats were positioned in the cabinet and the cabinet temperature controls were set to the desired temperature. The water in the internal humistats and the sand- CaCO_3 mixture was allowed to come to temperature overnight (~12 h).

The following day RO water was added to the sand- CaCO_3 mixture to attain 10% moisture content. The acid trap bottles for the initial sampling interval were filled to the desired

volume with 0.02 M phosphoric acid and placed in position. A 5 ml NH₄Cl solution at an N concentration to deliver the desired N rate was surface applied onto the sand-CaCO₃ mixture. All air connections were secured and the pump was engaged to commence the trial.

Trapping acid was changed with fresh acid at intervals of 1, 3, 6, 9, 12, 24, 48, 96, 144, 192, 240, 288, 336, 388, 432, and 504 h after starting the trial (trials II, III and IV ended at h 336). The replaced acid was then weighed and analyzed for NH₃ concentration colorimetrically with a Lachat QuickChem Automated Ion Analyzer (Lachat Instruments, Loveland, CO).

Once the trial concluded a 5 g sample of dry sand-CaCO₃ mixture from each chamber was extracted using 2 M KCl and analyzed colorimetrically for NH₃ and nitrate (NO₃) with a Lachat QuickChem Automated Ion Analyzer. Moisture content of the sand-CaCO₃ mixture was determined and then used to calculate how much of the mixture was needed to attain a five gram sample of dry sand-CaCO₃ mixture.

2.4.3 Statistical Analysis

Using PROC MEANS for SAS 9.2 (SAS Institute, Cary, NC) mean N captured and standard deviation, for each sampling interval as well as cumulative N captured were computed for each trial. System recovery efficiency (SRE) and acid trap efficiency (ATE) were calculated for all trials using the following formulas:

Eq. 1

$$\frac{\text{acidtrap}N + \text{Residual}N}{\text{Nadded} + \text{Prior}N} * 100 = SRE(\%)$$

Where:

acidtrapN = cumulative mg N captured in acid traps

ResidualN = total mg N extracted in 2M KCl from the sand-CaCO₃ mixture after completion of the trial

Nadded = mg N added to each chamber

Prior N = total mg N extracted in 2 M KCl from the sand-CaCO₃ mixture with no N added

SRE = System Recovery Efficiency

Eq. 2

$$(N_{added} + PriorN) - ResidualN = VolatilizationLoss(VL)$$

Where:

PriorN = N in media prior to addition of fertilizer N

Residual N = NO₃-N + NH₄-N in the media at the end of the trial

VL = Volatilization Loss

Eq. 3

$$\frac{acidtrapN}{VL} \times 100 = ATE(\%)$$

Where:

ATE = Acid trap efficiency

Two samples of the sand-CaCO₃ mixtures with no N applied were taken from two separately mixed batches and used to calculate *PriorN* for trials I and II. Both batches were mixed at the same rates and with the same sources of sand, CaCO₃, and water. No detectable NO₃-N or NH₃-N was present in those samples using the 2 M KCl extraction method and colorimetric analysis.

Analysis of variance was conducted for SRE and ATE using PROC MIXED in SAS 9.2 to determine if acid trapping efficiency changed with N rate in trial IV.

2.5 RESULTS AND DISCUSSION

2.5.1 Trials I, II, and III

Mean volatilization loss, acid trap N recovered, ATE, total N recovered from both the trapping acid and the sand-CaCO₃ mixture after completion of the trial (system recovery), and SRE for trials I, II, and III are shown in Table 2-3. I. Volatilization loss would be a parameter of interest during the study of simulated production systems using this laboratory system. The sand and NH₄Cl system evaluated does not replicate agricultural environments and was only intended to serve as a means to validate the laboratory system. The mean amount of N recovered

by the trapping acid was 18.7 ± 0.4 mg N. The mean total amount of system recovery was 18.8 ± 0.3 mg N. SRE was $94.1 \pm 1.5\%$ and ATE was $94.0 \pm 1.6\%$. Mean acid trap N recovery was 16.8 ± 0.4 mg N. The mean system recovery was 19.4 ± 0.3 mg N. ATE and SRE were $96.7 \pm 1.8\%$ and $97.1 \pm 1.6\%$, respectively. These values are similar or exceed the recovery efficiencies shown by Cabrera et al. (2001). The standard deviations of these values indicate that even relatively small, i.e. 1 mg N loss during a two week period, treatment differences in future studies should be readily detectable. Upon raising the temperature to 30°C the efficiency of the system decreased in trial III (Table 2-3). However, recovery efficiencies were greater than 90% for trial III, and the variation between chambers was similar to trial II (Table 2-3).

Mean cumulative N captured by the acid traps is shown in Fig. 2-2 for trials I, II, and III. Between flow rates, temperatures, and acid trap volumes, the amount of nitrogen trapped is very similar at the 336 h sampling interval. The standard deviations for total acid trapped at various times in trials I, II, and III are shown in Fig. 2-3. Variation in cumulative N captured by the acid traps increases from 1 to 96 hours then decreases for the duration of the first three trials. The maximum variation observed at 96 h can be attributed to the longer sampling interval (48 h compared to 24 h), resulting in larger amounts of NH_3 collected in the acid traps. Trial II exhibited less variation in terms of N capture than trial I, which indicates that by decreasing flow rate to 1.00 L min^{-1} and increasing the volume of trapping acid to 100 ml the system's variation is decreased. Ndegwa et al. (2009) also found that as the air flow rate decreased, the efficiency of the acid trap increased. Since the acid trap container was kept constant during trials I and II, doubling the volume of acid resulted in an increase in depth of the acid trap. Ndegwa et al. (2009) also found that deeper acid traps increased the efficiency of the trap. Because air flow rate was decreased and acid depth increased from trial I to trial II neither factor can solely be identified as responsible for the increase in acid trap and system efficiency, however both factors may have contributed to the increased recovery observed in trial II.

Trial III showed that similar cumulative amounts of NH_3 were captured when compared to trials I and II (Fig. 2-2). Based on the results from trials I and II, the same flow rate and acid trap volume were used in trial III. The variation in values was similar between trials II and III (Fig. 2-3). Increasing the temperature to 30°C had little effect on variation among chambers within the system. This is evidence that the system will produce repeatable measurements up to 30°C . Measurements above 30°C were not obtainable due to the heating strip capacity.

From the results of trials I and II, 100 ml of trapping acid and 1.00 L min⁻¹ air flow rate were chosen to evaluate the system over multiple nitrogen rates (trial IV), since variation between chambers was decreased and SRE and ATE were highest in trial II (Table 2-3).

2.5.2 Trial IV

Six N rates were applied randomly to the soil chambers within each cabinet to evaluate the efficiency of the system over a wide range of N application rates. Equations 1, 2 and 3 were used to calculate SRE and ATE for each N application rate and mean separations can be found in table 4, respectively. Percentages for the 0 kg N ha⁻¹ are not given because no measurable N was found in the acid traps at each sampling interval or in the sand after the trial was completed. The SRE decreased as the N rate increased with the 25 kg N ha⁻¹ rate having the highest SRE, 95.7±1.5% and 250 kg N ha⁻¹ rate having the lowest with 89.3±2.3%. Standard deviations ranged from 1.5 to 3.0% (Table 2-4).

The ATE for all N rates applied in trial IV decreased with increasing N application rates (Table 2-4). The highest ATE was 95.3±1.2% for the 25 kg N ha⁻¹ rate and was significantly higher than all other treatments. When N rates increased to 250 kg N ha⁻¹ the ATE dropped to 84.7±2.3%, and was significantly lower than all treatments, except the 200 kg N ha⁻¹ rate. The decrease in ATE with increasing N rates agrees with data by Ndgewa et al. (2009), who also found that the efficiency of the acid traps decreases as the amount of ammonia to be trapped increases. System recovery efficiency decreased as ATE decreased which is expected since both SRE and ATE are calculated using N captured in the acid traps as a variable.

2.6 CONCLUSIONS

The need to evaluate a system that will be used in quantitatively measuring a parameter of interest is essential in producing results that are precise and accurate. The laboratory ammonia volatilization system described was able to detect and capture over 90% of the ammonia volatilized and maintain variation within individual chambers which will allow for reliable comparisons of fertilizer or simulated production systems in future trials. Decreasing the air flow rate to each chamber and increasing trapping acid volumes between trial I and II resulted in the reduction of variation between chambers and increased ATE and SRE. We believe this is

due to the increased time during the gas-liquid interface in the acid traps, which allows for increased conversion of NH_3 to ammonium (NH_4^+) in the acid. This increased reaction time may also allow the NH_3 to be captured by individual traps more consistently across all chambers. Since the system performed best at an air flow rate of 1.00 L min^{-1} and with 100 ml of trapping acid this configuration was used for trial III. The relatively low SD values (1.2 to 3.5 %) for all N application rates indicate that relative comparisons between treatments can be made with confidence.

Increasing the temperature to 30°C decreased the SRE and ATE slightly compared to that of trials I and II, but was still above 90% at this temperature. The variation remained similar to that in trial II showing that repeatability did not decrease as temperature increased. With the high recovery efficiencies and low variation this system will be able to operate at temperatures up to 30°C in order to simulate different environments in future studies.

SRE and ATE decreased as N rates increased from 0 to 250 kg N ha^{-1} . This range covered N fertilization rates that are routinely used in commercial agricultural production systems. The reduced SRE and ATE rates at higher N rates can be attributed to the total amount of NH_3 volatilized per unit of time. As NH_3 volatilized per unit time increases, the amount of NH_3 within each air bubble increases, and since the time for the reaction to take place remains constant (constant depth of acid and air flow rate) a lower percentage of NH_3 is successfully captured in the trap. Greater acid trap volumes need to be tested to potentially increase SRE for higher N rates, i.e. 200 to 250 kg N ha^{-1} .

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2.8 TABLES

Table 2-1. Comparison of system efficiencies and variation for laboratory systems measuring NH₃ volatilization.

Study	N Source	Trapping Acid	System Efficiency [†]	System Variation
		<i>molarity (volume)</i>	%	
O'Halloran (1993)	Liquid Hog Manure	0.32M H ₃ BO ₃ (50&100mL)	82.1-83.5 ^{¶¶}	NR [¶]
		or 0.9M H ₂ SO ₄ (50mL)	94.9 ^{¶¶}	NR
Kissel et al. (2004)	Granular Urea	0.05M H ₂ SO ₄ (50mL)	72.9-100.6 ^{¶¶}	NR
Todd et al. (2006)	Cattle Manure	0.9M H ₂ SO ₄ (100mL)	NR	2.67 [‡] mg
Cole et al. (2005)	Cattle Manure	0.9M H ₂ SO ₄ (100mL)	NR	1.45 [‡] mg
Miles et al. (2008)	Poultry Litter	H ₃ BO ₃ (60mL)	NR	2.6-6.3% [§]
Ndegwa et al. (2009)	NH ₄ Cl	0.2M H ₂ SO ₄ (150&470mL)	93.5-94.8	NR
Torello et al. (1983)	(NH ₄) ₂ SO ₄	1.5M H ₃ BO ₃	95.1-103.0	NR

[†]System efficiency is accountable N post trial divided by applied or previously present N.

[‡]Standard error of the mean NH₃ recovered in the acid traps

[§]Standard deviation of the mean NH₃ recovered in acid traps

[¶] Data not reported in article

^{¶¶} Calculated from data provided in article for comparison reasons

Table 2-2. Detailed materials list with appropriate costs for volatilization system

Section	Description	Quantity	Approx. Cost ^[a]	Total Cost ^[a]
Air Supply	Air Pump	1	530	
	Supply Tank	1	100	
	Distribution Manifold	3	45	
	Flow Meter	18	1440	
	External Humistat	18	500	
	Internal Humistat	18	200	
	Tubing and Connections			150
Cabinet Structure	61 cm x 61 cm Paneling	15	165	
	Lid Panel	3	25	
	Insulation	3	55	
	Baffles	3	20	
	Chamber Cradle	3	130	
	Misc. Lumber and Hardware		50	
Power Supply	Flanged Inlet	3	70	
	Red Indicator Lamp	3	15	
	Enclosure	3	130	
	Green Indicator Lamp	3	20	
	Switch	3	25	
	Terminal Strips	6	40	
	Wiring		10	
	Power Cord (2.44 m)	3	15	
Temp. Control	Controller	3	270	
	Air Sensor	3	260	
	Heat Strip (20 cm)	3	55	
	Fan	3	55	
	Wiring and Connections		10	
Temp. Data Collection	A/D Converter	3	3750	
	Thermocouples	18	510	
Chamber	Three Hole Cap	18	3630	
	Beaker	18	840	
	Fittings		30	
Calibration	Traceable™ Thermocouple	1	590	
	Flow Meter	1	900	
	Drying Tube	1 pk	30	
	Fittings		50	
^[a] US Currency			Total	14715

Table 2-3. Volatilization N loss, acid trap N recovery, system N recovery and calculated efficiencies for trials I, II, and III with a 90 kg N ha⁻¹ surface application.

	Trial		
	I [‡]	II [¶]	III ^{¶¶}
Mean [†]	26°C		30°C
Volatilization Loss (mg N)	19.8±0.2 [§]	17.4±0.3	18.1±0.3
Acid Trap N Recovery (mg N)	18.7±0.4	16.8±0.4	16.7±0.4
System Recovery (mg N)	18.8±0.3	19.4±0.3	18.6±0.2
SRE (%)	94.1±1.5	97.1±1.6	93.0±1.2
ATE (%)	94.0±1.6	96.7±1.8	92.2±1.3

[†] Averaged across all chambers per trial
[‡] 2.00 L min⁻¹ air rate and 50 mL trapping acid
[¶] 1.00 L min⁻¹ air rate and 100 mL trapping acid
[§] mg N ± standard deviation (SD)

Table 2-4. Mean system recovery efficiencies (SRE) and standard deviation (SD) for all N rates over two weeks for trial IV at 1 L min air flow and 100 ml of 0.02 M phosphoric acid trap volume.

N Rate	Total Acid Trap N	SRE	SD	ATE	SD
kg·ha ⁻¹	mg	%			
0	0 f* [§]	-	-	-	-
25	4.75 e	95.7 a ^{¶¶}	1.5	95.3 a ^{¶¶}	1.2
50	8.48 d	93.0 b	3	91.7 b	3.5
150	22.55 c	91.0 bc	2	88.0 c	3
200	26.02 b	90.7 bc	1.1	86.0 cd	1.7
250	32.18 a	89.3 c	2.3	84.7 d	2.3

*Significant at the 0.05 probability level.

[§] LSD_{0.05} = 2.49 mg N

[¶]LSD_{0.05} = 2.4%

^{¶¶} LSD_{0.05} = 3.1%

2.9 FIGURES

Figure 2-1: General schematic of the system evaluated for in-lab NH_3 volatilization measurements.

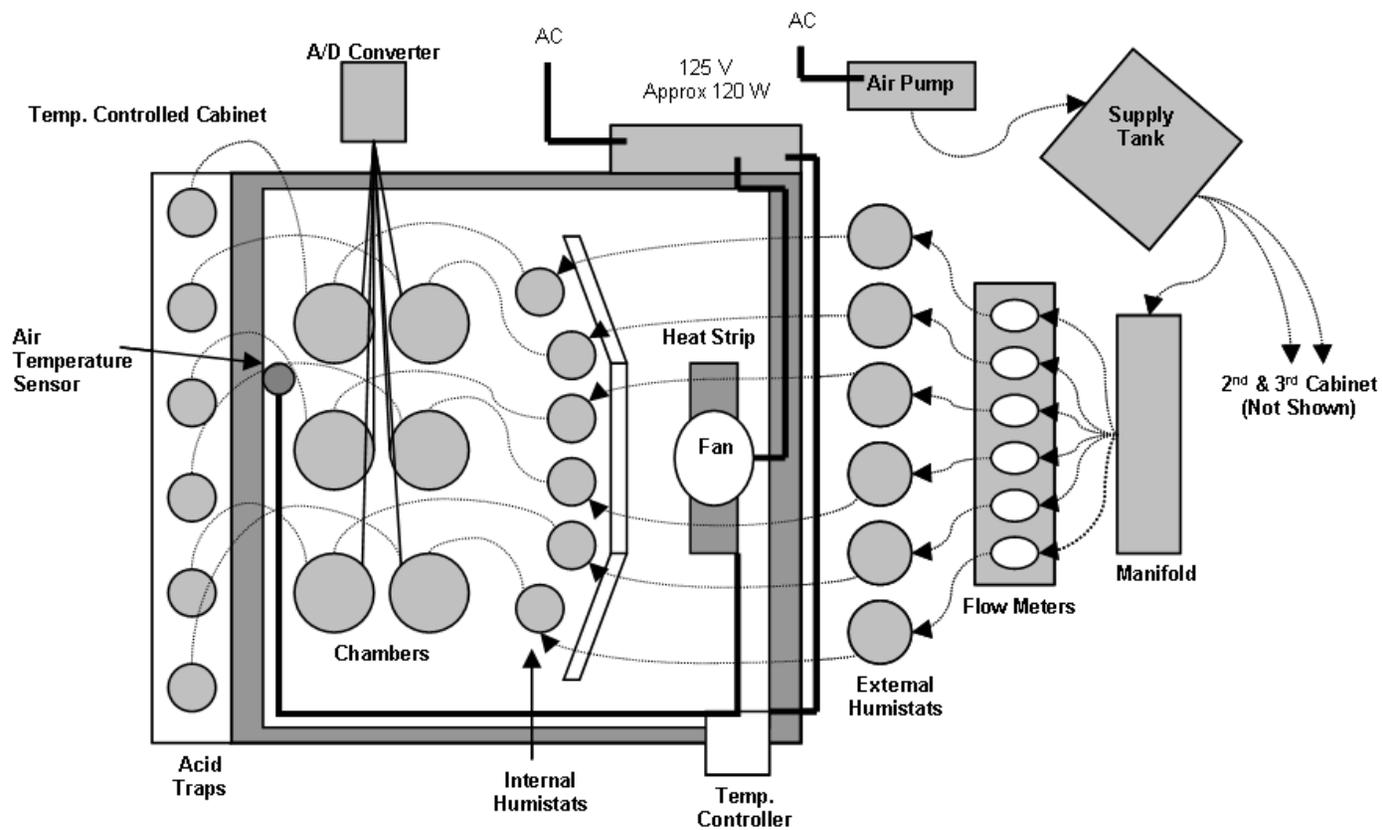


Figure 2-2: Cumulative N captured in acid traps during trials I, II, and III.

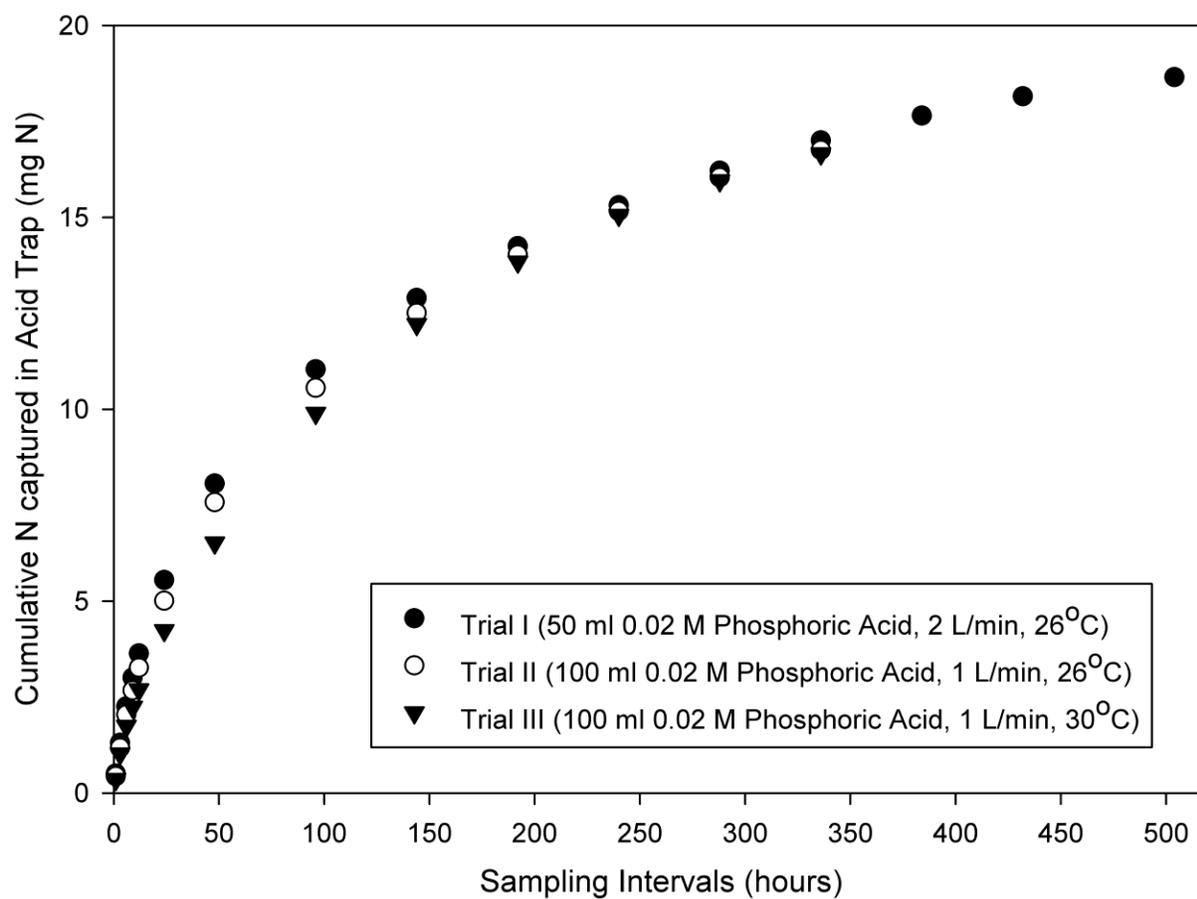
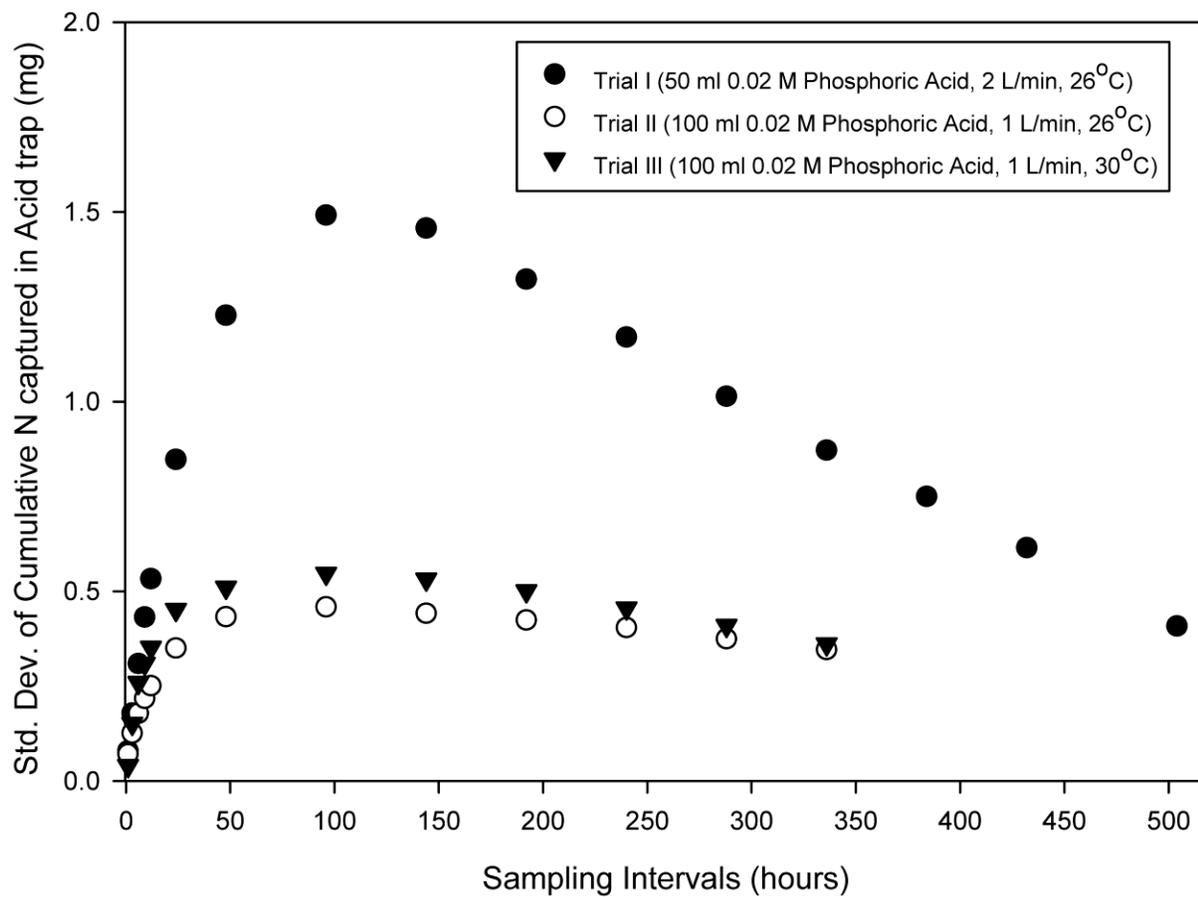


Figure 2-3: Standard deviation for cumulative N captured during trials I, II, and III.



2.10 APPENDIX

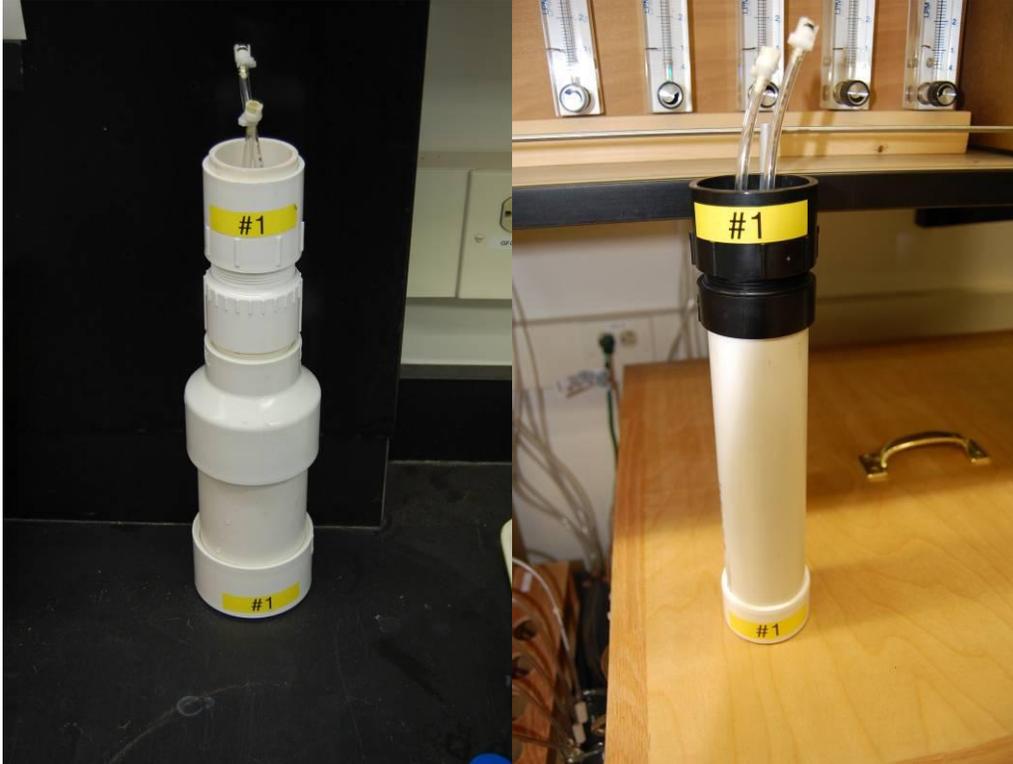
Appendix 2-A. Supply tank. Forced air is delivered to the tank by the pump, distributed into three air lines, and delivered to the distribution manifolds.



Appendix 2-B. Distribution manifolds and flow meters. Air flow is divided into 18 lines and routed to individual flow meters.



Appendix 2-C. External (left) and internal (right) humistats. Air is delivered from the flow meters into the external humistat then to the internal humistats. Air exiting the internal humistats is routed to the chambers.



Appendix 2-D. Chamber. Treatments are administered to soil or media inside the chamber. Air is delivered from the internal humistats into the chamber; air exiting is routed to the acid traps.



Appendix 2-E. View of heating element, temperature controller, and heat dispersal hardware.



3 AMMONIA VOLATILIZATION FROM SURFACE AND INJECTION APPLIED UREA AMMONIUM-NITRATE

3.1 ABSTRACT

Surface applications of urea-containing fertilizers have the potential for significant losses of N as volatilized NH₃. Injection of UAN has been proposed as a possible method of reducing potential NH₃-N losses by placing the fertilizer into the mineral soil. This study evaluated NH₃-N losses from surface-applied and injected UAN onto two residue covers, corn residue and wheat straw, and bare soil with the use of a laboratory system. Urea ammonium-nitrate was applied at two rates: 75 and 125 kg N ha⁻¹. Injection of UAN reduced NH₃-N losses greatly and losses were <1% of applied N for all N rates and residue covers. Ammonia-N losses from surface-applied UAN ranged from 15.3 to 32.5% of applied N. Surface application of UAN onto corn residue produced NH₃-N higher losses compared to UAN surface-applied to bare soil at both N rates and to wheat straw at an N rate of 125 kg N ha⁻¹. Injection of UAN was found to dramatically reduce NH₃-N losses compared to surface-applied UAN under the conditions used in this study.

3.2 INTRODUCTION

No-tillage crop production is gaining adoption in the Mid-Atlantic region due to lower cultivation costs and potentially higher yields. However, the presence of plant residues on the soil surface creates conditions that increase the potential for NH₃ volatilization from surface applied urea-containing fertilizers (Bandel et al., 1980; Ernst and Massey, 1960; Hargrove et al., 1979; Terman, 1979; and Volk, 1959). Incorporation of urea fertilizers by tillage reduces the potential for NH₃-N volatilization losses, but no-tillage management restricts the use of this practice. Injection is one possible method of applying urea solution fertilizers into the mineral soil below crop residues with minimal surface disturbance; thus, decreasing the potential for NH₃-N loss and retaining the benefits of no-tillage management.

Crop residues can be actively colonized by saprophytic microorganisms, which in turn, enhance the urease activity of the crop residue (Goos, 1985; and Lal et al., 1993).

Increased urease activity increases the potential for urea hydrolysis of urea-containing fertilizers and, subsequently, a higher potential $\text{NH}_3\text{-N}$ volatilization loss. However, studies suggest there is a difference in urease activity between the residues of plant species. Frankenberger and Tabatabai (1982) found graminaceous plants exhibited the highest urease activity of 21 plant species; whereas, cruciferae and tilliaceae plant families had no urease activity. McInnes et al. (1986) observed urease activity 20 times higher in wheat residue than in the surface 10 mm of soil beneath it. Barreto and Westerman (1989) reported similar results, where urease activity of wheat residue was found to be 28 times higher than the surface 10 mm of soil. Dick (1984) reported cropping rotations in no-tillage management resulted in differences in urease activity. A continuous corn rotation was found to have less urease activity than a corn-oats-alfalfa rotation in the upper 7.5 cm. These studies suggest typically high urease activity at the soil surface in no-tillage systems. However, very few, if any, studies have directly compared small grain and corn residues' urease activity or impact on NH_3 volatilization from applied urea containing fertilizers.

Increased water retention in no-tillage systems is another important factor contributing to an increased potential for NH_3 volatilization. In no-tillage systems, water infiltration at the soil surface is generally increased by the improved soil structure created by the addition of organic matter from the decomposition of surface plant residues. However, plant residues at the surface create a mulch-effect, where water easily infiltrates, but is retained for longer periods of time due to reduced evaporative losses (Jones et al., 1969). This creates conditions where urea hydrolysis can readily occur for longer periods compared to conventionally tilled, bare soils; thus, increasing the potential for $\text{NH}_3\text{-N}$ loss from surface applied urea fertilizers.

A characteristic of no-tillage systems is an observed increase in cation exchange capacity (CEC) from the addition of OM from decomposed plant residues. Reductions in NH_3 volatilization have commonly been observed with higher CEC levels compared to lower CEC soils (Fenn and Kissel, 1976). However, surface applied urea-containing granular or solution fertilizers are often positioned on the surface of non-decomposed plant residues. When this occurs, CEC within the proximity of the fertilizer is low, or

non-existent. This limits $\text{NH}_3 \rightarrow \text{NH}_4^+$ transformations, due to lack of buffering capacity and H^+ availability, and, leads to an increased potential for NH_3 volatilization.

Injecting urea-containing fertilizer solutions below plant residues in no-tillage systems reduces the potential for $\text{NH}_3\text{-N}$ loss compared to surface applications. The magnitude of $\text{NH}_3\text{-N}$ loss from soils with varying residue covers need to be examined in order to estimate the N loss potential of surface applied urea-containing solutions to these different residue situations and assess if different management practices may be required. Comparison of NH_3 volatilization losses from surface applications of UAN solutions to corn and small grain residue versus injection of UAN solution under controlled conditions would enable researchers and growers to determine if changes in UAN applications might be warranted. Results gathered from this and subsequent studies will help crop producers make an informed decision on whether or not adoption of urea fertilizer injection could be beneficial in their crop management system.

3.3 OBJECTIVES

To evaluate surface and injection application of UAN onto corn residue, wheat stubble, and bare soil on NH_3 volatilization under controlled laboratory conditions;

3.4 MATERIALS AND METHODS

3.4.1 System Conditions

The study was performed in the NH_3 volatilization chambers described by Woodward et al. (2011). The cabinets were adjusted to a temperature of 26°C . The mean soil temperature for the no residue cover trial was $26.1 \pm 0.2^\circ\text{C}$, and $25.8 \pm 0.2^\circ\text{C}$ for the corn residue cover trial. No temperature data was recorded for the wheat residue trial due to a malfunction of temperature recording equipment during the trial. Air flow rate was 1.00 L min^{-1} for each trial. This flow rate would replace the air above the soil/residue surface every 34 sec for the no residue cover treatment, 27 sec for the corn residue cover treatment, and 31 sec for the wheat residue cover treatment. These flow rates differ because the “head space” in the chambers differed with the volumes of different residues

that were used when weights of soil and residue were held constant. External and internal humistats were filled with 900 and 450 ml of reverse osmosis (RO) water, respectively. The humidity of the air within each chamber was near 100%. One-hundred milliliters of 0.02 M phosphoric acid was used as the trapping acid.

The soil within each trial was obtained from the top ~15cm of a Hayter silt loam soil (Ultic Hapludalfs) found in Montgomery County, VA. Plant matter, rock fragments, and foreign material above 2 mm were removed from the soil by sieving. The organic matter content of the soil was approximately 43 mg g⁻¹, determined by loss on ignition. The estimated CEC of the soil was 8.2 meq 100g⁻¹, determined by summation of cations. Soil pH was adjusted to 6.3-6.5 with the application of calcium oxide and three subsequent wetting-drying steps. Particle size analysis showed the soil to have a silt loam texture with 37.5% sand, 52.5% silt, and 10.0% clay. Field capacity of the soil was determined to be 12.1% moisture content through the use of a pressure plate technique where a suction was applied at -1/3 bar. Each chamber within each trial received approximately 300 g of air-dry soil. Ultra-purified water was added to the soil within each chamber to increase the moisture content to 2/3 field capacity. The water was mixed thoroughly with the soil and allowed to equilibrate for 24 h to insure even temperature and moisture throughout the soil.

3.4.2 Treatments

Three runs were conducted, separated by residue cover treatments: no residue/bare soil (trial I), corn residue (trial II), wheat stubble (trial III). Each residue treatment was evaluated at two N rates and was replicated three times. UAN was both surface-band and injection applied at two N rates: 75 and 125 kg N ha⁻¹, with the inclusion of two zero N rate treatments to determine ambient NH₃-N loss from the soil and/or residue treatments.

The soil surface was left bare in trial I. Surface UAN treatments were applied directly to the surface of the soil. Corn residue was added to the soil surface in each chamber for trial II at a rate of 5.14 g chamber⁻¹. This rate was determined by the measurement of surface residues left in four field study plots after harvest that yielded

approximately 9416 kg grain ha⁻¹. Corn residue used in the study was collected from these field plots. Residue was removed, air-dried for 24 h, and sorted by stems, leaves, and other. Each individual portion was weighed to determine the amounts of each portion that needed to be added to each chamber: stems, 1.50 g chamber⁻¹; leaves, 1.04 g chamber⁻¹; and other, 2.60 g chamber⁻¹. All residue was sieved to remove material <2 mm and >1.9 cm before being applied to the chamber. Once applied, 0.80 ml of RO water was sprayed in a fine mist to the surface of the plant residues. The C:N ratio of the corn residue was approximately 43:1.

The plant residue treatment for trial III was wheat straw to simulate small grain stubble residue. In order to achieve straw lengths that could be used in the chamber, the wheat straw was passed through a hammer mill with the absence of a mesh screen twice. The wheat straw was then sized by hand so that no straws greater than approximately 5 cm were present. The wheat straw was applied to the surface of the soil at an air-dried rate of 1.40 g chamber⁻¹ which simulated residues from a small grain cover crop yielding approximately 3,600 kg ha⁻¹ of biomass. Then 0.80 ml of RO water was applied to the residue before N application. The C:N ratio of the wheat straw was approximately 54:1.

Fertilizer rates were determined with the assumption that the UAN used for the study contained 30% N. The amount of UAN to be applied to attain the desired N rate was determined based on the weight of the soil in the chamber and the assumption that 2,245,455 kg of soil exists in a hectare furrow slice. The actual N content and urea, ammonium, and nitrate constituents were determined post-study. The UAN used in this study was composed of 6.95% Ammonia-N, 8.09% Nitrate-N, and 15.27% Urea-N for a total of 31.1% N. Total N was determined by dry combustion (Leco Nitrogen Analyzer); Nitrate-N was determined colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments); Ammonia-N was determined through distillation and back-titration of distillate; and Urea-N was determined by conversion of Urea-N into Ammonia-N with the use of jack bean meal and analyzed as Ammonia-N. Therefore, the actual N rate applied was 10.34 mg N chamber⁻¹ (low rate) and 17.24 mg N chamber⁻¹ (high rate) which equals 77.8 and 129.6 kg N ha⁻¹. Surface-band application was hand applied using a pipette. Injection application was performed by creating a 5 cm deep trench in the soil through surface residue across the diameter of the chamber (~7.6cm). The UAN was then

hand applied using a pipette into the bottom of the trench. The trench was left uncovered to simulate realistic field conditions. The zero N rate treatments were separated by no disturbance to the residue and/or soil, whereas the other treatment disturbed the residue and soil as to simulate the disturbance from the injection treatments.

Soil and residue in each chamber was allowed to equilibrate to the internal temperature of the cabinet before UAN treatments were applied. Once the UAN treatment was applied air flow was engaged and the trial commenced. Each trial continued for 504 h (3 weeks).

3.4.3 Sampling and Analytical Procedure

Ammonia traps were replaced at 1, 3, 6, 9, 12, 24, 48, 96, 144, 192, 240, 288, 336, 384, 432, and 504 h after air flow was engaged. Trapping acid was analyzed for NH₃-N content colorimetrically. Nitrogen captured at each interval in the undisturbed and disturbed zero N rate treatments was considered to be ambient N and subtracted from N captured in the surface and injection UAN treatments, respectively.

The NH₄-N and NO₃-N content of the soil within each chamber was determined by extraction with 2 M potassium chloride and analyzed colorimetrically. Total N of the soil was determined by dry combustion (VarioMax CNS Analyzer); and, NH₄-N and NO₃-N content was subtracted from the total N to yield organic-N. Ammonium-N, NO₃-N, and organic-N contents of the soil from the zero rate treatments were subtracted from the respective contents of the UAN treated soils to account for any existing N prior to the application of UAN, and soil N transformations naturally occurring during the trial. Residues from each chamber were extracted post-trial with 100 ml of millipure water, and NH₄-N and NO₃-N content was determined colorimetrically. Total N content of the residues within each chamber was determined by dry combustion at 900°C.

3.4.4 Statistical Procedure

Cumulative mean NH₃-N losses from each treatment within individual trials were compared by Tukey HSD using the GLM procedure in SAS 9.2 (SAS Institute, Cary, NC). The probability level used in this evaluation was 0.05. The treatments were

arranged as a randomized complete block, where the individual cabinets were considered the blocks.

Residue cover influence on cumulative $\text{NH}_3\text{-N}$ loss from surface-applied UAN was evaluated as a split-plot design using orthogonal contrasts. The probability level used in this evaluation was 0.05. The GLM procedure in SAS 9.2 was used to perform the comparisons.

3.5 RESULTS AND DISCUSSION

3.5.1 Captured Ammonia-N

3.5.1.1 No Residue Cover

Mean captured $\text{NH}_3\text{-N}$ results, expressed as a percent of total applied N, are shown in Table 3-1. Both application methods had similar captured $\text{NH}_3\text{-N}$ results for the first 9 h after UAN application. Captured $\text{NH}_3\text{-N}$ from the surface application method at both N rates became significantly higher than injection application at 12 h after UAN application. A dramatic increase in the rate of $\text{NH}_3\text{-N}$ capture from the surface application method was observed at 24 h at both N rates (Fig. 3-1). After 48 h, the rate of $\text{NH}_3\text{-N}$ capture from the surface application treatment began to decrease, but $\text{NH}_3\text{-N}$ capture did not cease throughout the trial.

Total $\text{NH}_3\text{-N}$ captured from the surface application of UAN over 3 weeks was 15.3 and 17.0% of applied N at rates of 75 and 125 kg N ha⁻¹, respectively. Captured $\text{NH}_3\text{-N}$ from the surface application of UAN at a rate of 125 kg N ha⁻¹ was significantly higher than the 75 kg N ha⁻¹ surface application rate. This may be due to an increase in urea hydrolysis at the high N rate which would result from an increase in pH in the proximity of the fertilizer. This would increase the potential transformation of NH_4^+ to NH_3 and would limit NH_3 transformations to NH_4^+ , resulting in increased $\text{NH}_3\text{-N}$ loss.

Captured $\text{NH}_3\text{-N}$ from the injection application method at both N rates was very low throughout the entirety of the trial. Total $\text{NH}_3\text{-N}$ loss from the injection method at 75

and 125 kg N ha⁻¹ rates were 0.1 and 0.4% of applied N, respectively. Losses were lower than expected, with almost negligible NH₃-N loss from the injection of UAN.

3.5.1.2 Corn Residue

Mean captured NH₃-N results, expressed as a percent of total applied N, are shown in Table 3-1. Captured NH₃-N from the surface application of UAN became significantly higher than the injection method at 9 h after application at an N rate of 75 kg N ha⁻¹; however, at an N rate of 125 kg N ha⁻¹ surface application was significantly higher at only 3 h after application. At 3 h after application, captured NH₃-N at both N rates increased dramatically with the surface application method and continued until 48 h (Fig. 3-2). An additional increase in the rate of NH₃-N capture was observed at h 240 for both N rates of surface UAN application. This may be due to the decomposition of the corn residue and subsequent release of NH₃ from microbial processes. This was also observed in the wheat straw trial; however, NH₃-N losses were less pronounced.

Total captured NH₃-N from the surface application of UAN over the 3 wk trial was 25.4 and 32.5% of applied N at N rates 75 and 125 kg N ha⁻¹, respectively. As seen in the no residue cover treatment, captured NH₃-N from UAN surface applied at the high N rate was significantly higher than the lower rate. The reasoning given for this effect in the no residue cover treatment also applies here; however, the additional N may also have a priming effect on the decomposition of plant residues, which may have increased NH₃-N loss (Westerman and Kurtz, 1973). Total captured NH₃-N from the injection application of UAN was 0.3 and 0.2% of applied N at N rates 75 and 125 kg N ha⁻¹, respectively. Again, results were as expected with the injection application of UAN greatly reducing NH₃-N loss compared to surface application.

3.5.1.3 Wheat Straw

Mean captured NH₃-N results, expressed as a percent of total applied N, can be found in Table 3-1. Captured NH₃-N from the surface application of UAN became significantly higher than the injection method at 6 and 3 h after application at N rates 75 and 125 kg N ha⁻¹, respectively. Similar to the corn residue treatment, NH₃-N capture rate

of the surface application method increased from 3 h after application until 48 h (Fig. 3-3).

Cumulative mean $\text{NH}_3\text{-N}$ captured from the surface application of UAN was 19.9 and 17.7% of applied N at N rates 75 and 125 kg N ha⁻¹, respectively. Total $\text{NH}_3\text{-N}$ captured from the injection application of UAN at the 75 kg N ha⁻¹ rate was 0.1% of applied N and 0.1% of applied N at the 125 kg N ha⁻¹ rate.

3.5.1.4 Comparison between Residue Cover Treatments

Urea ammonium-nitrate surface-applied to corn residue had higher losses than the surface application of UAN onto bare soil at both N rates, and higher losses than the surface application of UAN onto wheat straw at an N rate of 125 kg N ha⁻¹. Cumulative $\text{NH}_3\text{-N}$ losses from surface-applied UAN onto wheat straw were found to be similar to losses from bare soil at both N rates. Losses of $\text{NH}_3\text{-N}$ from UAN surface-applied onto wheat straw were expected to be similar to losses observed from corn residue; however, this was not observed at the higher N rate. This may be due to low urease activity in the wheat straw, which had been weathered in the field for approximately 8 months. The corn residue used in the study was obtained with 5 wk after harvest, and, therefore, urease activity can be assumed to be relatively high.

3.5.2 Nitrogen Recovered from Soil and Residue

The mean N recovered from the soil and residue for each treatment is shown in Table 3-2. Ammonium-N and $\text{NO}_3\text{-N}$ recovered from the soil was relatively consistent; however, significant variation was observed in the other-N portion. The other-N portion can be assumed to primarily represent the organic-N fraction, and results indicate that the soil may not have been mixed to proper homogeneity. In this study, where a high concentration of N is placed in a relatively small volume within or onto the soil, processing the soil to a level of homogeneity where this variation is reduced may not be possible.

Nitrogen measured from the plant residues also contributed significantly to the variation of recovered N. This was expected since mixing of the plant residues to homogeneity is unrealistic and was limited to sorting of the plant into equal portions of material. Overall, this is a good representation of the variation of N existing in soil and plant material in no-tillage conditions; however, this variation did not create noticeable variation in $\text{NH}_3\text{-N}$ loss.

3.6 CONCLUSIONS

Injection of UAN dramatically reduced NH_3 volatilization compared to the method of surface-banding under all conditions within this study. Placing UAN into the mineral soil essentially eliminated $\text{NH}_3\text{-N}$ losses either with or without residue cover. The highest $\text{NH}_3\text{-N}$ losses were experienced when UAN was surface-applied to corn residue. This may be due to greater urease activity, which would increase urea hydrolysis and the potential for NH_3 volatilization. Microbial activity may have been enhanced by the residue, and with the possible priming effect observed during the trial could have released $\text{NH}_3\text{-N}$ during residue decomposition processes.

Ammonia-N loss from surface applied UAN onto bare soil and wheat straw were similar. Ammonia volatilization was expected to be greater in the wheat straw cover than the bare soil and closer to $\text{NH}_3\text{-N}$ losses observed from UAN surface-applied to corn residue. This was expected based on similar studies that found considerably higher urease activity in wheat stubble than the underlying soil (McInnes et al., 1986; Barreto and Westerman (1989). However, the wheat straw used in this study had weathered in the field for approximately 8 months before being removed. Schilke-Gartley and Sims (1993) found plant residues exposed to sunlight, high temperatures, and moisture fluctuations for long periods of time exhibit decreased urease activity. This may explain less $\text{NH}_3\text{-N}$ loss from surface-applied UAN onto wheat straw compared to corn residue.

Overall, injection of UAN reduced $\text{NH}_3\text{-N}$ losses to near negligible levels where surface applications of UAN resulted in losses ranging from 15.3 to 32.5% of applied N. The conditions in this study were established to encourage $\text{NH}_3\text{-N}$ losses, and were maintained throughout a 3 wk period. These conditions, i.e. steady wind, soil moisture

near 2/3 field capacity, moist residue, and high humidity, can be commonly observed in field settings in the Mid-Atlantic region, though rainfall is likely to occur within 3 wk after application. In certain situations a major portion of surface-applied UAN can be lost as NH₃, but even more so, the results indicate injection of UAN can greatly reduce the potential for NH₃ volatilization.

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3.8 TABLES

Table 3-1. Cumulative captured NH₃-N at each sampling interval for all residue cover trials.

Time After Application	<u>No Residue Cover</u>				<u>Corn Residue</u>				<u>Wheat Straw</u>															
	Injection		Surface		Injection		Surface		Injection		Surface													
N Rate:	75 kg N ha ⁻¹		125 kg N ha ⁻¹		75 kg N ha ⁻¹		125 kg N ha ⁻¹		75 kg N ha ⁻¹		125 kg N ha ⁻¹													
	%																							
1	0.02	a*	0.03	a	0.02	a	0.00	a	0.04	a	-0.04	a	0.02	a	0.04	a	-0.01	a	-0.01	a	0.00	a	0.02	a
3	0.02	a	0.03	a	0.02	a	0.00	a	0.03	a	0.21	a	0.02	a	0.27	b	0.01	a	0.06	a	0.01	a	0.14	b
6	0.02	a	0.05	a	0.02	a	0.03	a	0.03	a	0.67	a	0.02	a	0.78	b	0.02	a	0.24	b	0.01	a	0.35	b
9	0.02	a	0.09	a	0.02	a	0.06	a	0.03	a	1.36	b	0.02	a	1.56	b	0.03	a	0.45	b	0.01	a	0.61	b
12	0.02	a	0.13	b	0.02	a	0.11	b	0.04	a	2.26	b	0.02	a	2.58	b	0.03	a	0.69	b	0.01	a	0.91	b
24	0.03	a	0.69	b	0.02	a	0.75	b	0.10	a	6.57	b	0.02	a	8.03	b	0.05	a	2.51	b	0.03	a	2.91	b
48	0.03	a	5.74	b	0.02	a	6.03	b	0.23	a	12.46	b	0.04	a	19.66	b	0.08	a	7.22	b	0.05	a	7.97	b
96	0.06	a	9.63	b	0.06	a	10.70	b	0.26	a	15.25	b	0.05	a	24.10	b	0.11	a	12.04	b	0.05	a	11.89	b
144	0.07	a	11.32	b	0.11	a	12.49	b	0.23	a	16.12	b	0.04	a	25.69	b	0.12	a	14.04	b	0.04	a	13.17	b
196	0.07	a	12.42	b	0.16	a	13.62	b	0.23	a	17.15	b	0.05	a	26.40	b	0.12	a	15.23	b	0.04	a	14.07	b
240	0.07	a	12.90	b	0.20	a	14.46	b	0.23	a	18.67	b	0.05	a	27.33	b	0.11	a	16.40	b	0.04	a	14.88	b
288	0.07	a	13.49	b	0.23	a	15.11	b	0.25	a	20.51	b	0.07	a	28.42	b	0.11	a	17.31	b	0.04	a	15.58	b
336	0.07	a	14.01	b	0.26	a	15.65	b	0.29	a	22.09	b	0.11	a	29.53	b	0.12	a	18.23	b	0.03	a	16.27	b
384	0.07	a	14.44	b	0.30	a	16.12	b	0.34	a	23.40	b	0.18	a	30.57	b	0.12	a	18.85	b	0.03	a	16.83	b
432	0.07	a	14.80	b	0.33	a	16.52	b	0.35	a	24.38	b	0.22	a	31.47	b	0.12	a	19.34	b	0.03	a	17.25	b
504	0.07	a	15.27	b	0.36	a	17.04	b	0.33	a	25.35	b	0.23	a	32.51	b	0.12	a	19.89	b	0.03	a	17.69	b

* Comparisons are made between application methods at each N rate and time interval. Values with similar letters indicate no significant difference at probability level 0.05.

Table 3-2. Nitrogen recovered from the soil and residue post-trial.

Residue Cover	N Rate kg N ha ⁻¹	Application Method	Soil N			Residue N			Total N [#]	Corrected Total ^{††}
			NO ₃ -N [†]	NH ₄ -N [†]	Other N [‡]	NO ₃ -N [§]	NH ₄ -N [§]	Other N [¶]		
No Cover	0	Injected	9.02	0.39	703.083	NA ^{**}	NA	NA	712.50	
	0	Surface	8.86	0.42	719.727	NA	NA	NA	729.01	
	75	Injected	11.51	6.92	722.779	NA	NA	NA	741.21	28.71
	75	Surface	10.96	8.13	725.246	NA	NA	NA	744.34	15.33
	125	Injected	11.71	14.26	716.145	NA	NA	NA	742.11	29.62
	125	Surface	11.21	13.17	727.944	NA	NA	NA	752.33	23.32
Corn Residue	0	Injected	8.71	0.50	742.32	1.42	1.29	34.19	788.42	
	0	Surface	9.11	0.52	750.31	1.29	0.72	33.97	795.92	
	75	Injected	11.33	1.16	738.35	3.16	1.37	36.18	791.55	3.12
	75	Surface	10.56	0.48	730.69	7.09	3.08	40.67	792.56	-3.35
	125	Injected	13.24	4.05	738.65	9.07	1.84	30.94	797.80	9.37
	125	Surface	9.99	0.83	729.20	14.73	8.14	43.80	806.69	18.26
Wheat Straw	0	Injected	9.79	0.37	724.601	1.05	0.17	8.20	744.17	
	0	Surface	9.65	0.32	698.542	1.67	0.19	7.46	717.83	
	75	Injected	12.93	2.45	708.778	1.18	0.17	11.31	736.81	-7.36
	75	Surface	10.83	0.68	709.395	3.66	1.46	11.17	737.19	19.36
	125	Injected	14.24	3.68	733.324	1.35	0.21	10.04	762.85	18.68
	125	Surface	12.59	1.24	724.977	6.27	2.04	9.85	756.97	39.13

[†]Determined colorimetrically from 2 M KCl extraction

[‡]Determined by subtracting soil NO₃-N and NH₄-N from total N determined by dry combustion

[§]Determined colorimetrically from water extraction

[¶]Determined by dry combustion of plant material post-extraction

[#]Sum of recovered N from soil and residue

^{††}Total N of 0 kg N ha⁻¹ treatments subtracted from Total N of respective treatment

^{**}Not applicable

3.9 FIGURES

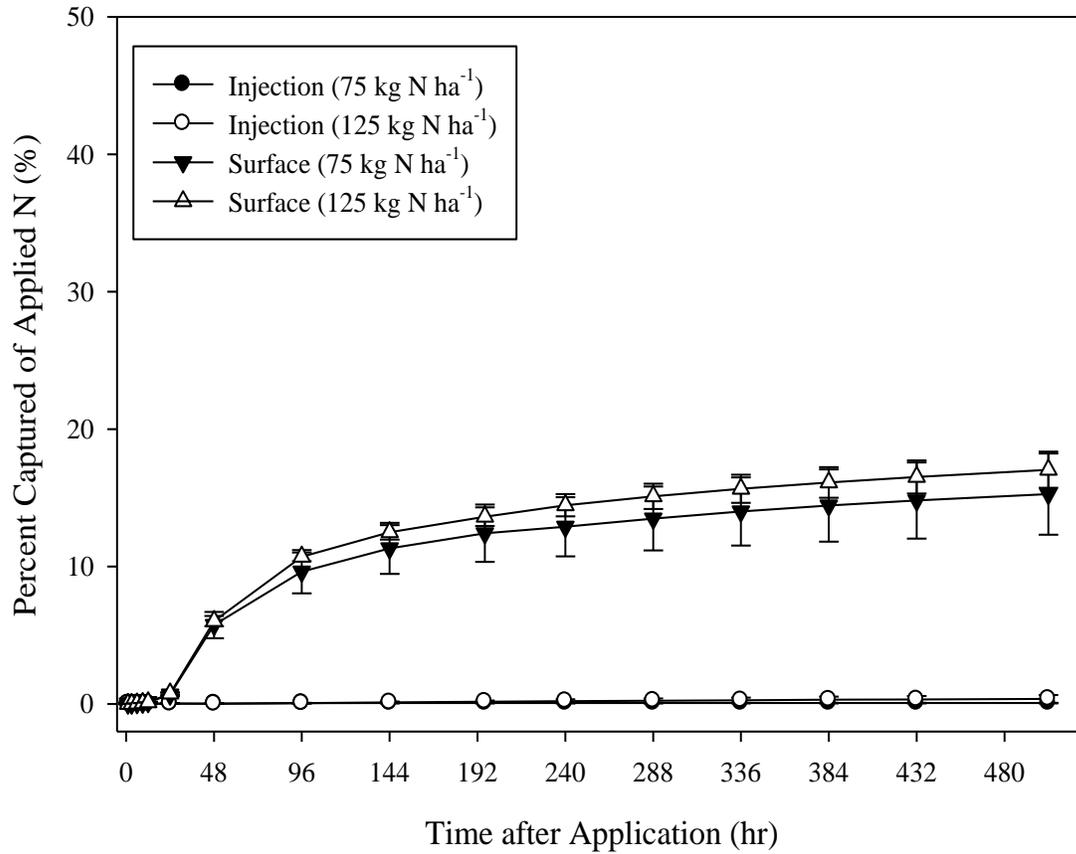


Figure 3-1. Cumulative mean captured $\text{NH}_3\text{-N}$, as percent of applied N, no residue cover.

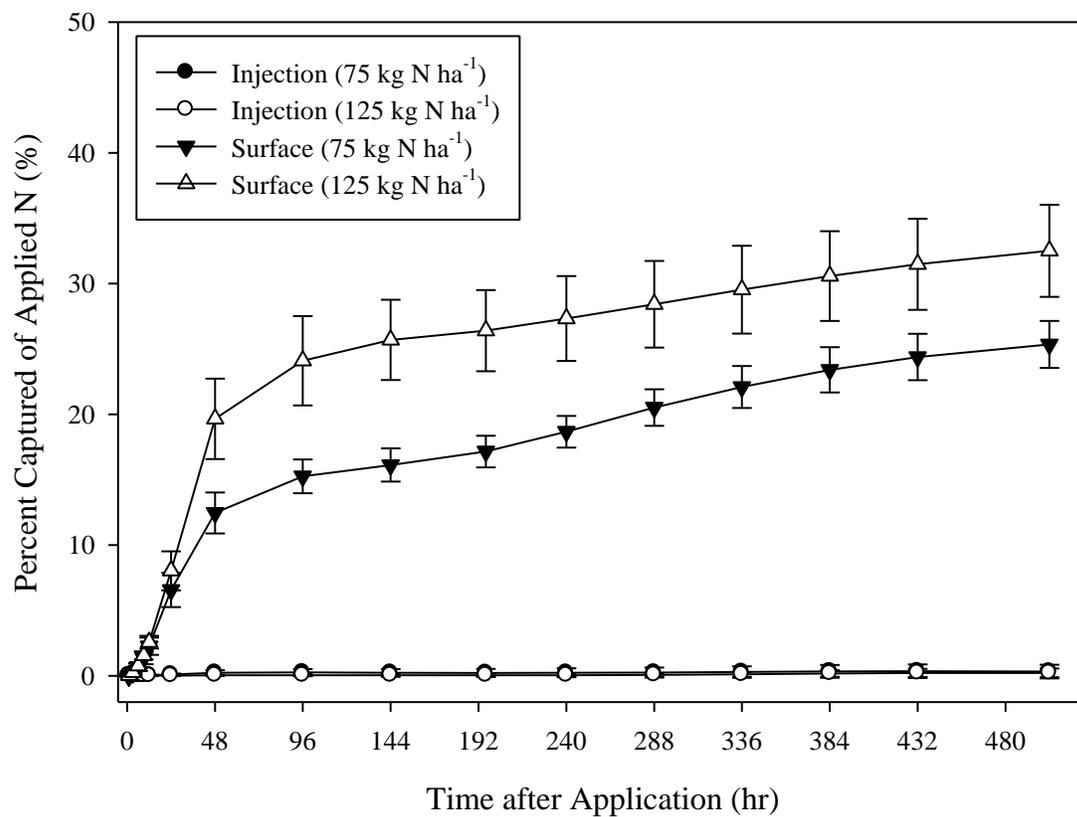


Figure 3-2. Cumulative mean captured $\text{NH}_3\text{-N}$, as percent of applied N, corn residue cover.

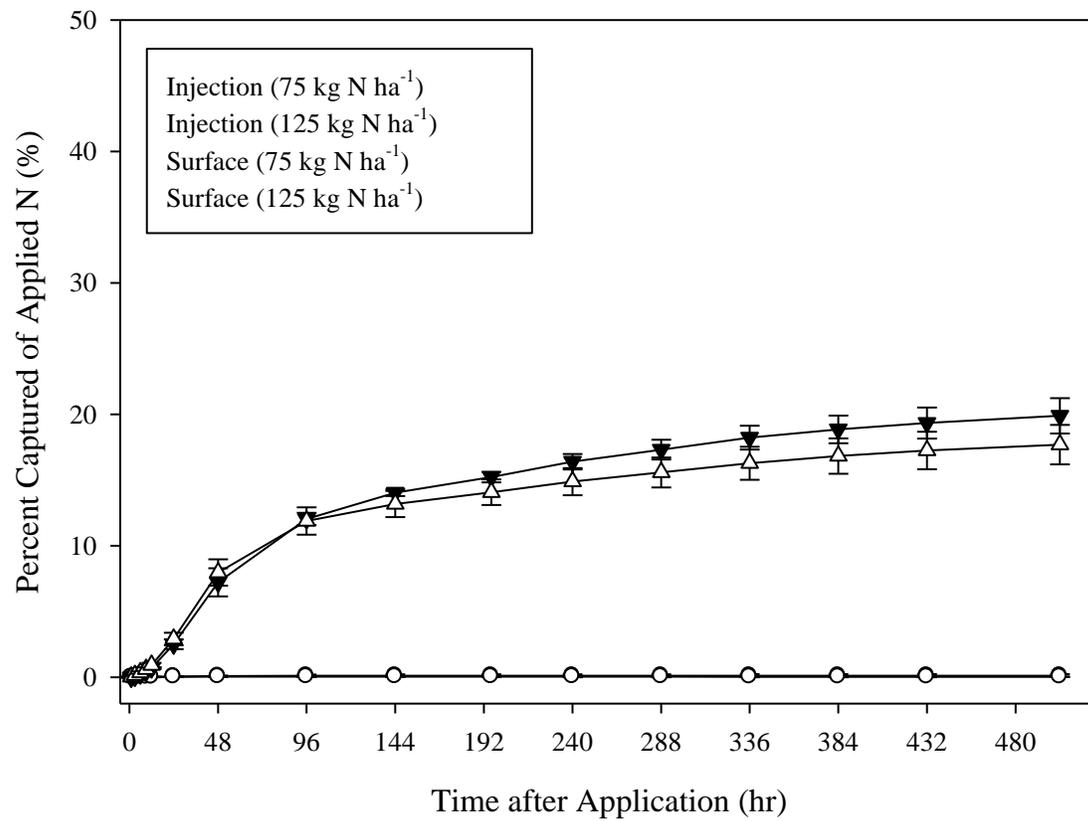


Figure 3-3. Cumulative mean captured $\text{NH}_3\text{-N}$, as percent of applied N, wheat straw cover.

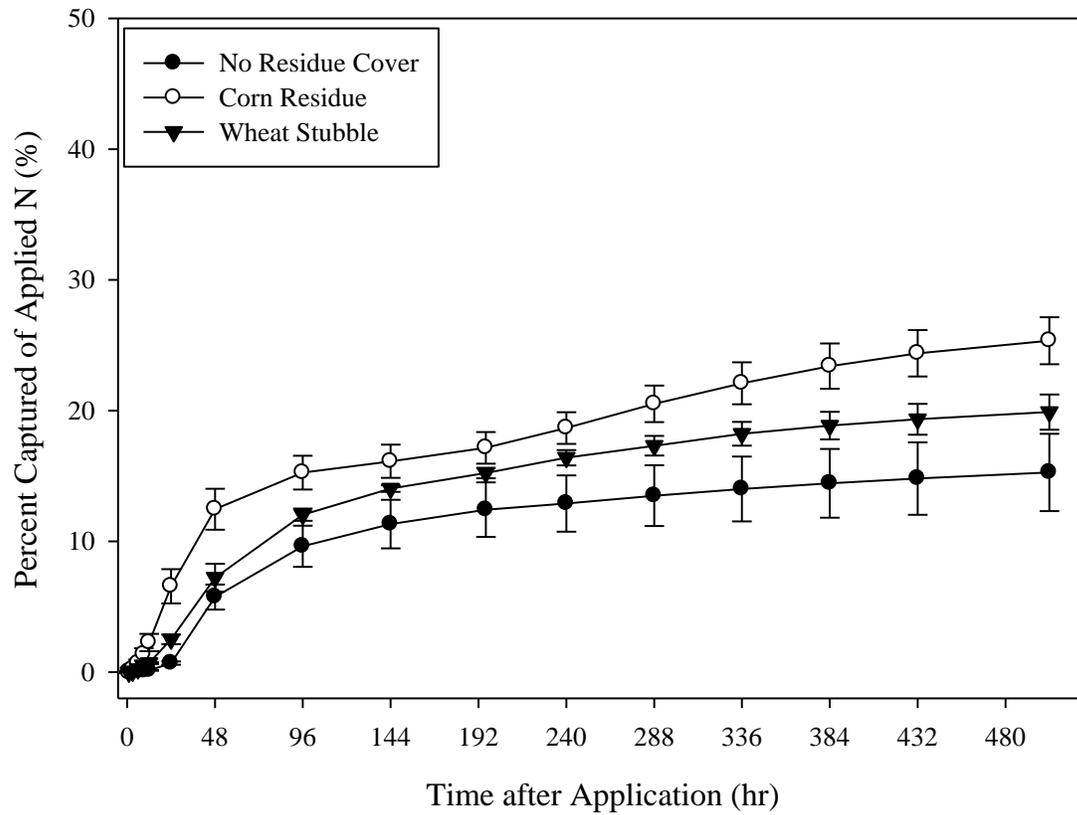


Figure 3-4. Cumulative captured NH₃-N from surface applied UAN at a rate of 75 kg N ha⁻¹ onto the surface residue cover treatments.

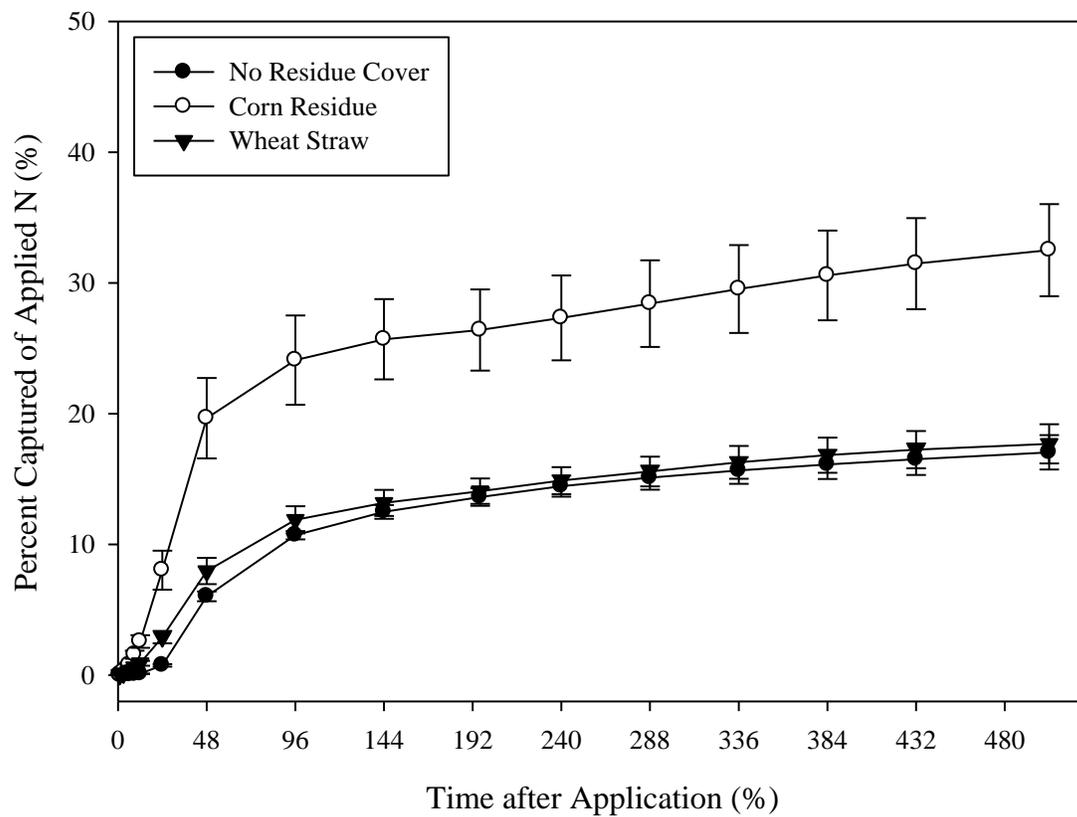


Figure 3-5. Cumulative captured NH₃-N from surface applied UAN at a rate of 125 kg N ha⁻¹ onto the surface residue cover treatments.

4 UREA AMMONIUM-NITRATE SOLUTION PLACEMENT IN NO-TILLAGE CORN (*Zea mays* L.) PRODUCTION

4.1 ABSTRACT

Increased adoption of no-tillage corn production coupled with increasing N fertilizer prices suggests that currently recommended N application methods be re-evaluated. Injection of urea ammonium-nitrate (UAN) at sidedress may decrease N needed to maintain optimal grain yields compared to the common practice of surface-banding. A total of 15 trials were conducted over three years to compare the two methods of UAN application on the basis of grain yield measured at all sites; ear leaf tissue N content measured at 13 sites; and stalk NO₃ measured at 7 sites.. Urea ammonium-nitrate was injected and surface-banded at rates ranging from 0 to 169 kg N ha⁻¹. At sites where an N response was detected, grain yield and plant N and NO₃ contents were compared at all individual N rates and the response trend evaluated via regression. Only the ear leaf tissue N content at one site demonstrated a significant difference (p=0.05) between application methods where injection had a greater rate of tissue N increase with increasing N rate compared to surface-banding. Comparison between the two application methods at each N rate yielded inconsistent differences but injection of UAN resulted in greater grain yield, tissue N, or stalk NO₃ where differences were observed in most cases. Ear leaf tissue N content and grain yield results from N responsive sites were combined to determine the optimum N rate where tissue N or yield was at maximum for both methods; and injection was found to have an optimum N rate of 125 kg N ha⁻¹ where surface-banding had an optimum N rate of 150 kg N ha⁻¹. The results from the study indicate that in certain situations injecting UAN for no-tillage corn at sidedress may reduce the optimal N rate to achieve maximum yields; however, this is not consistently observed.

4.2 INTRODUCTION

Volatilization of ammonia (NH₃) increases with rising temperature, soil moisture, and microbial activity, and decreasing humidity and cation exchange capacity (Ernst, 1960; Gasser,

1964; Touchton and Hargrove, 1982). No-tillage systems favor these conditions because of increased plant residue on the surface of the mineral soil. Placing UAN solutions below crop residues into the mineral soil may help reduce $\text{NH}_3\text{-N}$ losses as a result of increased contact between fertilizer and soil, and decreased exposure to the atmosphere. However, grain yield and N uptake response differences in corn production may be negligible between the two methods, surface and injection, depending on climatic and environmental factors during and shortly after the time of application. This has caused variation within previous studies that focused on the placement of UAN solutions.

Volk (1959) was the one of the first to roughly compare UAN application methods and $\text{NH}_3\text{-N}$ loss between bare soil and sod, which is somewhat comparable to conventional tillage and no-tillage, respectively. UAN solutions broadcast sprayed onto bare soil exhibited highly varying $\text{NH}_3\text{-N}$ losses, but were typically less than treatments applied to sod. He acknowledged soil moisture as the main factor influencing $\text{NH}_3\text{-N}$ losses. Rapid soil moisture loss experienced with the bare soil in conjunction with low $\text{NH}_3\text{-N}$ loss suggests urea was not hydrolyzed in these conditions. Sod provided a buffer to the rapid loss of moisture, therefore increasing the urea hydrolysis rate and subsequent volatilization of NH_3 . In 1982, Touchton and Hargrove studied multiple application methods of various N fertilizers: shallow incorporation, unincorporated surface banding, and broadcast spraying of UAN solution in corn production. No significant yield and tissue N content differences were found between the surface banded and subsurface application of UAN, but broadcast spray of UAN resulted in a significant decrease in N use efficiency (NUE), defined as unit of grain yield per unit of N applied.

Mengel et al. (1982) found that injection of UAN solution below the crop residue produced higher yields in no-till systems as compared to broadcast spray application. In conventional tillage systems, yield differences were less significant between subsurface and surface banded UAN, further supporting Volk's (1959) assessment. In 1986, Fox et al. completed a study focusing on N sources, time of application, and application methods on no-till systems. The results of the study were similar to Touchton and Hargrove (1982) in that little yield and tissue N content differences were found between subsurface and surface banding of UAN solution. Fox and Bandel (1986) and Fenn and Hossner (1985) also observed the same results.

Howard and Tyler (1989) evaluated more N sources than had been previously studied, including: UAN, prilled urea, prilled AN, cogranulated urea-urea phosphate (UUP), and anhydrous ammonia (AA). Application methods were surface banding, broadcasting, and subsurface application into no-till corn systems. Unlike previously mentioned studies, Howard and Tyler (1989) observed a significant increase of N-use efficiency (NUE), defined as unit of grain yield per unit of N applied, when UAN and urea were subsurface applied compared to surface application. Another study on N sources and methods of application is Fox and Piekielek (1993). They compared urease inhibitors and urea sources in conjunction with injection, surface-banding, and broadcast application methods. In regards to the NUE of corn production, surface banded and injection application of UAN at both planting and sidedress was found to be similar to N-(n-butyl)thiophosphoric tiamide (NBPT) treated UAN and ammonium thiosulfate (ATS) surface applied. Injection of UAN was found to be the most efficient of the three application methods tested.

From aforementioned studies, the effect of UAN placement on corn yield and N uptake is variable, which may be due to a number factors regulating NH_3 volatilization. Numerous studies evaluating UAN placement were performed in the 1980s and early 1990s but typically in conventionally tilled systems. Recent increases in N fertilizer prices and heightened environmental concerns regarding N movement into the surrounding environment have created more interest in developing or evaluating existing methods of N management. Injection of UAN has been identified as a potential method of reducing N losses in no-tillage systems in Virginia. To evaluate agronomic performance of injected sidedress UAN on corn, experiments in all major corn production regions in Virginia were conducted.

4.3 OBJECTIVE

To evaluate injection and surface-banding sidedress UAN application methods on corn grain yield, ear leaf tissue N content, and stalk NO_3 concentration.

4.4 MATERIALS AND METHODS

Field trials were initiated in May of 2008 at two sites in Virginia. In 2009 and 2010 five and eight sites were established, respectively. Nitrogen fertilization before or at planting was determined and applied by the land owner or manager of the property. Sites located at the Virginia Tech Kentland research farm were planted, fertilized, and maintained either by farm personnel or by the researchers. Essential nutrients and soil fertility conditions, with the exception of N, were maintained by the land owners or managers to ensure no yield-limiting deficiencies.

4.4.1 Site Selection and Characterization

Sites were established in fields under no-tillage management for at least one growing season to ensure plant residue on the soil surface. Site identifications, locations, and soil descriptions are shown in Table 4-1. Temperature and precipitation data were acquired from the National Climatic Data Service of the National Oceanic and Atmospheric Administration (NOAA). Actual weather stations were chosen by proximity to the specific site. Monthly temperature average and precipitation totals from weather stations located near each site are shown in Fig. 4-1 to 4-9.

4.4.2 Treatments, Sampling, and Analytical Procedure

At each site UAN was surface-banded and injected at five N rates: 34, 67, 101, 135, and 169 kg N ha⁻¹, except site AE10 where the N rates were 39, 79, 118, and 157 kg N ha⁻¹. A zero N rate treatment was included at each site to determine residual soil N supplying capacity. A randomized complete block design with four replications was used at all sites. Plots were 4 rows (3m) wide and depending on the site layout, plot lengths were 7.5 or 9m.

Surface-banding of UAN was performed by dribbling the solution in a narrow band between rows on the residue surface. Injection application was accomplished via no-till coulters that cut surface residue and created a narrow furrow approximately 5cm deep between corn rows in the mineral soil (Fig. 4-10). Directly behind the coulters was an injection knife that directed the UAN solution into the bottom of the furrow. Minimal surface plant residue disturbance takes place when using this method.

Tissue N content in the ear leaf was measured at all sites with the exception of FM and FSD. Six ear leaves were removed from random plants within each plot at or near silking. The tissue was ground, mixed to homogeneity, and a subsample analyzed for N content by dry combustion at 900°C (VarioMax CNS Analyzer). Corn grain yield was measured at all sites from the middle two rows of each plot. Moisture in the grain was measured using a grain tester (Dickey-John) or the instrumentation on the harvesting combine (Harvest Master). Reported grain yield has been corrected to 15.5 g g⁻¹ moisture content.

At or near physiological maturity six segments of corn stalk were taken from each plot at sites PD09, TAR09, AE09, FM10, VD10, and VI10, using the method described by (Binford et al., 1990). Stalk segments were 30.3 cm long and were taken 15 cm above the ground surface. Stalks were dried and ground to pass a 40-mesh sieve (<0.40 mm). Twenty-five milliliters of ultrapure water was used to extract free nitrate from 250 mg of ground stalk tissue. The stalk tissue and water was shaken for 30 min and filtered. The extract was then analyzed for NO₃-N concentration colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments) (Miller, 1998).

4.4.3 Statistical Procedure

All study sites were organized as a randomized complete block design with four replications of each treatment. Ear leaf tissue N content, grain yield, and stalk NO₃ from each site were first evaluated to determine if a response to increasing N input existed. This was performed using linear and quadratic orthogonal contrasts in the GLM procedure of SAS 9.2 (SAS Institute, Cary, NC); both linear and quadratic contrasts were used to insure that sites were modeled correctly and that false results did not exist. Sites and application methods exhibiting an N rate effect were regressed by either a linear or quadratic model depending on best fit determined by r² value. The slopes of the surface and injection regressions, which are related to the rate of N response, were compared using the REG procedure in SAS 9.2. The two application methods were also compared at each N rate by Tukey HSD using the GLM procedure. The optimal N rate of both application methods at each site was determined by the N rate where the y-variable (ear leaf tissue N or grain yield) was at the predicted maximum from the regression. This was performed on both ear leaf tissue N content and grain yield at each N responsive site.

Mean grain yield and tissue N content at N responsive sites from injection and surface-banding applications were combined, regressed, and optimal N rate was determined for both methods.

4.5 RESULTS AND DISCUSSION

4.5.1 N Responsive Sites

Mean grain yield for each site can be found in Table 4-2, and mean ear leaf tissue N content can be found in Table 4-3. Grain yield, ear leaf tissue N content, and stalk NO₃ concentration responded significantly to increasing N rate at sites PD09 and VI10 (Table 4-4). Stalk-NO₃ was not measured at sites KMT09, AE10, KAB10, and PD10, but an N rate response was detected in both grain yield and ear leaf tissue N content at each site (Table 4-4).

Site VD10 ear leaf tissue N content exhibited a response to N rate; however, grain yield and stalk NO₃ did not demonstrate a response (Table 4-5). Below average precipitation at this site coupled with above average temperatures reduced grain yield and stalk NO₃ concentrations (Fig. 4-8, Table 4-2). Drought stress may have been minimal from the time of UAN treatment application to silking, which would explain the N rate response in ear leaf tissue N content and not in grain yield or stalk NO₃. Site KBB10 also expressed an N rate response in ear leaf tissue N content, but not in grain yield (Table 4-5). This site had a similar rainfall and temperature pattern seen at site VD10; and grain yields were low compared to nearby sites in previous years (Fig. 4-3; Table 4-2). Again, N uptake and crop growth may not have been impeded until near or after silking, which would explain the difference in N rate response. An N rate response in ear leaf tissue N content was exhibited at site KBB10, but like sites VD10 and KAB09, no N response in grain yield was detected (Table 4-5). This site did have adequate rainfall and normal temperatures during the growing season, which can be seen in high grain yields; however, UAN application treatments may have been applied incorrectly at this site, but this could not be verified (Fig. 4-2; Table 4-2).

Grain yield at sites FM10, FSD10, and KCS08 was significantly affected by N rate however, no ear leaf tissue N content measurements were taken at sites FM10 and FSD10 (Table 4-6). Ear leaf tissue N content at KCS08 was unaffected by N rate increase. This may be due to below average rainfall amounts in May and June, which would range from the time of UAN

treatment application to silking (Fig. 4-1). High ear leaf tissue N content may indicate normal N uptake but limited crop growth, leading to a high N concentrations in the plant tissue (Table 4-3).

Two sites exhibited an N rate response only in stalk NO_3 : TAR09 and AE09 (Table 4-7). Site TAR09 was situated on a sandy loam soil and experienced a rainfall deficit during the growing season (Table 4-1; Fig. 4-6). Drought stress was visible in the crop throughout the growing season; however, rainfall amounts were only slightly less than average. Though ear leaf tissue N content and grain yields were low and were not N rate responsive, enough rainfall could have occurred for N uptake and accumulation in the stalk. The lack of N rate response in the ear leaf tissue N content and grain yield at site AE09 may be due to an additional application of N by the landowner after application of UAN treatments. This was unconfirmed, but high tissue N and grain yield results indicate this may have occurred (Table 4-2 and 4-3).

Ear leaf tissue N and grain yields at site KB08 were unresponsive to N rate. Rainfall at this site was below average in May and June; which would have limited crop growth, but may have not limited N uptake (Fig. 4-1). This is evident in the high ear leaf tissue N contents measured in the treatments (Table 4-3). Grain yields, though seemingly above average, did not exhibit a response to N rate, and in the UAN injection treatment grain yield decreased with increasing N rate. With the information available, no explanation can be given as to why this occurred.

4.5.2 Comparison of Application Methods

4.5.2.1 Ear Leaf Tissue Nitrogen Content

A comparison of the slopes of the regressions for application method at each site was performed (Table 4-8). Only site KAB10 demonstrated a significant difference, where earleaf N concentration increased more rapidly from injection of UAN as N rates increased compared to surface-banding. Sites exhibiting a significant difference between application methods in regards to ear leaf tissue N content at one or more N rates were: KMT09, KAB09, PD09, PD10, and KAB10. Significant differences between application methods were not observed at sites AE10, VD10, VI10, and KBB10 (Fig. 4-11; Fig. 4-12; Fig. 4-13; and Fig. 4-14), respectively). Ear leaf tissue N content was higher for the injection application treatment at an N rate of 135 kg N ha^{-1} at site KMT09 (Fig. 4-15). At site KAB09, injection application of UAN produced

significantly higher tissue N content compared to surface application at an N rate of 101.1 kg N ha⁻¹ (Fig. 4-16). At an N rate of 34 kg N ha⁻¹, the injection application method increased tissue N at sites PD09 and PD10 (Fig. 2-17 and 2-18, respectively). At site KAB10, the injection method produced higher tissue N content at an N rate of 67 kg N ha⁻¹ (Fig. 4-19).

Differences between UAN application treatments were expected to be observed at the lower N rates; however, results do not support this expectation. The UAN injection treatment produced significantly higher ear leaf tissue N content at five sites and at varying N rates compared to the surface application method. However, these differences were seen throughout the range of application rates.

4.5.2.2 Grain Yield

The comparison of slopes for each of the N-responsive sites can be found in Table 4-8. Mean values and minimum significant difference displayed by use of error bars at each N rate with regressions by method can be found in each site's respective figure: KCS08, Fig. 4-20; KMT09, Fig. 4-21; PD09, Fig. 4-22; AE10, Fig. 4-23; FM10, Fig. 4-24; FSD10, Fig. 4-25; VI10, Fig. 4-26; and KAB10, Fig. 4-27. Based on the comparison of the regression slope no sites demonstrated differences in method of application at $p=0.10$ (Table 4-8). Grain yields with surface application of UAN were significantly higher at N rates 101 and 169 kg N ha⁻¹ at the VI site. However, injection of UAN produced significantly higher grain yields at the KAB10 site at N rates 67 and 101 kg N ha⁻¹, and at this site, surface-banding produced higher grain yields at 169 kg N ha⁻¹ than injection. No other differences between application methods were observed. All grain yield results are similar to previous studies, in that a comparison of injection and surface applications of UAN typically results in no significant difference or varying differences that lead to an inconclusive result (Fenn and Hossner, 1985; Fox and Bandel, 1986; Fox et al., 1986; Touchton and Hargrove, 1982).

4.5.2.3 Stalk Nitrate

Variability between stalk NO₃ means was large at most sites; therefore, no significant difference was observed between the regression slopes of both methods (Table 4-8). Site TAR09

exhibited a significant difference between application methods at N rates of 34 and 101 kg N ha⁻¹, where injection application was greater than surface at the lower rate and less at the higher N rate (Fig. 4-28). No difference in stalk NO₃ between application methods was observed at site AE09 at each N rate (Fig. 4-29). Injection application of UAN produced higher stalk NO₃-N concentrations at 67 and 101 kg N ha⁻¹ at site VI10 (Fig. 4-30). The site had a high yield potential and grain yield results indicate the N rate to reach optimal yield was not met by the highest N rate applied. This could have resulted in low stalk NO₃ concentrations, which indicate N deficiency.

4.5.2.4 Optimal N Rate

Injection of UAN reduced the N rate needed to attain the predicted maximum ear leaf tissue N contents and grain yields compared to surface-banding at most sites (Table 4-9). When results from N responsive sites were combined, the N rate needed to reach the predicted maximum ear leaf tissue N content and grain yield was 125 kg N ha⁻¹ for injection application and 150 kg N ha⁻¹ for surface-banding application (Fig. 4-31 and Fig. 3-32). This suggests that though injection of UAN is not always observed as more efficient than surface-banding at specific sites, it may be more advantageous over several sites and years.

4.6 CONCLUSIONS

We expected to observe the injection application of UAN to increase grain yield, ear leaf tissue N content, and stalk NO₃ at lower N rates than the surface-banding method, and to be similar to surface-banding at higher rates. This included the acknowledgement that this may only occur at sites where the UAN treatments were applied in conditions where soil moisture and temperature was high and no rainfall and moderate to high winds were expected in the short-term forecast. Average to optimal rainfall and temperatures during the growing season would have also been needed to observe any significant difference between application methods.

When the slopes of the regressions of both methods were compared at each individual site, only one site of 15 exhibited a higher ear leaf tissue N content when UAN was injected compared to surface applied. No other differences using this statistical procedure were observed

when grain yield or stalk NO_3 was the dependent variable. When comparing application methods at individual N rates, injection of UAN was found to increase grain yield, tissue N, and stalk NO_3 at varying N rates at many sites; however, the N rate where these differences were observed varied greatly and no trend could be identified. This is counter to the expectation mentioned above, but the results are similar to many previous studies (Fenn and Hossner, 1985; Fox and Bandel, 1986; Fox et al., 1986; Touchton and Hargrove, 1982). The predicted N rate to achieve the maximum ear leaf tissue N content or grain yield was 25 kg N ha^{-1} lower from injecting UAN than surface-banding application. This suggests the practice of injecting UAN may be a viable application method to increase N availability; however, injection may not be more efficient in certain situations.

The result from this study suggests that the injection of UAN in many situations is not more efficient than the surface-banding application method; however, it also should be recognized that it is unlikely injecting UAN will actually result in lower yields or tissue N compared to surface-banding. Injection of UAN is a management practice that reduces the risk of N-loss, and therefore, may be more efficient when used across many sites and years.

4.7 REFERENCES

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4.8 TABLES

Table 4-1. Site identification, location, and soil description for UAN application method study.

Year	Site Name	Site ID	Coordinates		Soil Series	Taxonomic Description
			Latitude	Longitude		
2008	Kentland Bottom Kentland Cemetery Strips	KB08	37°11'49" N	80°34'19" W	Guernsey silt loam	Fine, Mixed, Superactive, Mesic Aquic Hapludalf
		KCS08	37°11'44" N	80°35'8" W	Unison and Braddock	Mixed, Semiactive, Mesic, Typic Hapludult
2009	Kentland Mid-Terrace Kentland Adam's Bottom	KMT09	37°12'5" N	80°33'56" W	Hayter loam	Fine-loamy, Mixed, Active, Mesic Ultic Hapludalf
		KAB09	37°12'20" N	80°33'47" W	Hayter loam	Fine-loamy, Mixed, Active, Mesic Ultic Hapludalf
	Paul Davis Farm	PD09	37°31'55" N	76°52'54" W	Pamunkey fine sandy loam	Fine-loamy, Mixed, Semiactive, Thermic Ultic Hapludalf
	Tidewater AREC	TAR09	36°40'45" N	76°45'48" W	Lynchburg fine sandy loam	Fine-loamy, Siliceous, Semiactive, Thermic Aeric Paleaquult
	Ag Expo	AE09	37°46'41" N	77°18'52" W	State loamy fine sand	Fine-loamy, mixed, Semiactive, Thermic Typic Hapludult
2010	Ag Expo	AE10	38°5'38" N	76°48'47" W	26% Kempsville loam	Fine-loamy, Siliceous, Subactive, Thermic Typic Hapludult
					21% Rumford and Tetotum	Coarse-loamy, Siliceous, Subactive, Thermic Typic Hapludult
					53% Suffolk sandy loam	Fine-loamy, Siliceous, Semiactive, Thermic Typic Hapludult
	Fitzgerald-Middlebrook	FM10	38°3'34" N	79°11'5" W	Frederick-Christian gravelly silt loam	Fine, Mixed, Semiactive, Mesic Typic Paleudults
	Fitzgerald-Stuarts Draft	FSD10	38°1'5" N	79°1'30" W	Allegheny-Cotaco fine sandy loam	Fine-loamy, Mixed, Semiactive, Mesic Typic Hapludult
	VACI Dryland	VD10	38°5'33" N	76°43'49" W	State fine sandy loam	Fine-loamy, mixed, Semiactive, Thermic Typic Hapludult
	VACI Irrigated	VI10	38°5'39" N	76°43'33" W	State fine sandy loam	Fine-loamy, mixed, Semiactive, Thermic Typic Hapludult
	Paul Davis Farm	PD10	37°31'53" N	76°52'59" W	Pamunkey fine sandy loam	Fine-loamy, Mixed, Semiactive, Thermic Ultic Hapludalf
	Kentland Big Barn	KBB10	37°11'45" N	80°34'50" W	Unison and Braddock	Fine, Mixed, Semiactive, Mesic, Typic Hapludult
	Kentland Adam's Bottom	KAB10	37°12'16" N	80°33'42" W	Hayter loam	Fine-loamy, Mixed, Active, Mesic Ultic Hapludalf

Table 4-2. Mean grain yield as a function of N[†] rate and application method for all sites.

Site	Method	Nitrogen Rate (kg N ha ⁻¹)						
		0.0	34	67	101	135	169	
					Mg ha ⁻¹			
KB08	Injection	10.6	12.5	10.6	10.4	8.9	9.9	
	Surface		10.4	10.7	10.2	10.5	10.9	
KCS08	Injection	10.1	11.4	11.4	11.5	12.6	12.1	
	Surface		10.8	11.1	12.1	11.7	12.6	
KMT09	Injection	13.1	14.0	15.5	16.0	16.2	15.9	
	Surface		14.9	15.8	15.2	16.3	15.8	
KAB09	Injection	7.7	8.9	7.9	9.0	9.1	8.7	
	Surface		7.7	7.6	8.8	8.7	8.7	
PD09	Injection	7.1	7.5	9.2	8.9	8.0	8.5	
	Surface		8.2	9.2	9.1	8.4	8.7	
TAR09	Injection	6.3	6.3	6.8	7.1	5.8	6.2	
	Surface		6.2	6.3	6.6	6.5	6.1	
AE09	Injection	15.3	15.3	16.7	16.5	16.7	15.9	
	Surface		16.4	15.1	15.5	15.7	15.0	
FM10	Injection	7.9	8.9	10.2	10.7	11.3	10.6	
	Surface		9.5	10.1	10.4	9.8	10.7	
FSD10	Injection	7.2	9.1	8.1	9.9	10.2	9.6	
	Surface		9.8	8.4	9.6	9.2	10.2	
VD10	Injection	4.3	4.0	4.6	6.0	4.3	4.6	
	Surface		4.6	6.0	5.2	4.0	4.5	
VI10	Injection	9.2	10.4	11.5	11.6	12.8	11.8	
	Surface		10.6	11.0	12.8	12.6	13.3	
PD10	Injection	4.4	4.5	5.2	4.9	3.7	3.7	
	Surface		4.2	5.1	4.9	5.4	4.4	
KBB10	Injection	7.0	4.7	6.7	5.5	5.5	6.6	
	Surface		6.4	7.6	5.7	6.6	4.5	
KAB10	Injection	6.1	9.0	10.6	10.8	9.5	8.1	
	Surface		7.9	8.9	9.5	8.8	10.3	
			Nitrogen Rate (kg N ha ⁻¹)					
		0.0	39	79	118	157		
AE10	Injection	3.9	5.0	5.1	5.3	5.4		
	Surface		5.1	5.3	5.4	5.7		

[†]N source was UAN solution

Table 4-3. Mean ear leaf tissue N[†] content as a function of N rate and application method from all sites except sites FM10 and FSD10.

Site	Method	Nitrogen Rate (kg N ha ⁻¹)					
		0.0	34	67	101	135	169
		g N kg ⁻¹					
KB08	Injection	38.4	38.7	39.1	37.4	39.0	38.8
	Surface		38.5	39.5	37.6	39.2	38.5
KCS08	Injection	37.5	34.4	35.8	36.1	35.1	36.7
	Surface		36.4	36.1	37.4	34.3	36.1
KMT09	Injection	27.8	28.9	33.8	35.0	36.2	33.5
	Surface		31.4	34.5	34.8	32.6	33.6
KAB09	Injection	25.2	29.9	30.6	31.8	33.5	33.9
	Surface		27.8	30.4	30.5	31.5	32.8
PD09	Injection	24.3	29.9	30.3	29.9	30.1	32.1
	Surface		27.5	29.8	29.6	30.9	31.0
TAR09	Injection	26.3	28.2	26.7	27.4	28.2	28.1
	Surface		26.7	26.3	29.3	30.4	29.6
AE09	Injection	33.3	33.9	33.6	33.3	35.3	33.2
	Surface		34.3	34.0	33.1	34.9	34.7
VD10	Injection	26.8	27.0	28.2	29.0	29.8	29.0
	Surface		27.0	28.2	29.1	29.9	30.4
VI10	Injection	26.9	27.5	30.4	31.2	31.7	31.4
	Surface		27.2	28.7	31.4	30.5	31.9
PD10	Injection	19.0	22.7	23.6	23.0	24.0	25.1
	Surface		22.0	22.2	23.4	24.7	23.3
KBB10	Injection	25.6	28.8	30.2	31.4	30.6	31.0
	Surface		28.7	29.5	30.7	29.9	30.8
KAB10	Injection	18.1	28.5	32.6	32.6	32.7	31.1
	Surface		27.2	28.5	31.9	31.5	33.3
		N Rate (kg N ha ⁻¹)					
		0.0	39	79	118	157	
AE10	Injection	18.4	22.0	23.2	24.1	24.4	
	Surface		22.0	24.2	24.6	25.7	

[†]N source was UAN solution

Table 4-4. Determination of ear leaf tissue N content, grain yield, and stalk NO₃ response to N rate for sites PD09, VI10, KMT09, AE10, KAB10, and PD10.

Site	Appl. Method	Contrast Model	Earleaf N	Grain Yield	Stalk NO ₃
				Pr>F	
PD09	Injected	Linear	<0.0001 [†]	0.0310 [†]	0.1514
		Quadratic	0.0405 [†]	0.0197 [†]	0.0236 [†]
	Surface	Linear	<0.0001 [†]	0.0201 [†]	0.8076
		Quadratic	0.0297 [†]	0.0117 [†]	0.0172 [†]
VI10	Injected	Linear	<0.0001 [†]	<0.0001 [†]	<0.0001 [†]
		Quadratic	0.1168	0.0044 [†]	0.1337
	Surface	Linear	<0.0001 [†]	0.0002 [†]	<0.0001 [†]
		Quadratic	0.4423	0.0839	0.3676
KMT09	Injected	Linear	0.0007 [†]	0.0013 [†]	nd ^{††}
		Quadratic	0.0340 [†]	0.1075	nd
	Surface	Linear	0.0226 [†]	0.0084 [†]	nd
		Quadratic	0.0335 [†]	0.0990	nd
AE10	Injected	Linear	<0.0001 [†]	<0.0001 [†]	nd
		Quadratic	0.0061 [†]	0.0075 [†]	nd
	Surface	Linear	<0.0001 [†]	0.0001 [†]	nd
		Quadratic	0.0064 [†]	0.0073 [†]	nd
KAB10	Injected	Linear	<0.0001 [†]	0.0101 [†]	nd
		Quadratic	<0.0001 [†]	<0.0001 [†]	nd
	Surface	Linear	<0.0001 [†]	<0.0001 [†]	nd
		Quadratic	<0.0001 [†]	0.0934	nd
PD10	Injected	Linear	<0.0001 [†]	0.031 [†]	nd
		Quadratic	0.1403	0.0197 [†]	nd
	Surface	Linear	0.0002 [†]	0.0201 [†]	nd
		Quadratic	0.0380 [†]	0.0117 [†]	nd

[†]Indicates a significant response to increasing N rate at probability level of 0.05

^{††}No data available

Table 4-5. Determination of ear leaf tissue N content, grain yield, and stalk NO₃ response to N rate for sites VD10, KAB10, and KBB10.

Site	Appl. Method	Contrast Model	Earleaf N	Grain Yield	Stalk NO ₃
VD10	Injected	Linear	0.0026 [†]	0.4637	0.8866
		Quadratic	0.5102	0.3450	0.1526
	Surface	Linear	0.0004 [†]	0.7610	0.3017
		Quadratic	0.4658	0.1202	0.0856
KAB09	Injected	Linear	<0.0001 [†]	0.2428	nd ^{††}
		Quadratic	0.0373 [†]	0.5644	nd
	Surface	Linear	<0.0001 [†]	0.0922	nd
		Quadratic	0.1124	0.9593	nd
KBB10	Injected	Linear	<0.0001 [†]	0.8991	nd
		Quadratic	<0.0001 [†]	0.3443	nd
	Surface	Linear	<0.0001 [†]	0.1083	nd
		Quadratic	0.0024 [†]	0.3696	nd

[†]Indicates a significant response to increasing N rate at probability level of 0.05

^{††}No data available

Table 4-6. Determination of ear leaf tissue N content, grain yield, and stalk NO₃ response to N rate for sites FM10, FSD10, and KCS08.

Site	Appl. Method	Contrast		Earleaf N	Grain Yield	Stalk NO ₃
		Model				
					Pr>F	
FM10	Injected	Linear		nd ^{††}	<0.0001 [†]	0.0026 [†]
		Quadratic		nd	0.0299 [†]	0.0034 [†]
	Surface	Linear		nd	0.0023 [†]	0.1202
		Quadratic		nd	0.0956	0.1463
FSD10	Injected	Linear		nd	0.0013 [†]	nd
		Quadratic		nd	0.2037	nd
	Surface	Linear		nd	0.0055 [†]	nd
		Quadratic		nd	0.4818	nd
KCS08	Injected	Linear		0.9109	0.0042 [†]	nd
		Quadratic		0.3660	0.3683	nd
	Surface	Linear		0.3765	0.0010 [†]	nd
		Quadratic		0.8153	0.6766	nd

[†]Indicates a significant response to increasing N rate at probability level of 0.05

^{††}No data available

Table 4-7. Determination of ear leaf tissue N content, grain yield, and stalk NO₃ response to N rate for sites TAR09, AE09, and KB08.

Site	Appl. Method	Contrast Model	Tissue N	Pr>F Grain Yield	Stalk NO₃
TAR09	Injected	Linear	0.1893	0.6354	0.0008 [†]
		Quadratic	0.8671	0.2851	0.0650 [†]
	Surface	Linear	0.0001 [†]	0.7711	0.0001 [†]
		Quadratic	0.9683	0.4322	0.3101
AE09	Injected	Linear	0.3873	0.1248	0.0026 [†]
		Quadratic	0.2612	0.0677	0.7939
	Surface	Linear	0.0383 [†]	0.4686	0.0137 [†]
		Quadratic	0.6179	0.5777	0.0812 [†]
KB08	Injected	Linear	0.8719	0.0016 [†]	nd ^{††}
		Quadratic	0.7651	0.5060	nd
	Surface	Linear	0.9319	0.7720	nd
		Quadratic	0.8092	0.5645	nd

[†]Indicates a significant response to increasing N rate at probability level of 0.05

^{††}No data available

Table 4-8. Comparison between application method regression slope at each site exhibiting an N rate response.

Dependent Variable	Site	Pr>F
Grain Yield	KCS08	0.5855
	KMT09	0.3593
	PD09	0.9086
	AE10	0.4502
	FM10	0.8975
	FSD10	0.6183
	VI10	0.8075
	KAB10	0.4747
Ear Leaf Tissue N	KMT09	0.1287
	KAB09	0.8302
	PD09	0.6330
	AE10	0.7663
	VD10	0.4177
	VI10	0.622
	PD10	0.229
	KBB10	0.3903
KAB10	0.0476 [†]	
Stalk NO3	TAR09	0.9765
	AE09	0.9834
	FSD10	0.8300
	VI10	0.2876

[†]Significant difference at p=0.05

Table 4-9. N rate needed to achieve predicted maximum yields based upon regression analysis

Site	Method	Optimum N Rate	
		Ear Leaf Tissue N [†]	Yield [‡]
		kg N ha ⁻¹	
KCS08	Injected	NR [§]	167
	Surface	NR [§]	BMR [¶]
KMT09	Injected	130	137
	Surface	120	122
PD09	Injected	133	104
	Surface	150	106
FM10	Injected	NR [§]	133
	Surface	NR [§]	136
FSD10	Injected	NR [§]	151
	Surface	NR [§]	BMR [¶]
VI10	Injected	BMR [¶]	134
	Surface	BMR [¶]	BMR [¶]
KAB10	Injected	113	93
	Surface	136	BMR [¶]
KAB09	Injected	150	NR [#]
	Surface	BMR [¶]	NR [#]
VD10	Injected	150	NR [#]
	Surface	BMR [¶]	NR [#]
PD10	Injected	150	NR [#]
	Surface	117	NR [#]
KBB10	Injected	113	NR [#]
	Surface	117	NR [#]

[†]N rate needed to achieve maximum ear leaf tissue N

[‡]N rate needed to achieve maximum grain yield

[§]Ear leaf tissue N content not responsive (NR) to increasing N rate

[¶]Beyond Maximum N Rate (BMR) needed to achieve maximum ear leaf tissue N or grain yield is beyond maximum applied N rate

[#]Grain yield not responsive to increasing N rate

4.9 FIGURES

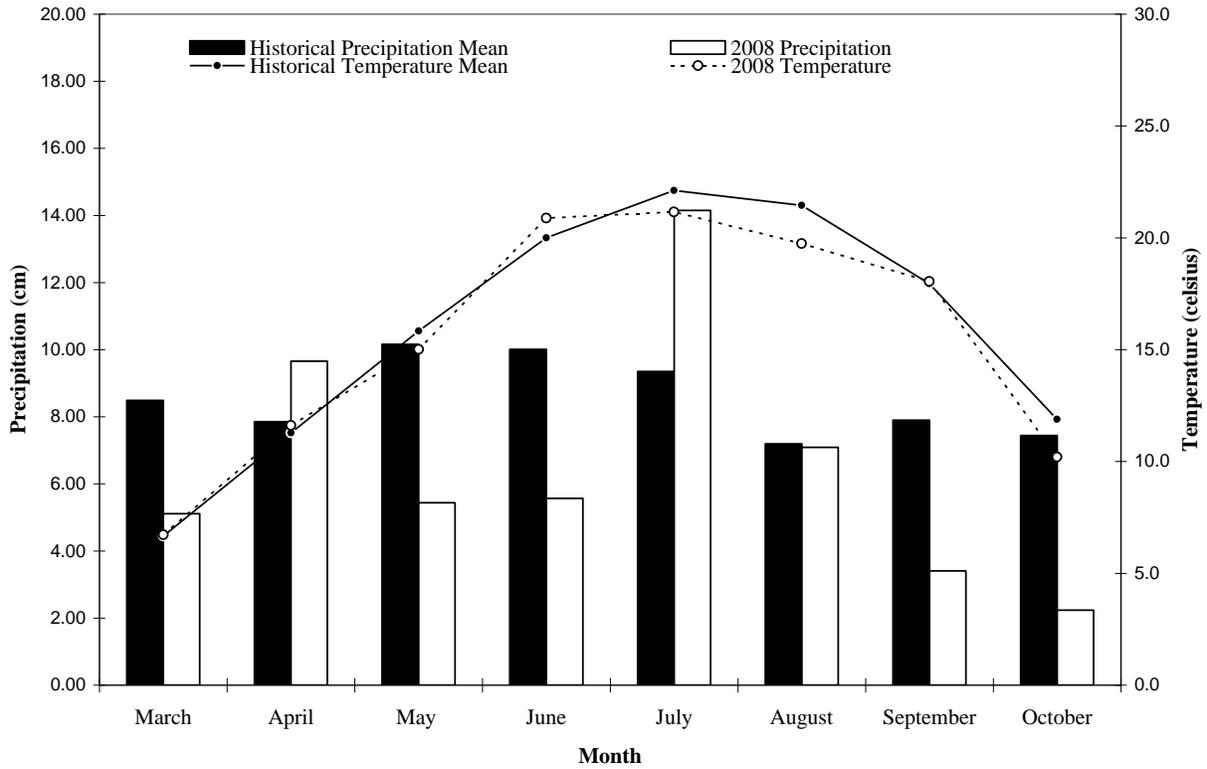


Figure 4-1. Monthly precipitation totals and monthly mean temperature for sites KB08 and KCS08, and 40 yr (1971-2010) historical averages. KB08 and KCS08 weather data procured from weather station located on Kentland Research Farm. Historical weather data procured from NOAA weather station (Station ID: 446955).

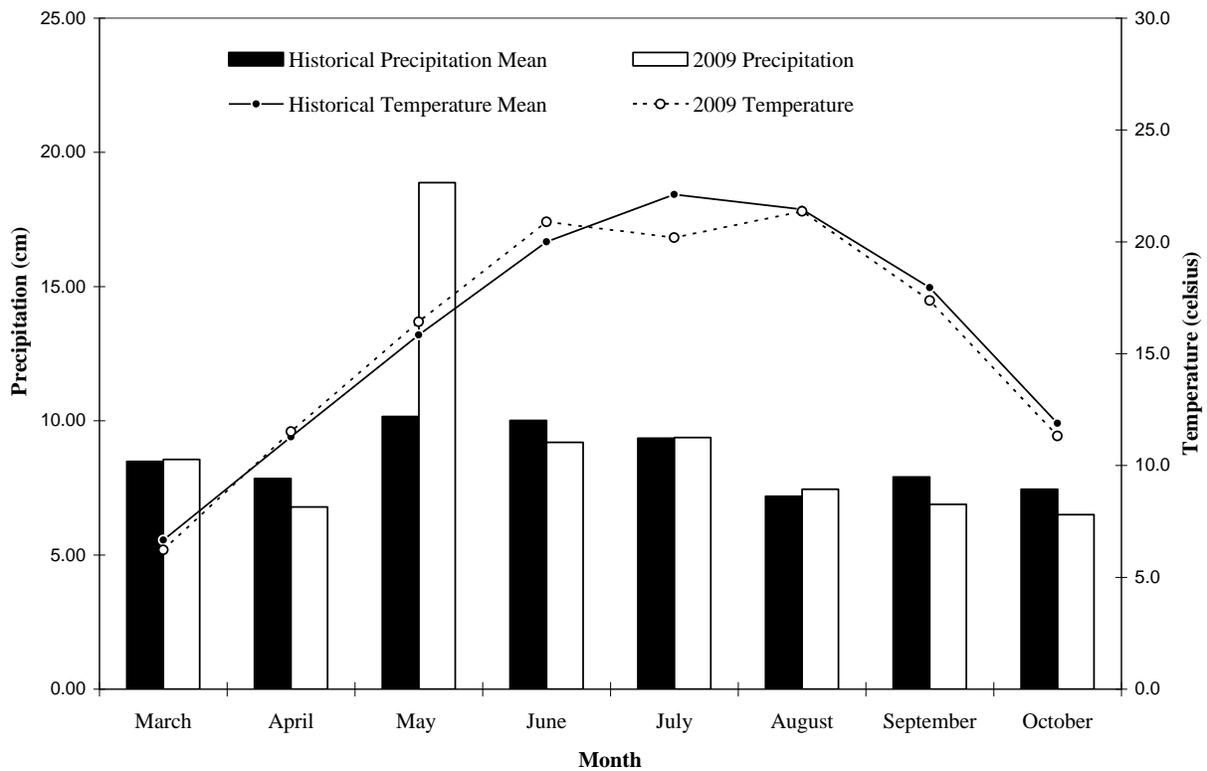


Figure 4-2. Monthly precipitation totals and monthly mean temperature for sites KMT09 and KAB09, and 40 yr (1971-2010) historical averages. KMT09 and KAB09 weather data procured from weather station located on Kentland Research Farm. Historical weather data procured from NOAA weather station (Station ID: 446955).

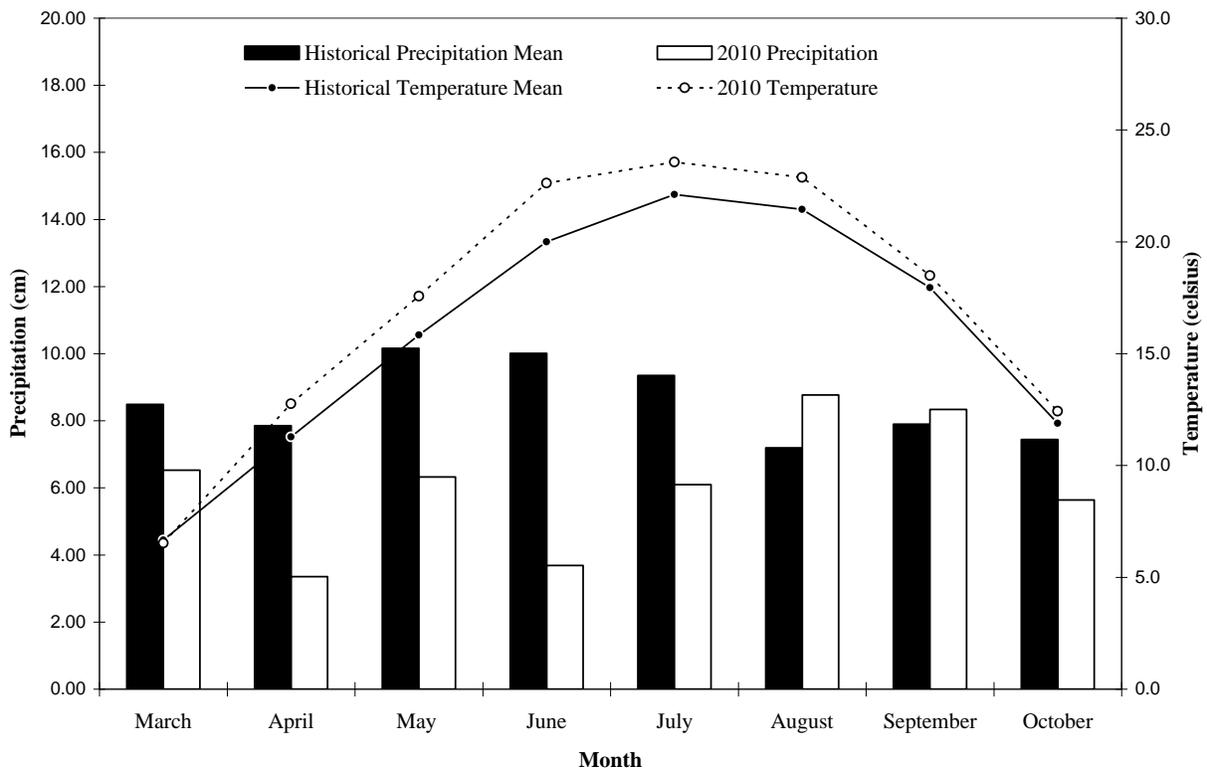


Figure 4-3. Monthly precipitation totals and monthly mean temperature for sites KBB10 and KAB10, and 40 yr (1971-2010) historical averages. KBB10 and KAB10 weather data procured from weather station located on Kentland Research Farm. Historical weather data procured from NOAA weather station (Station ID: 446955).

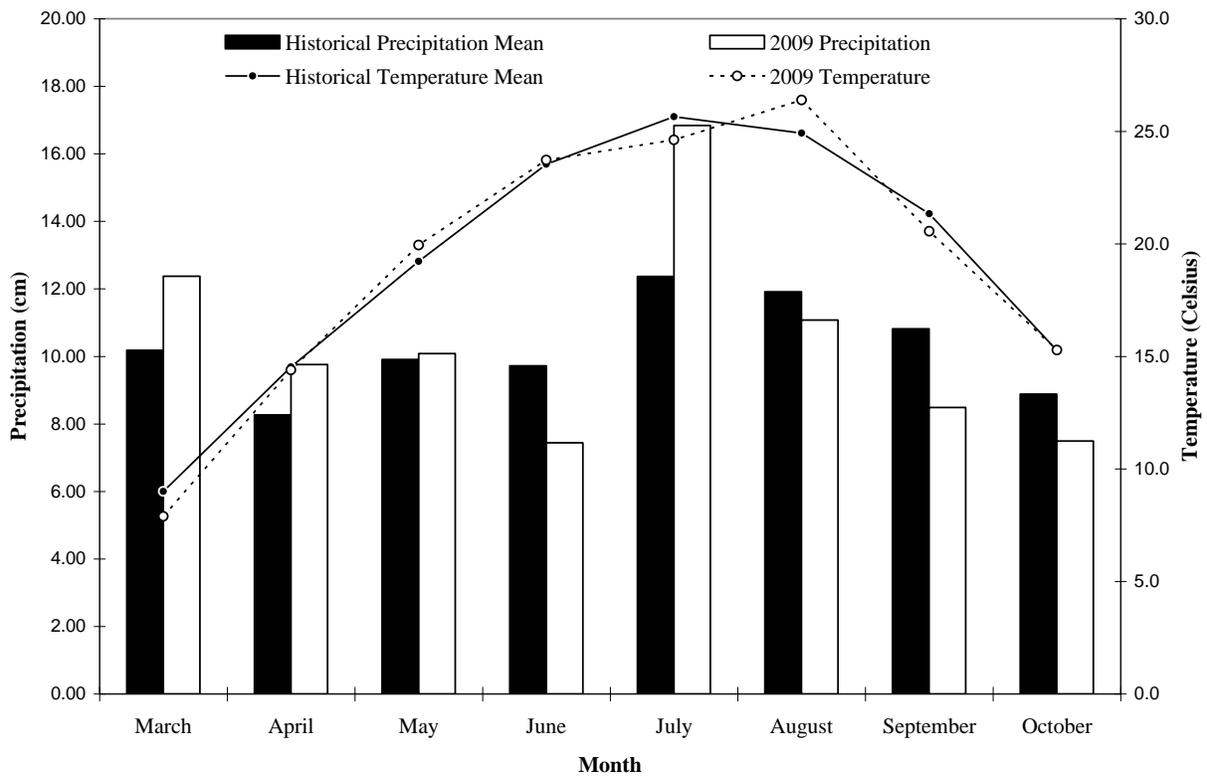


Figure 4-4. Monthly precipitation totals and monthly mean temperature for site PD09, and 55 yr (1955-2010) historical averages. PD09 weather data procured from NOAA weather station located in West Point, VA (37:33 lat, -76:48 long).

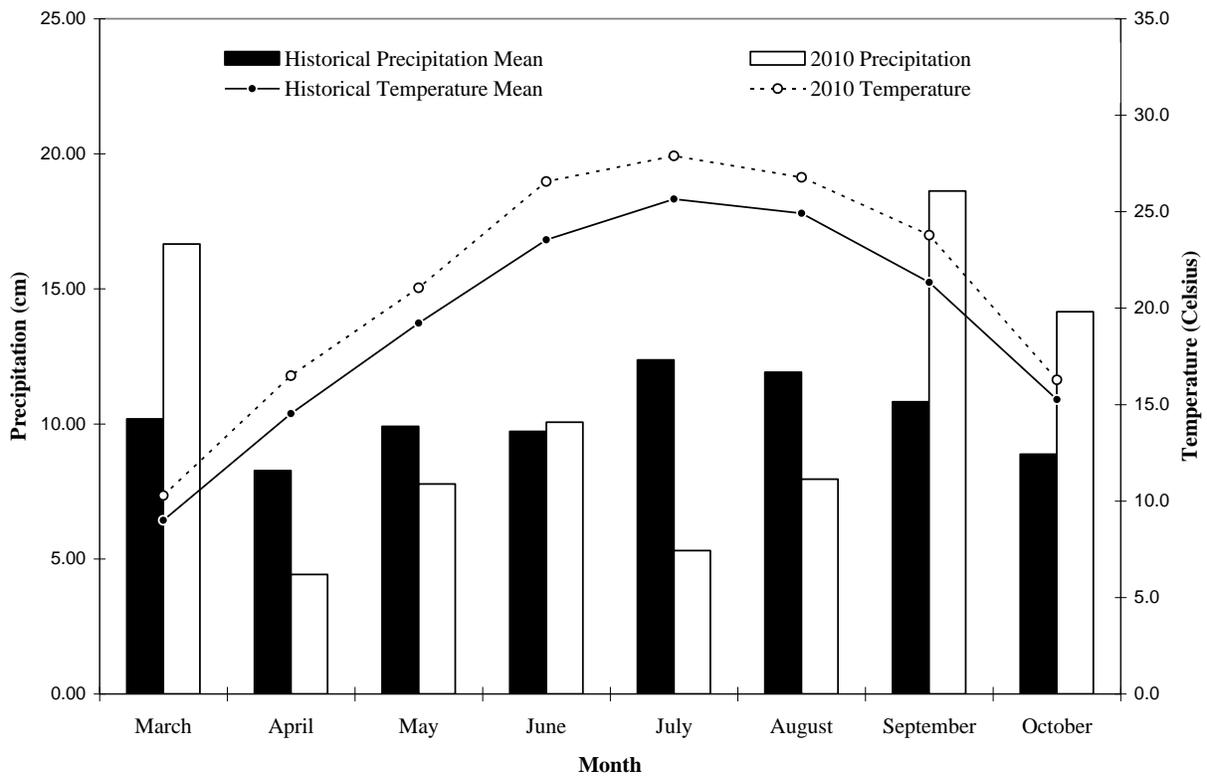


Figure 4-5. Monthly precipitation totals and monthly mean temperature for site PD10, and 55 yr (1955-2010) historical averages. PD10 weather data procured from NOAA weather station located in West Point, VA (37:33 lat, -76:48 long).

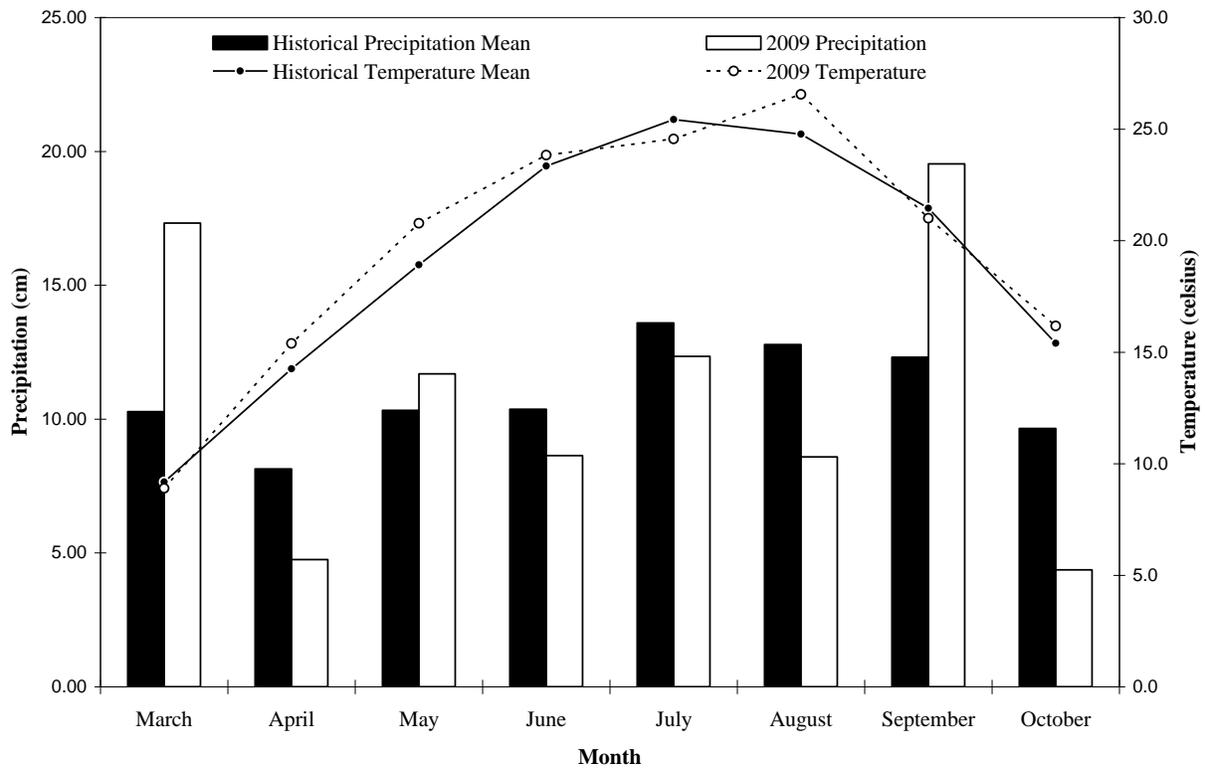


Figure 4-6. Monthly precipitation totals and monthly mean temperature for site TAR09, and 50 yr (1960-2010) historical averages. TAR09 weather data procured from NOAA weather station located in Holland, VA (36:40 lat, -76:46 long).

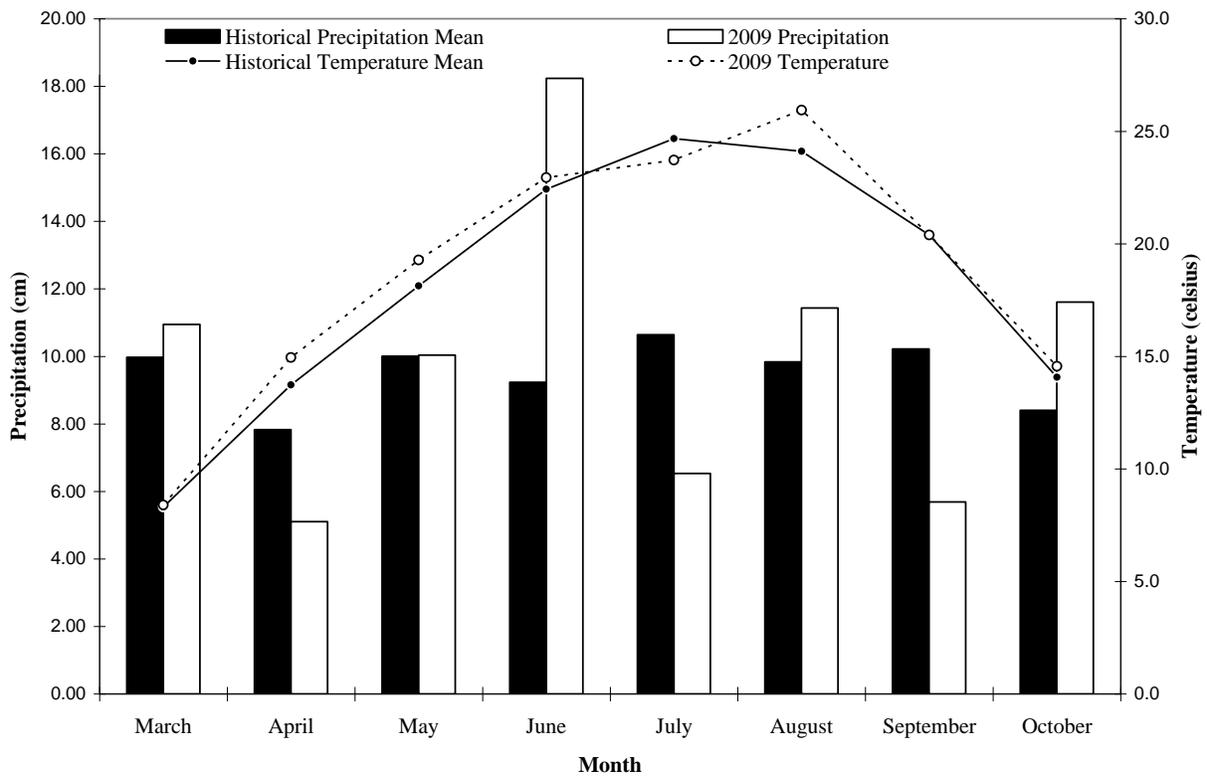


Figure 4-7. Monthly precipitation totals and monthly mean temperature for site AE09, and 50 yr (1960-2010) historical averages. AE09 weather data procured from NOAA weather station located in Ashland, VA (37:45 lat, -77:29 long).

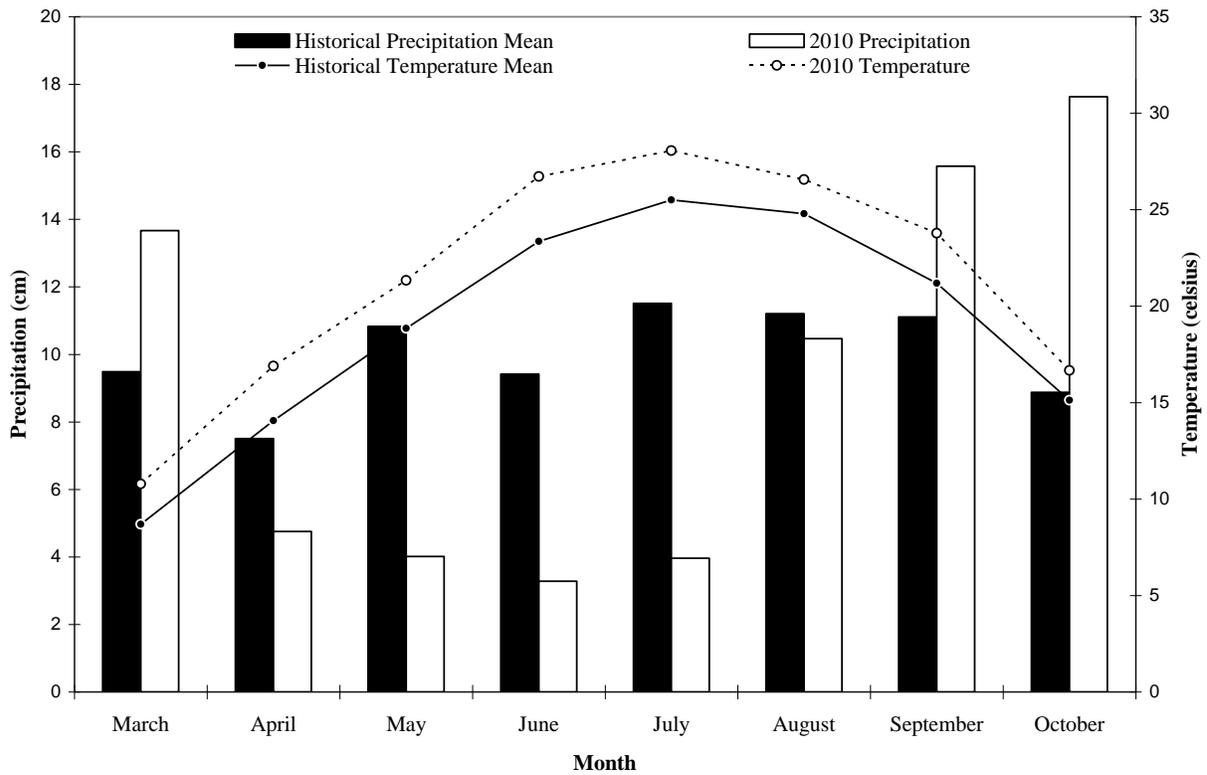


Figure 4-8. Monthly precipitation totals and monthly mean temperature for sites AE10, VD10, and VI10, and 50 yr (1960-2010) historical averages. Weather data procured from NOAA weather station located in Warsaw, VA (37:59 lat, -76:46 long).

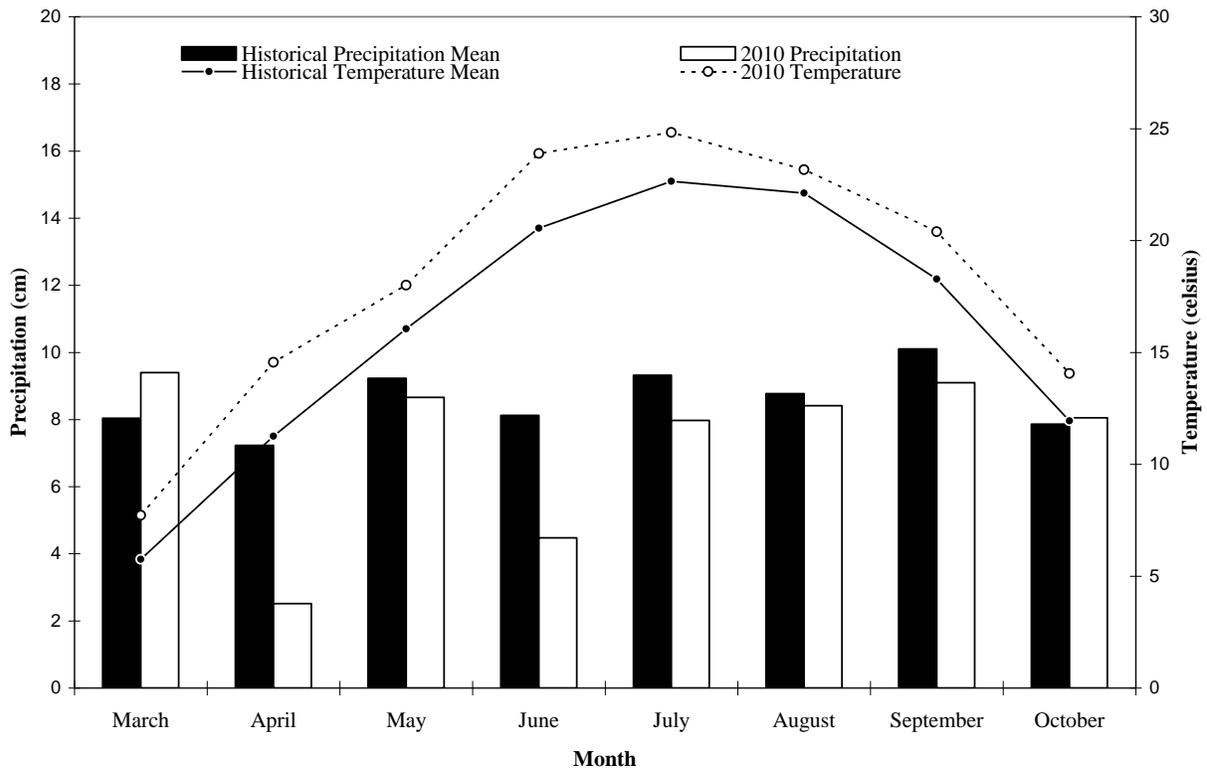


Figure 4-9. Monthly precipitation totals and monthly mean temperature for sites FM10 and FSD10, and 50 yr (1960-2010) historical averages. Weather data procured from NOAA weather station located in Staunton, VA (38:10 lat, -79:05

Figure 4-10. A coulter and knife assembly for injection of UAN in no-tillage systems.



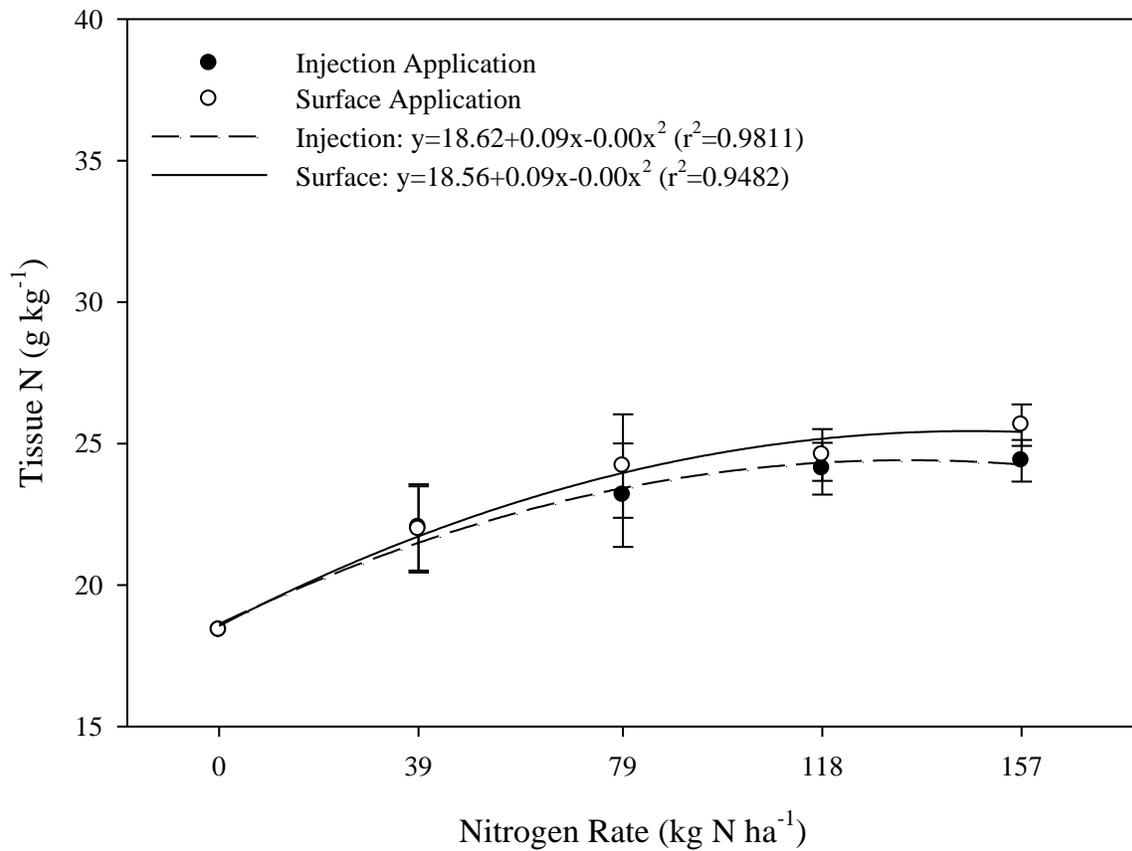


Figure 4-11. Site AE10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

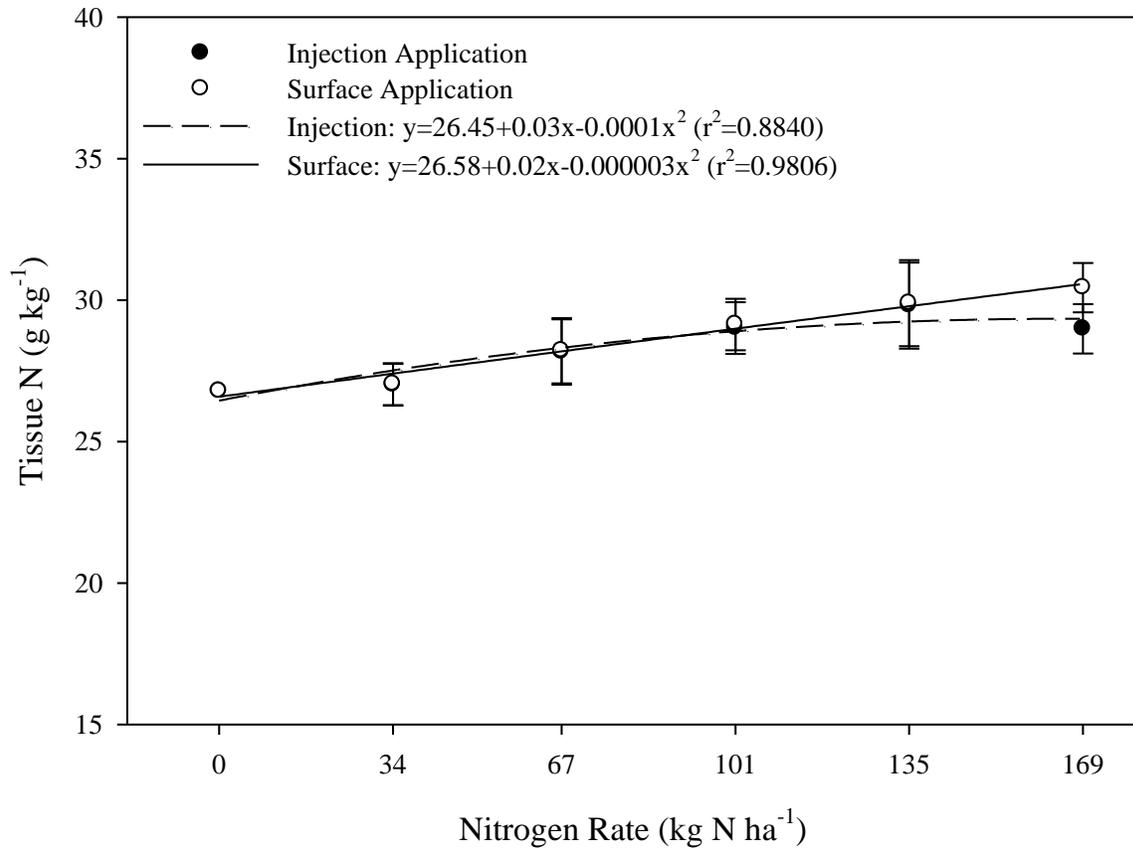


Figure 4-12. Site VD10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

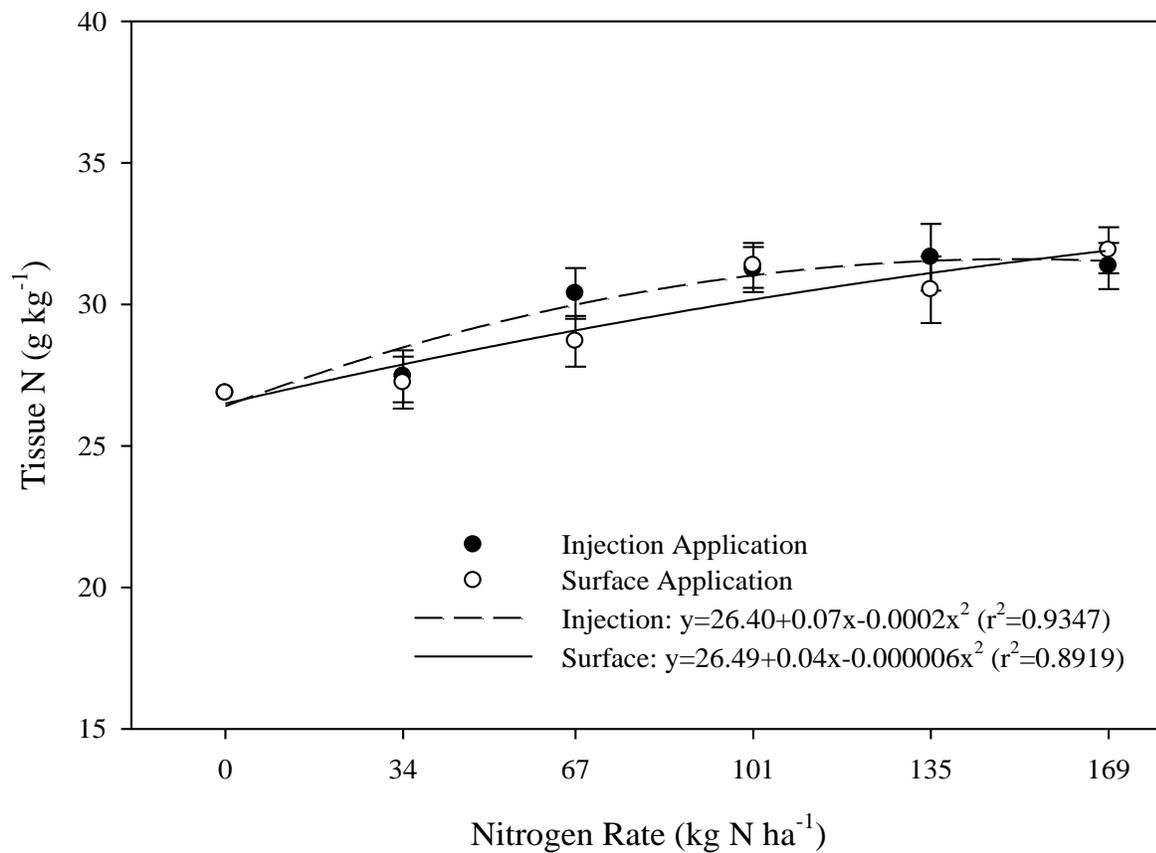


Figure 4-13. Site VI10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

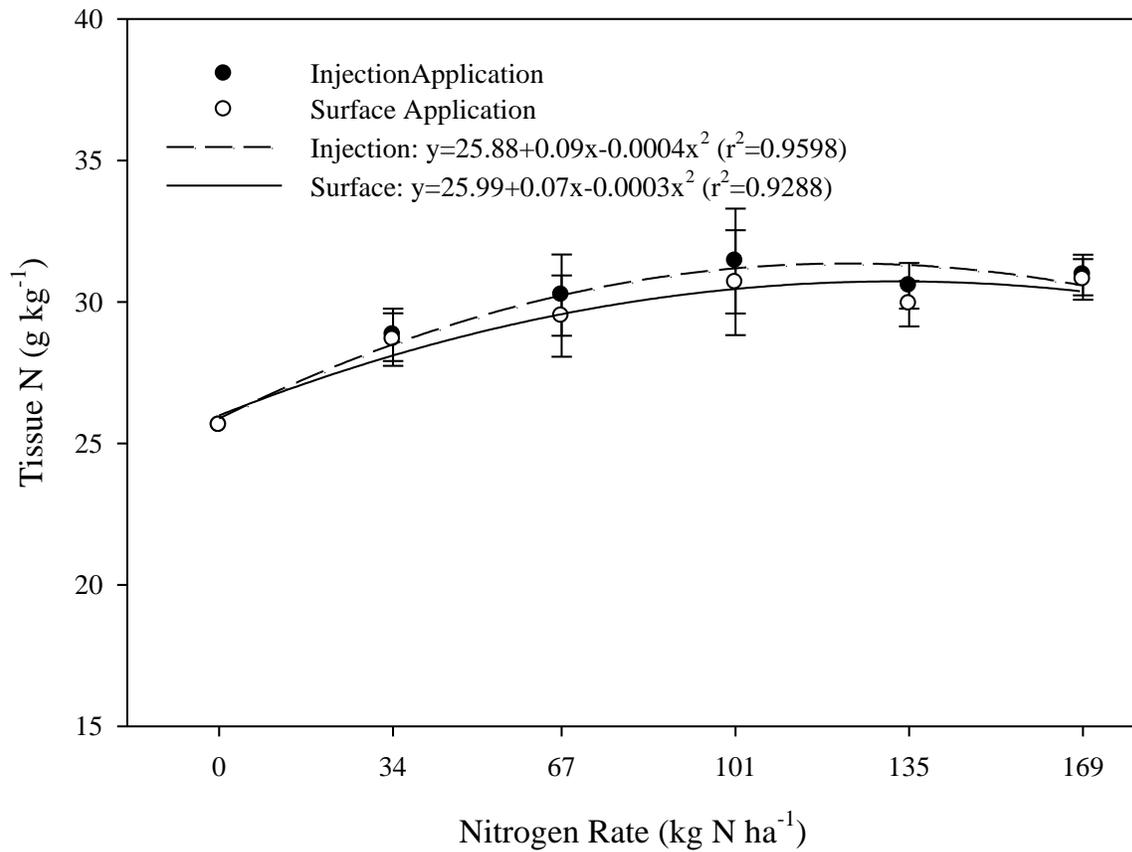


Figure 4-14. Site KBB10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

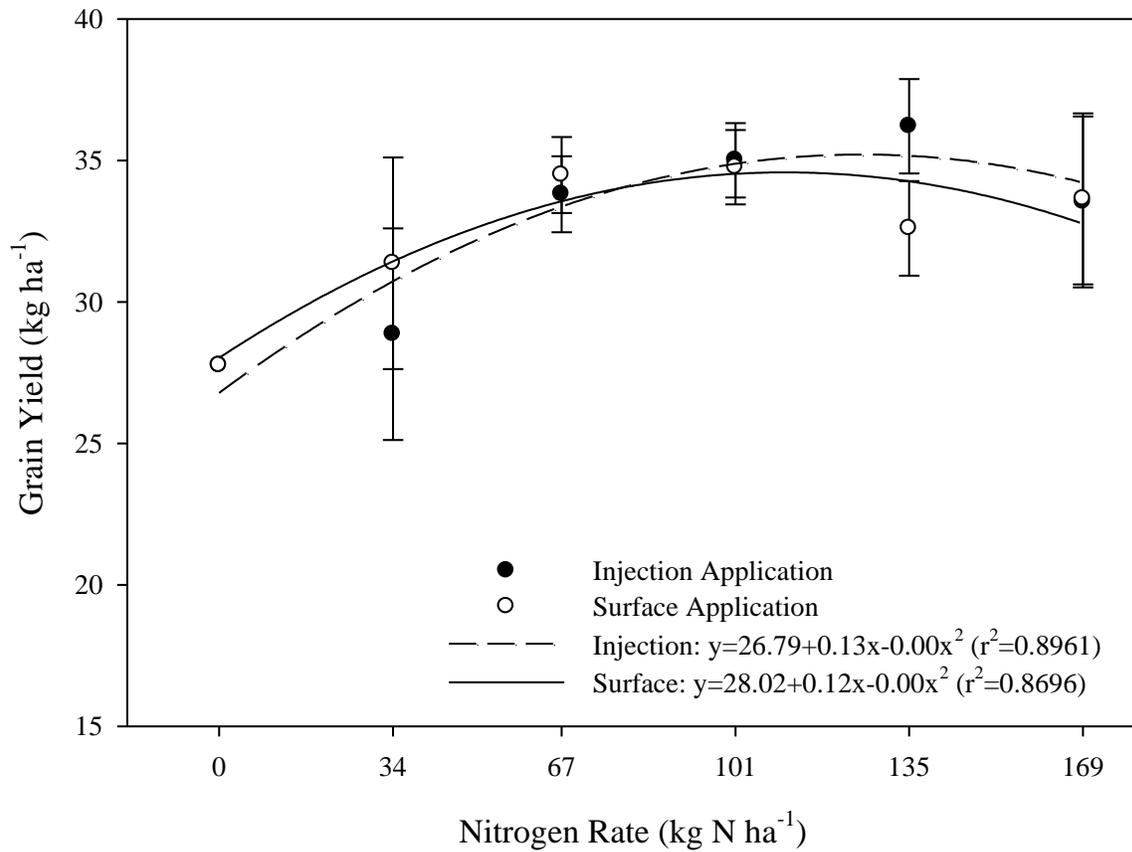


Figure 4-15. Site KMT09 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

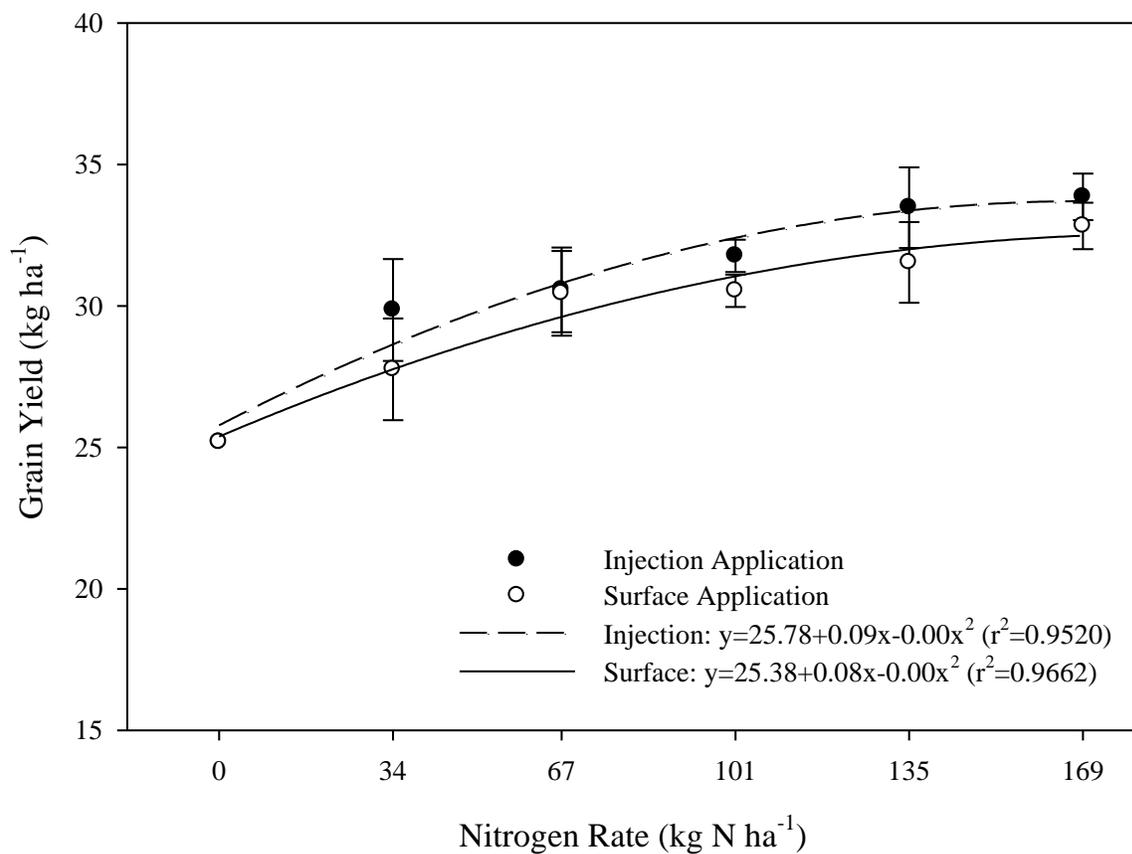


Figure 4-16. Site KAB09 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

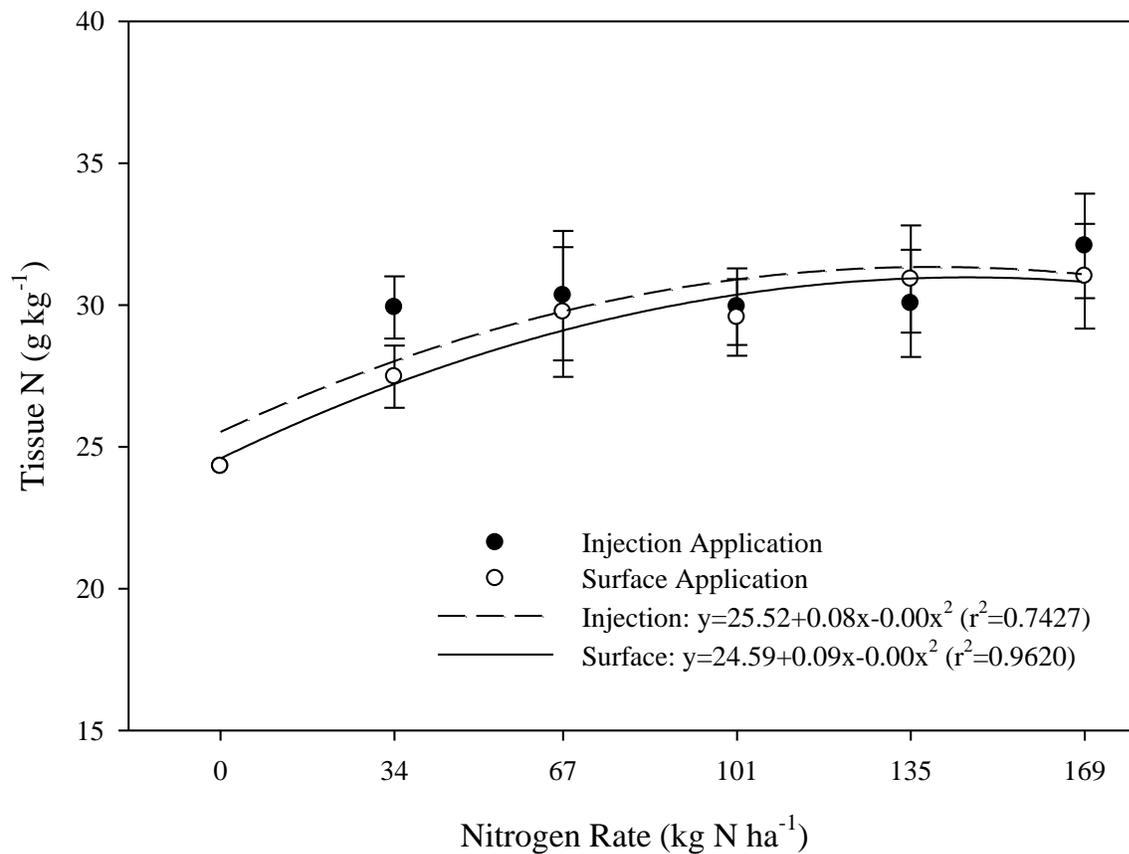


Figure 4-17. Site PD09 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

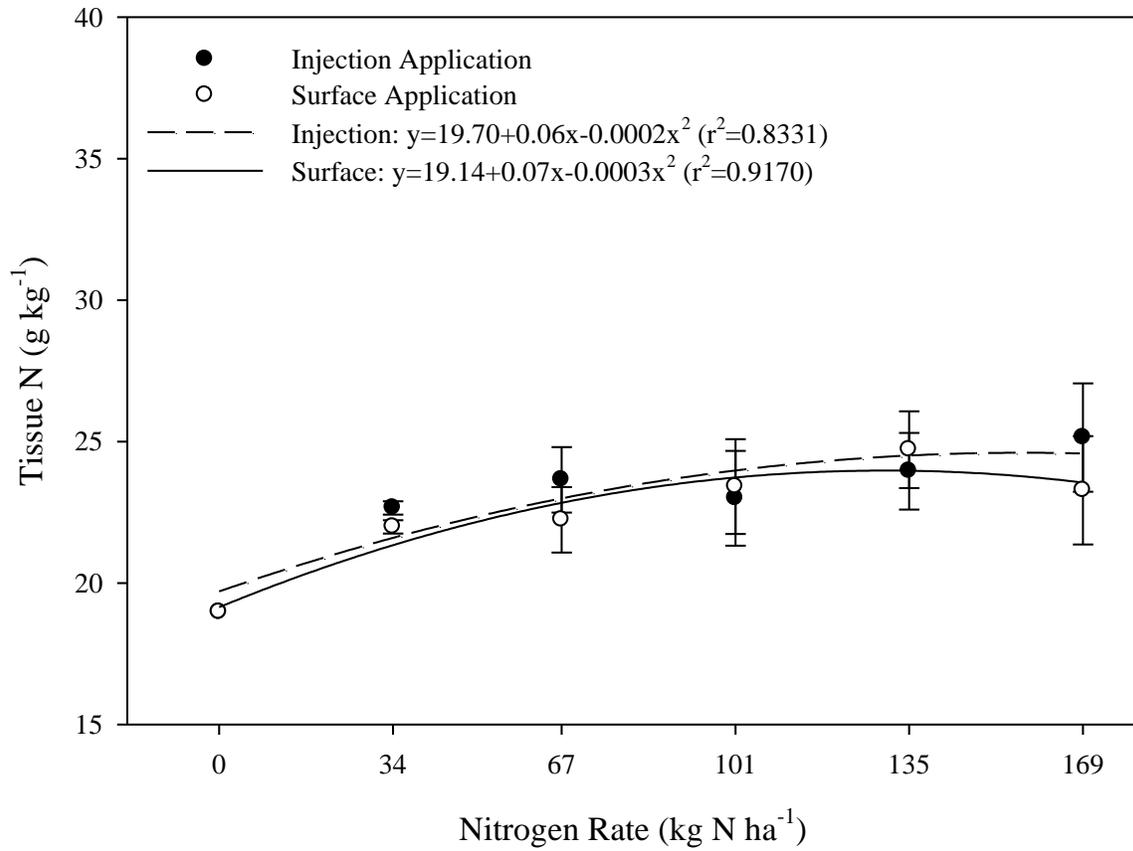


Figure 4-18. Site PD10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

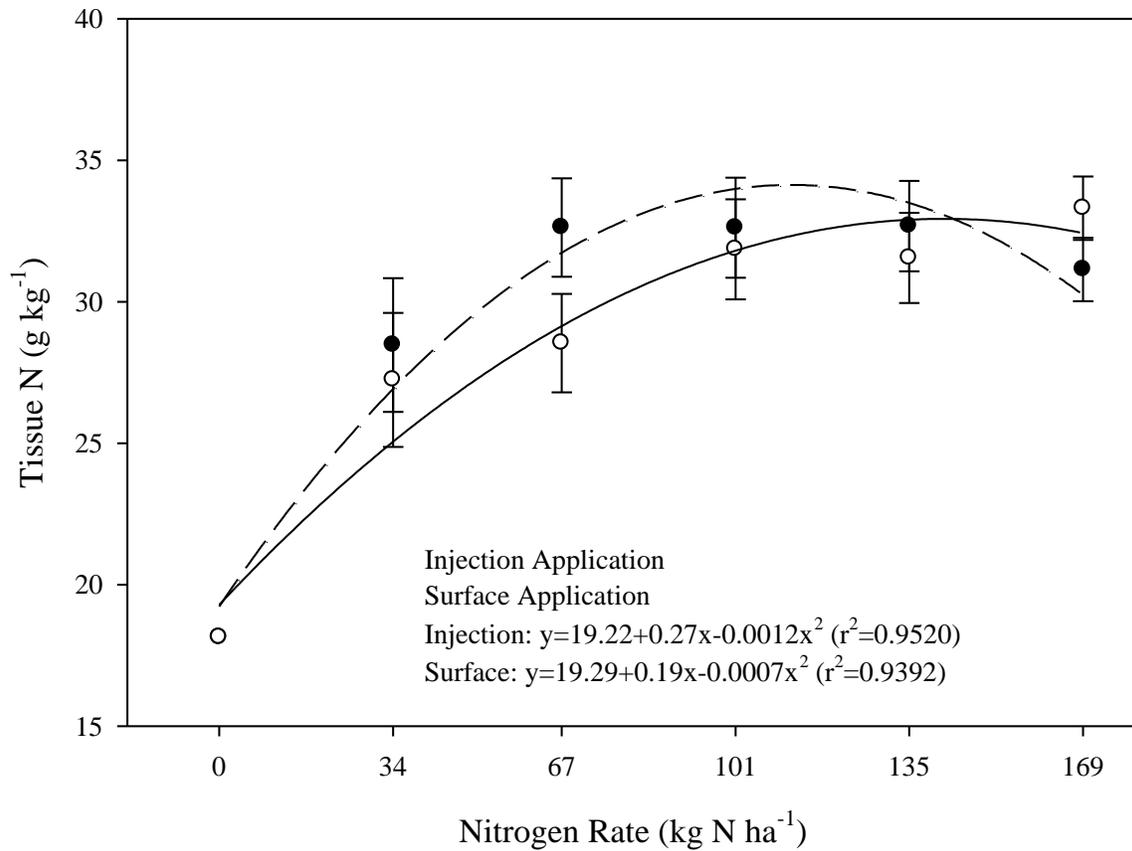


Figure 4-19. Site KAB10 mean ear leaf tissue N content, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.05$).

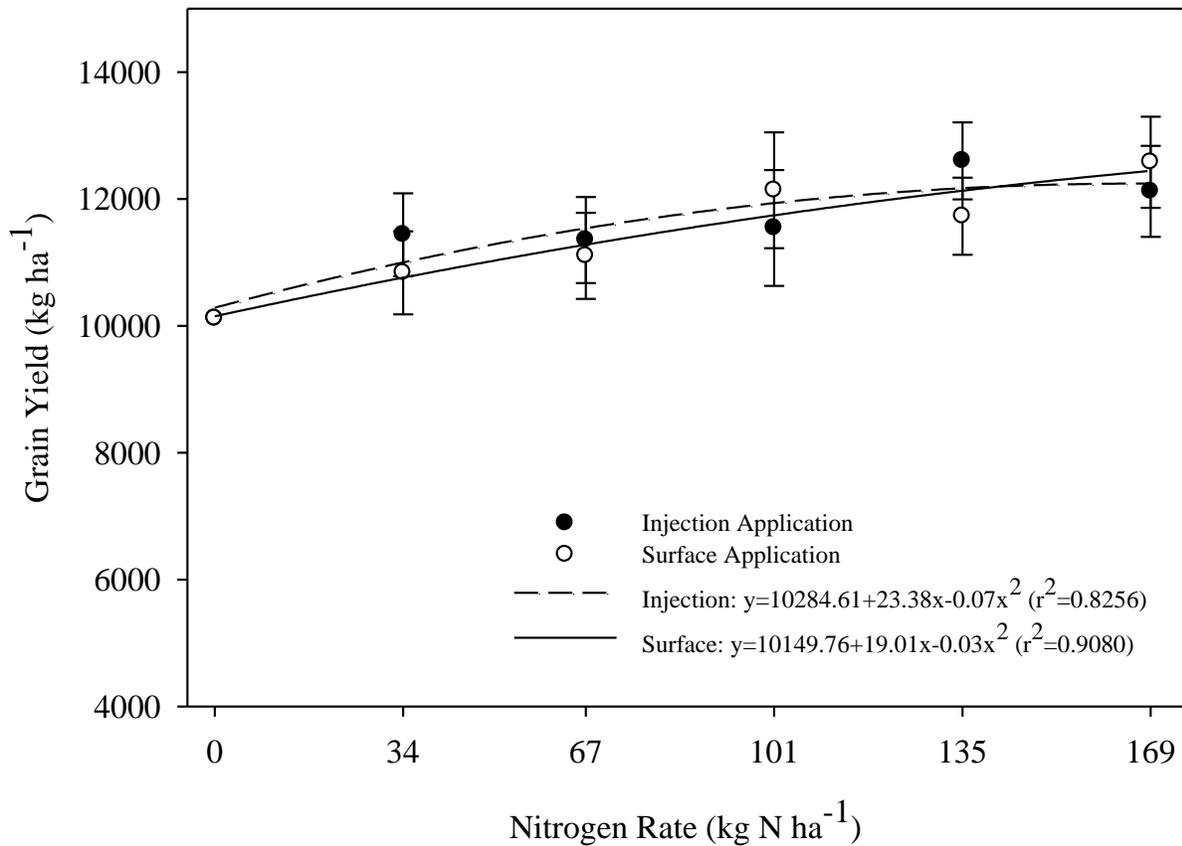


Figure 4-20. Site KCS08 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

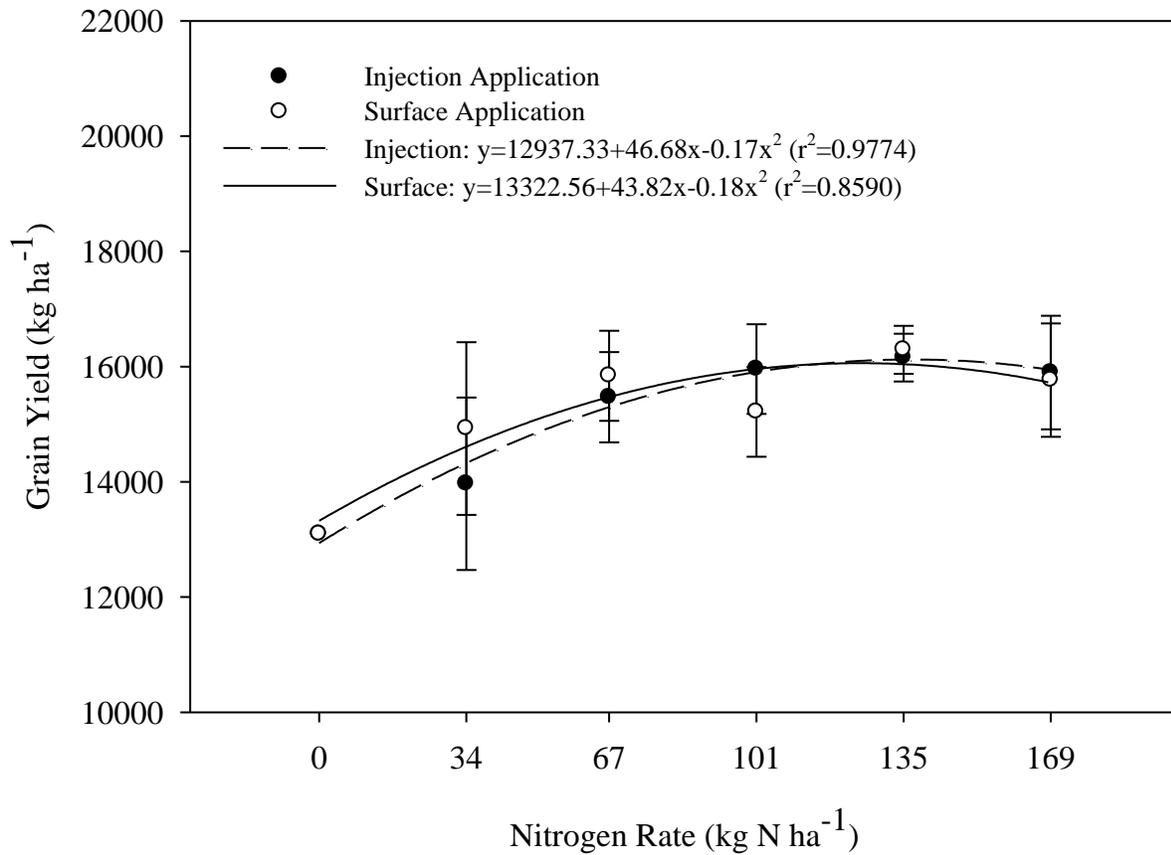


Figure 4-21. Site KMT09 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

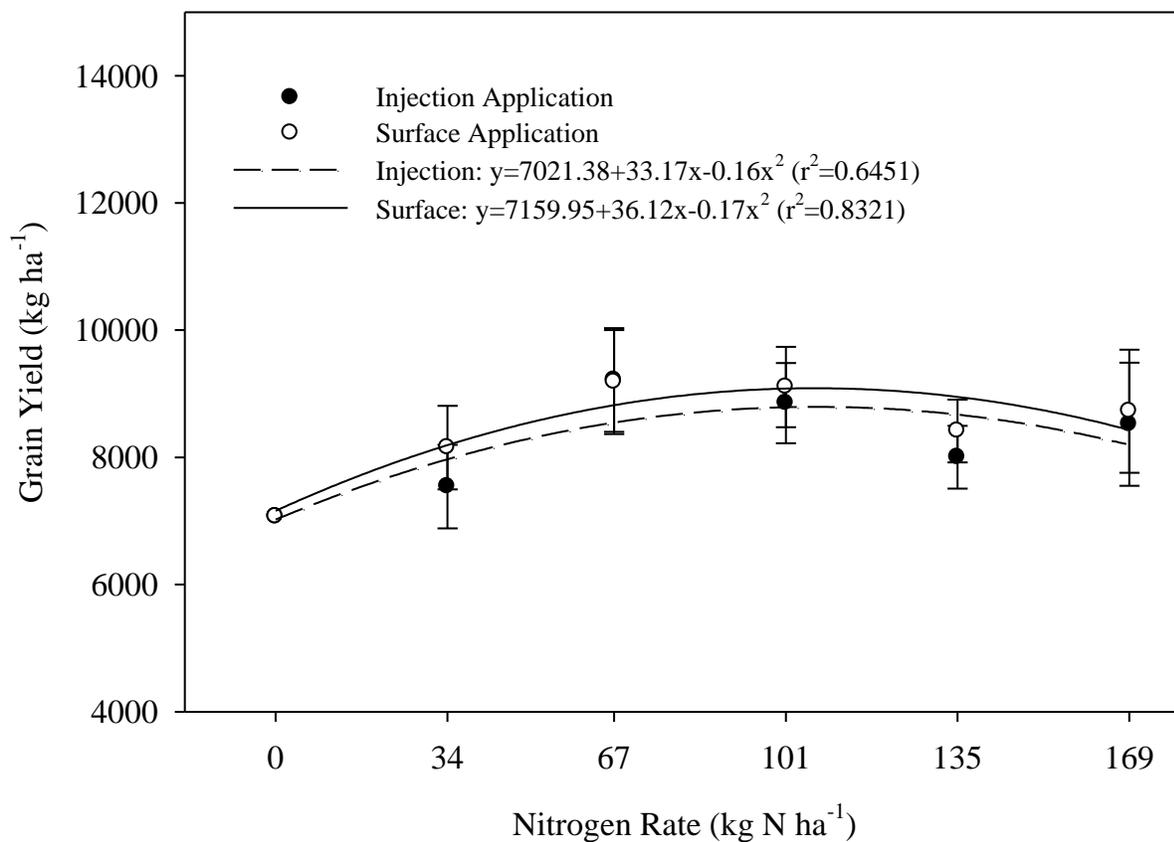


Figure 4-22. Site PD09 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

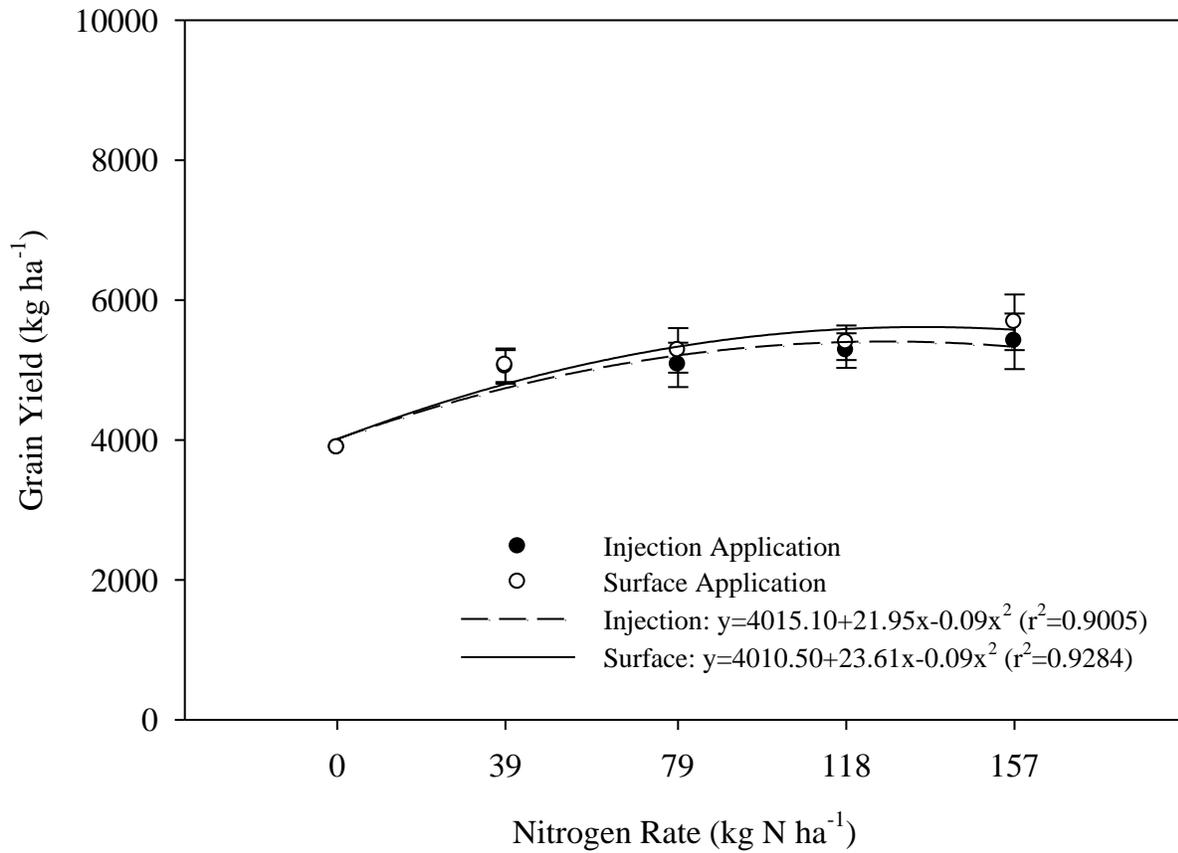


Figure 4-23. Site AE10 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

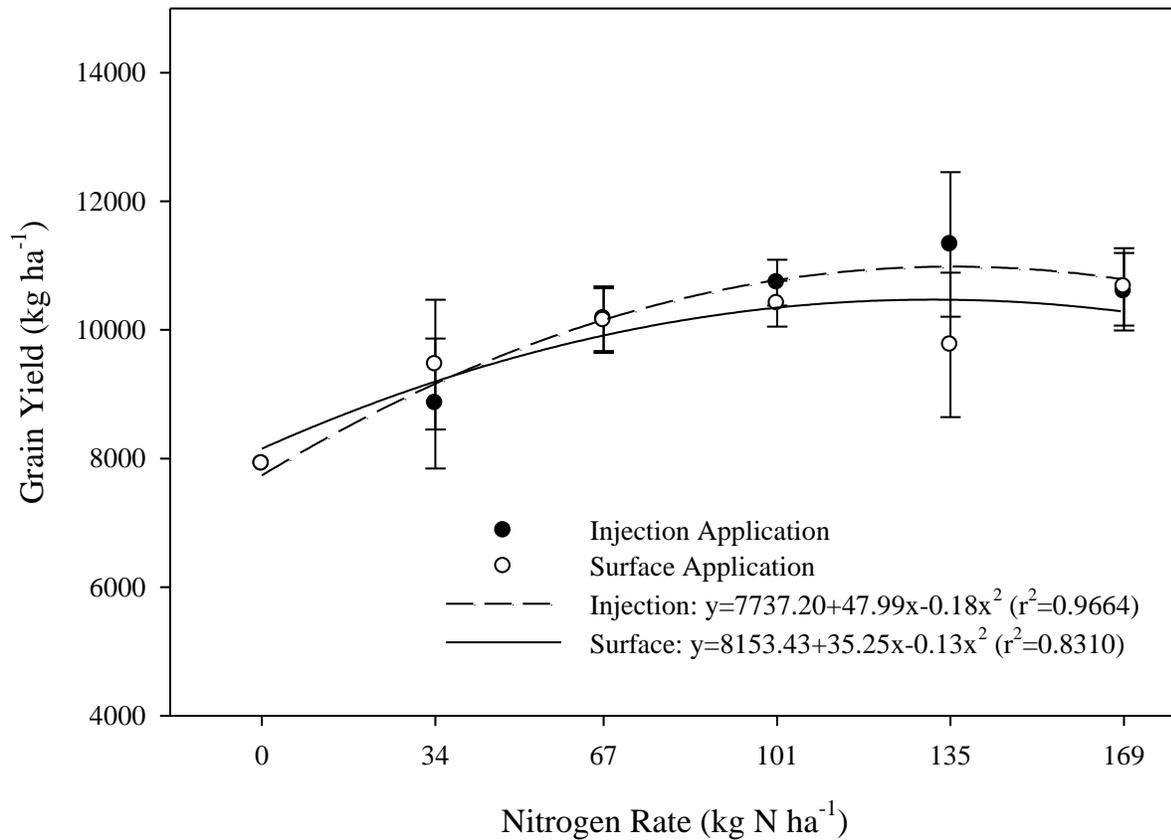


Figure 4-24. Site FM10 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

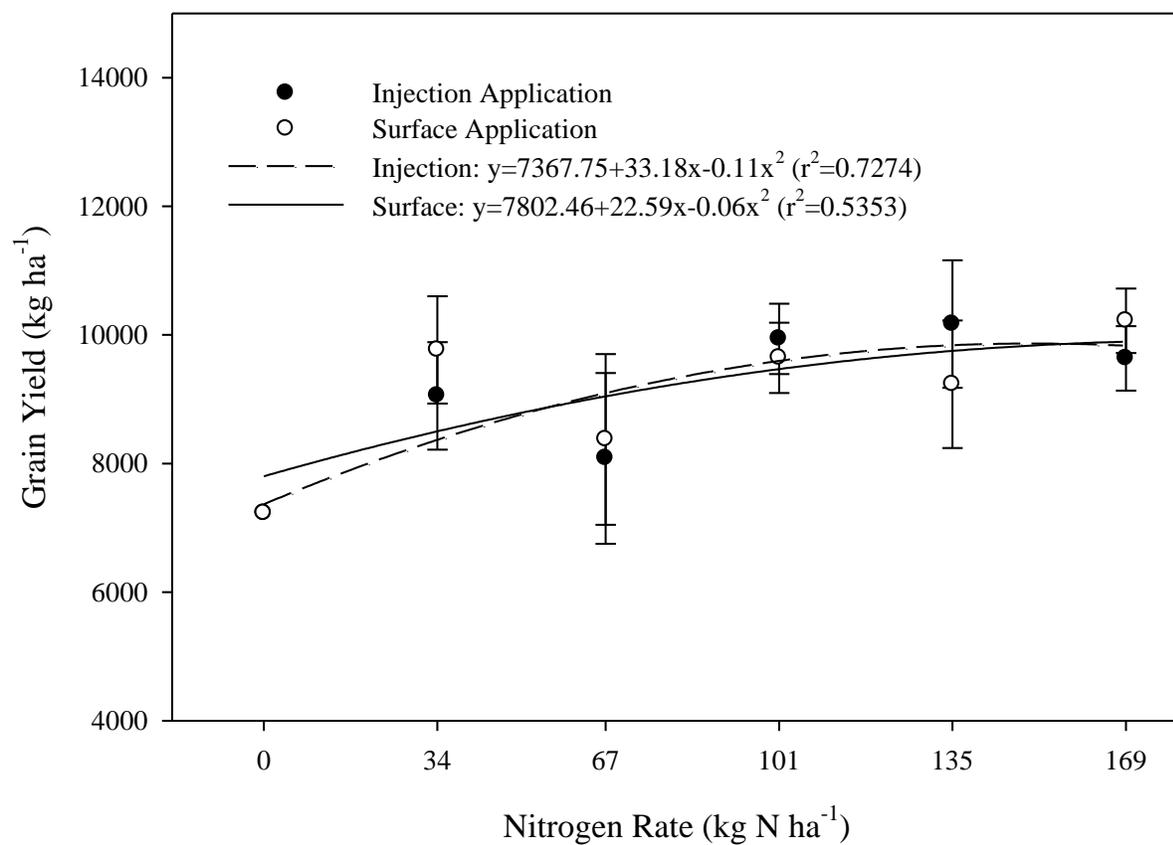


Figure 4-25. Site FSD10 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

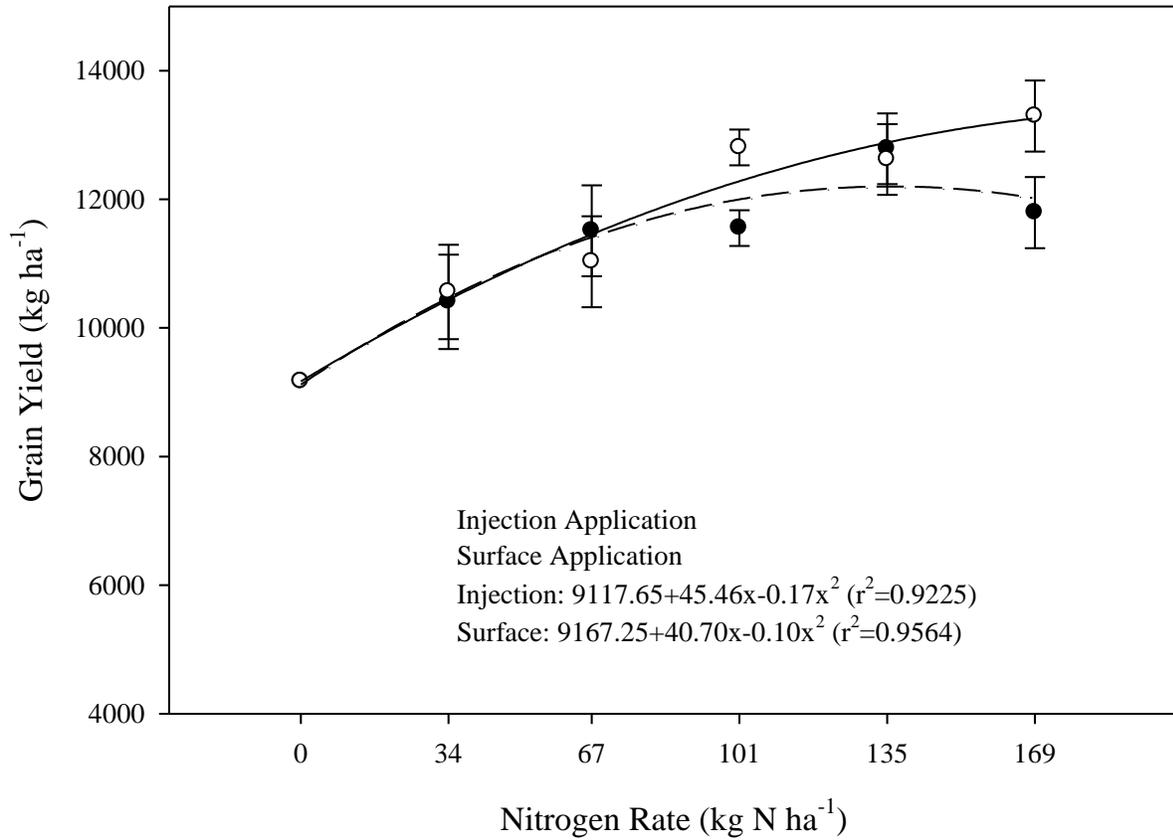


Figure 4-26. Site VI10 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

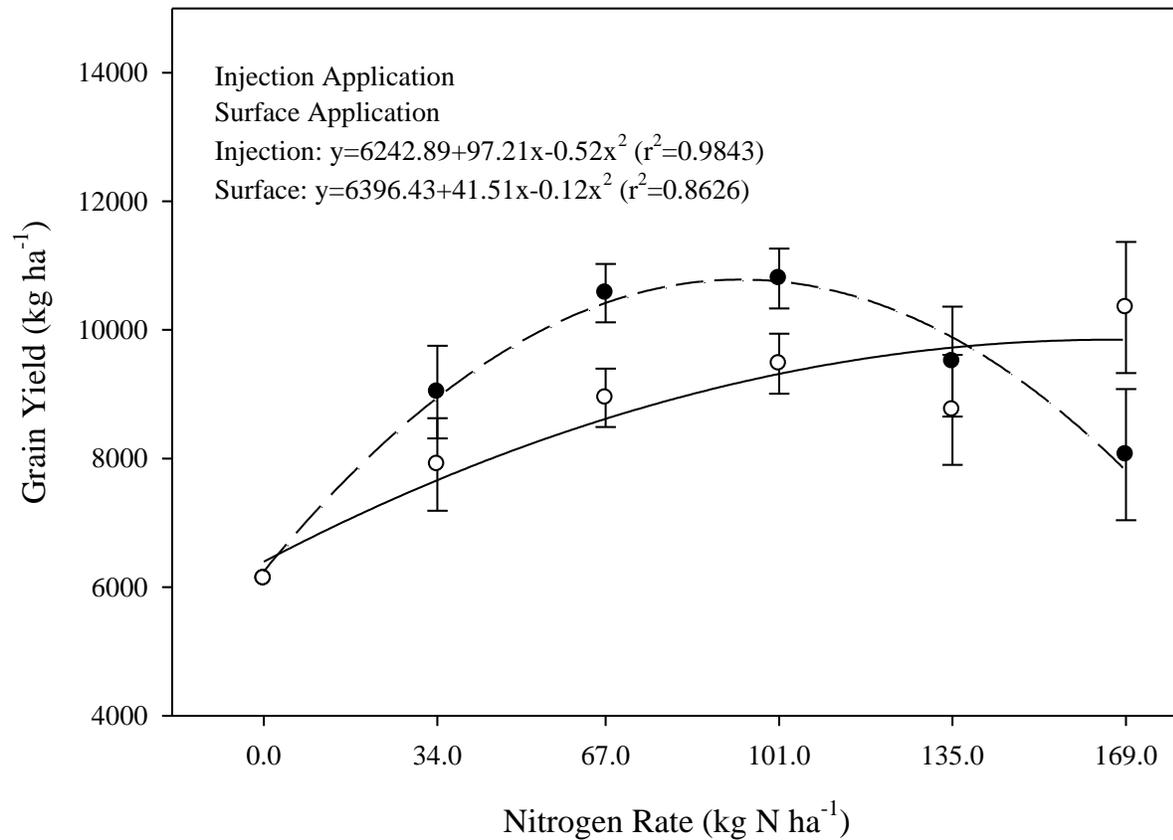


Figure 4-27. Site KAB10 mean grain yield, minimum significant difference represented by error bars, and quadratic regression and associated r^2 values. Overlapping error bars indicate no significant difference ($p=0.10$).

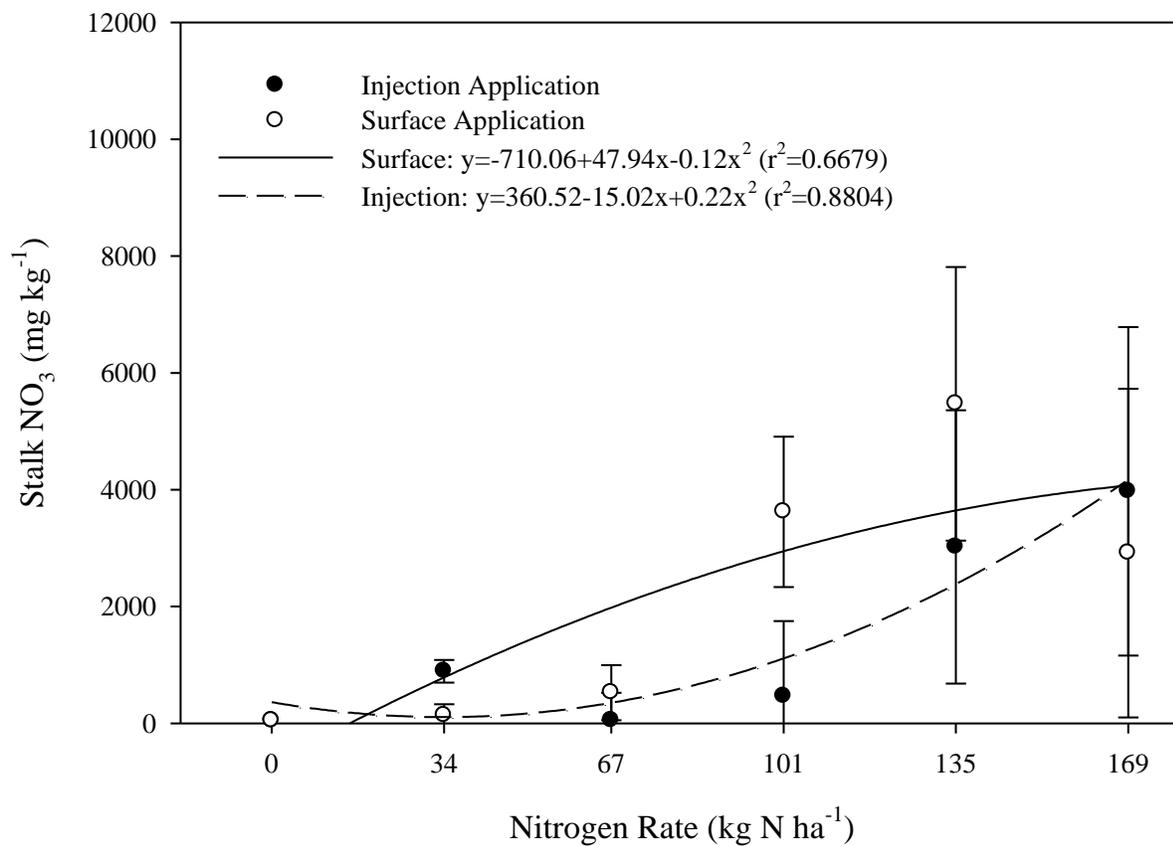


Figure 4-28. Site TAR09 mean stalk NO₃, minimum significant difference represented by error bars, and quadratic regression and associated r² values. Overlapping error bars indicate no significant difference (p=0.05).

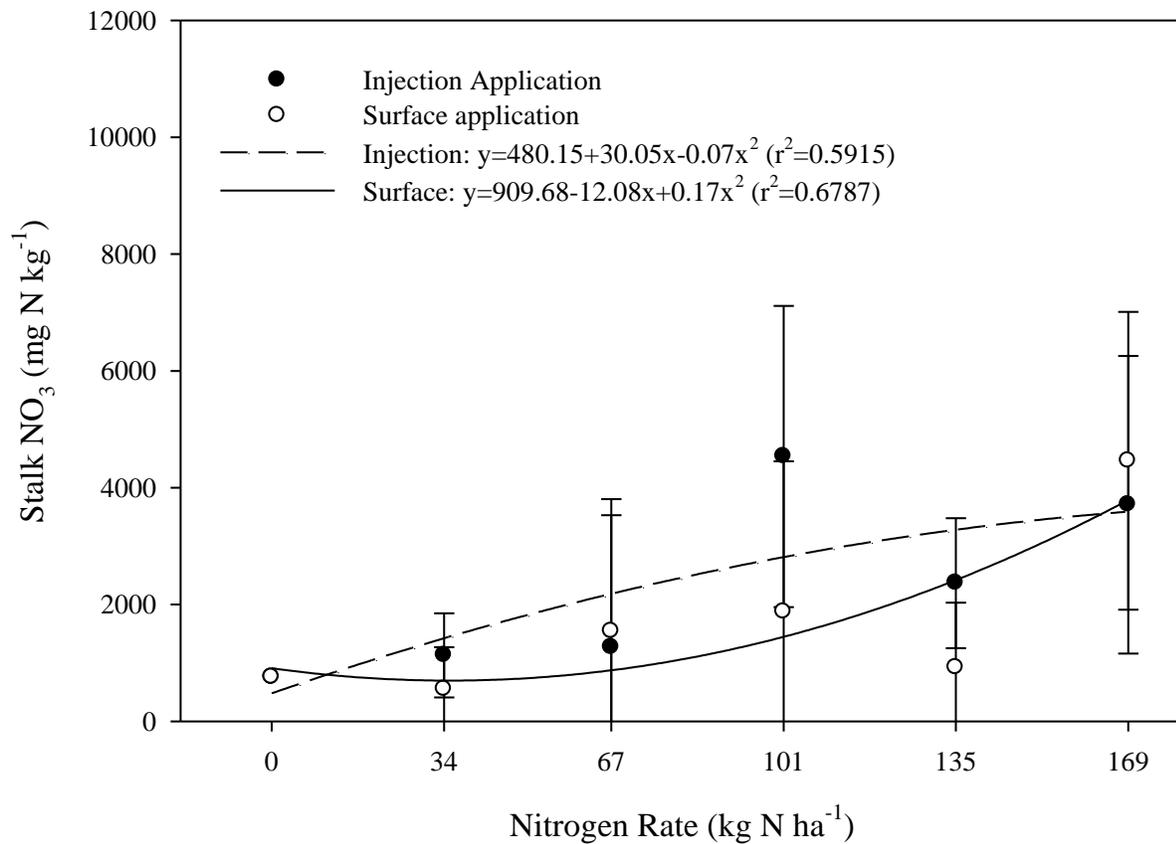


Figure 4-29. Site AE09 mean stalk NO₃, minimum significant difference represented by error bars, and quadratic regression and associated r² values. Overlapping error bars indicate no significant difference (p=0.05).

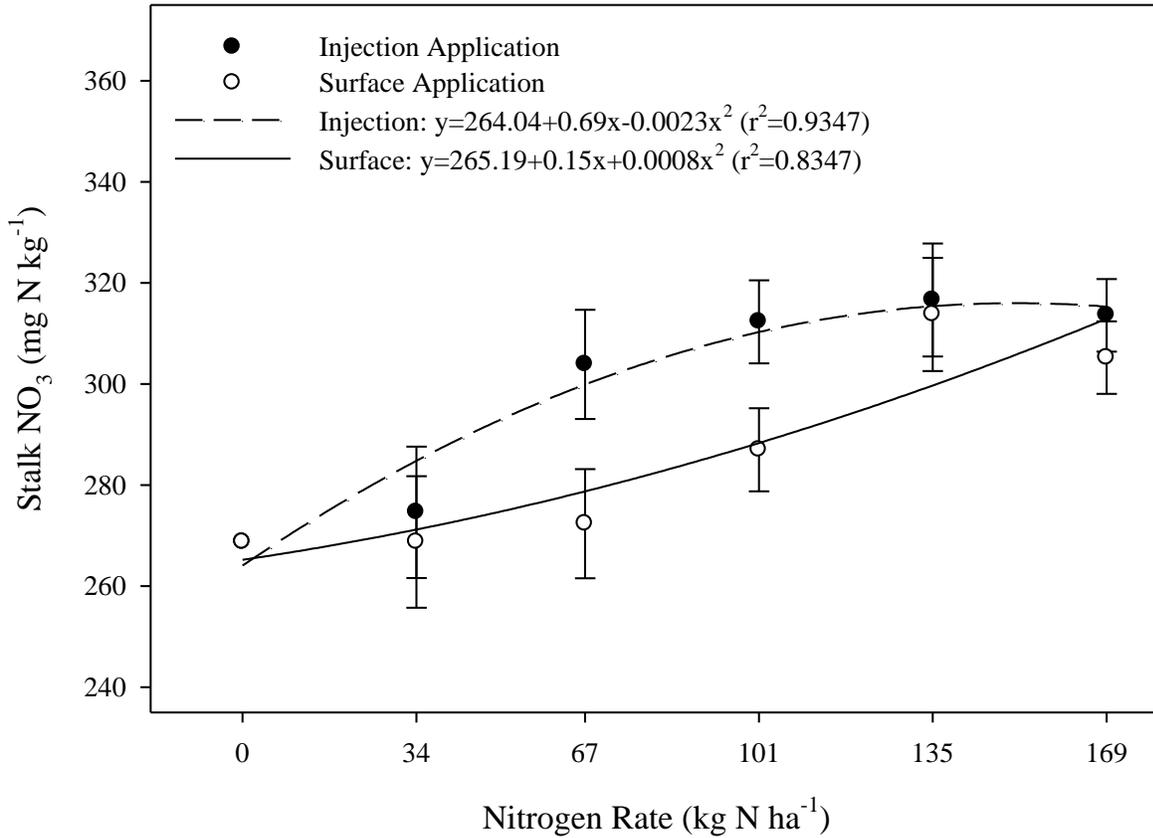


Figure 4-30. Site VI10 mean stalk NO₃, minimum significant difference represented by error bars, and quadratic regression and associated r² values. Overlapping error bars indicate no significant difference (p=0.05).

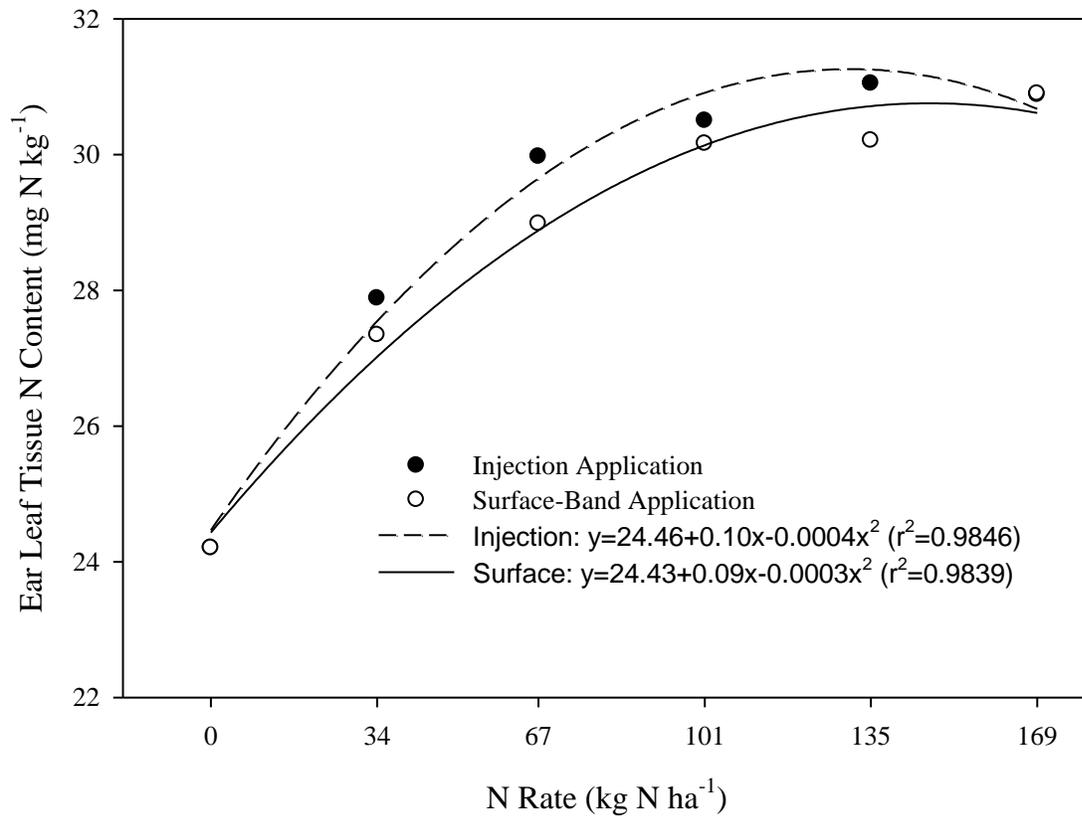


Figure 4-31. Mean ear leaf tissue N content from all sites with an N response. Data has been regressed to determine N rate where maximum tissue N exists.

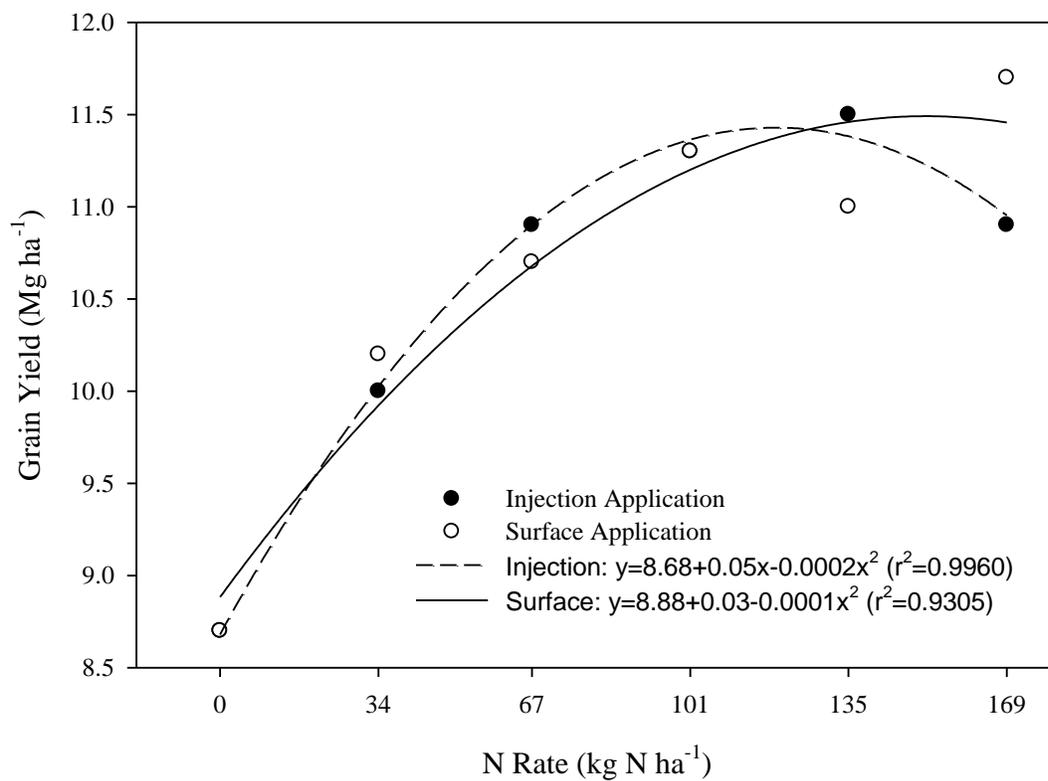
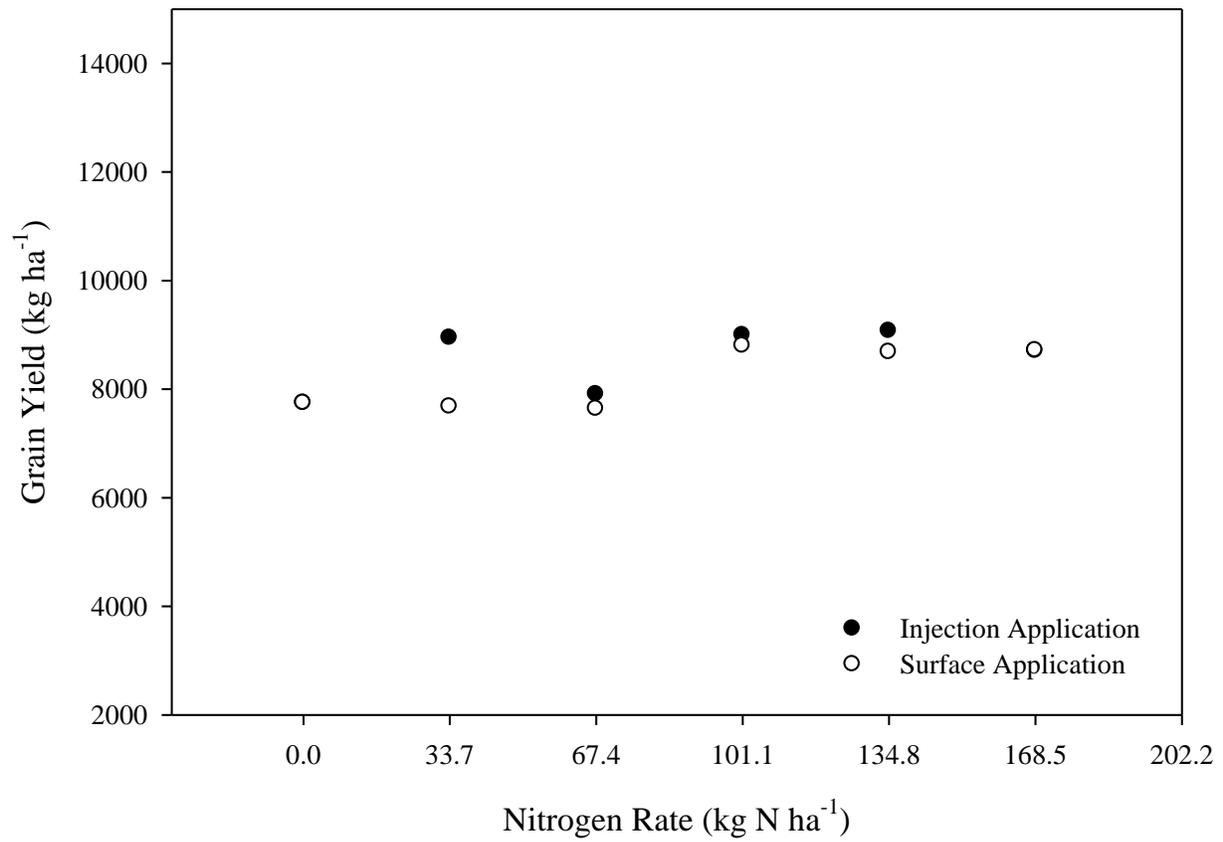
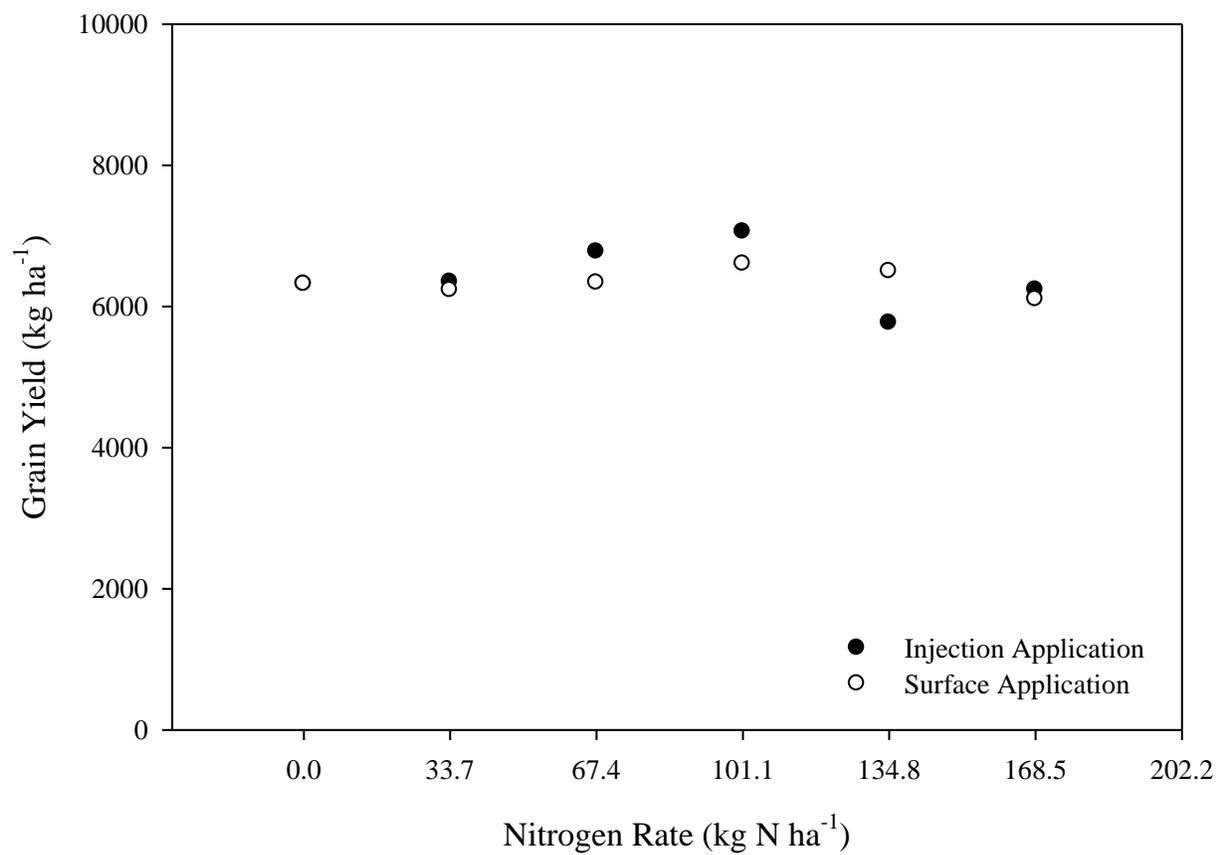


Figure 4-32. Mean grain yield from all N responsive sites. Data has been regressed to determine N rate where maximum grain yield exists.

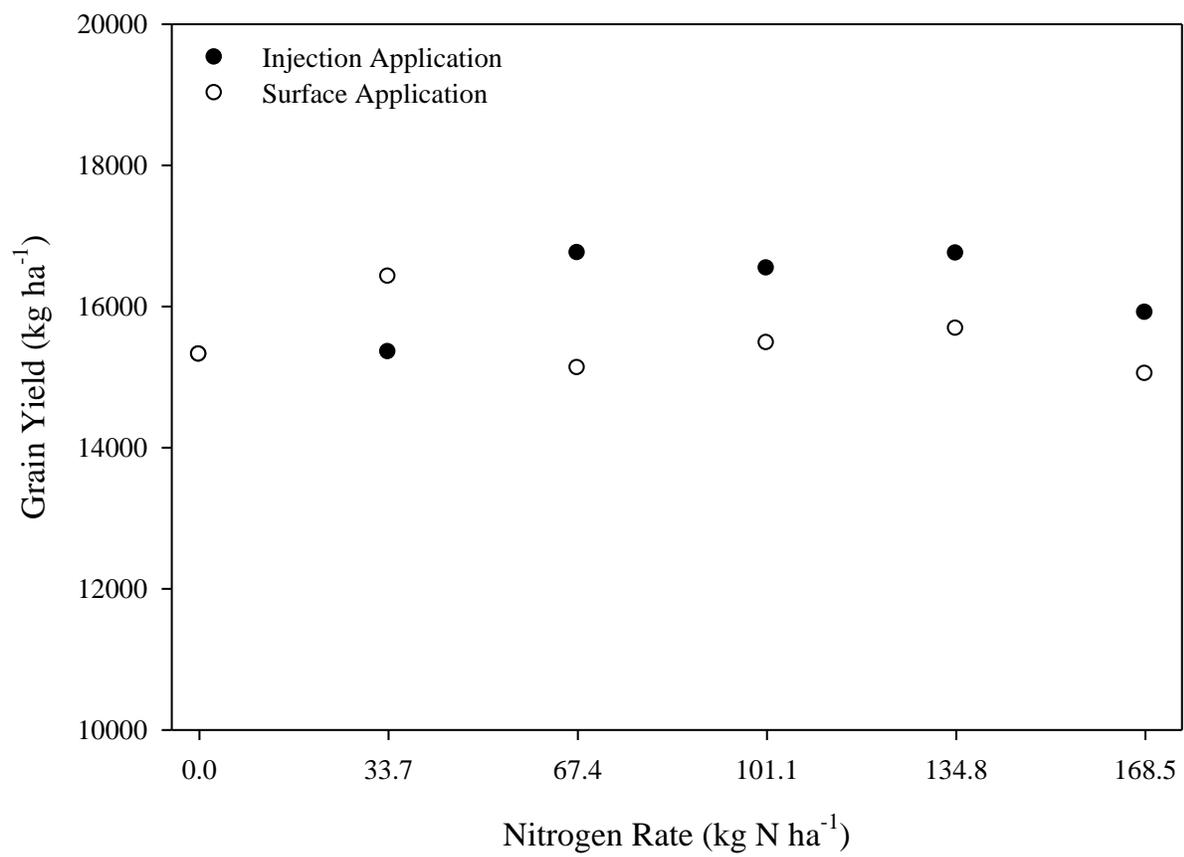
4.10 APPENDIX



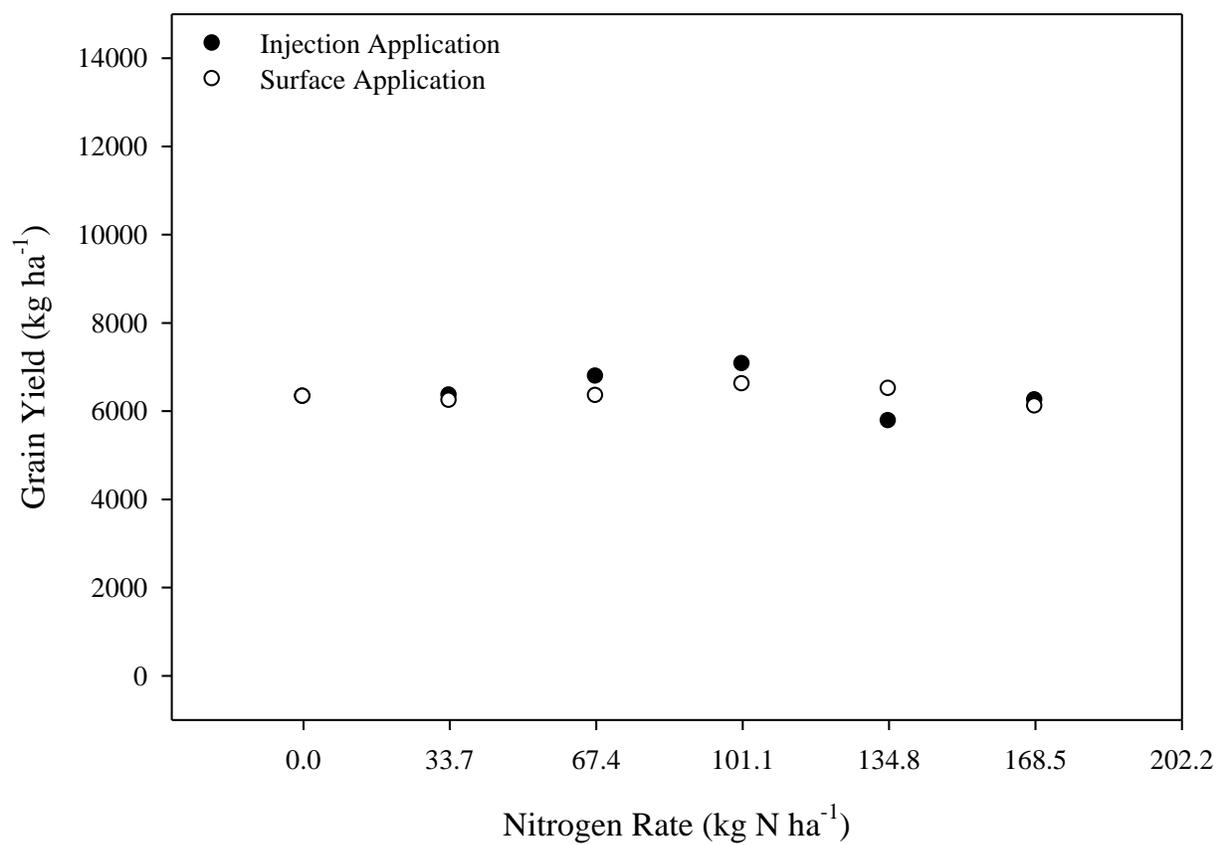
Appendix 4-A. Site KAB09 mean grain yield exhibiting no N rate response.



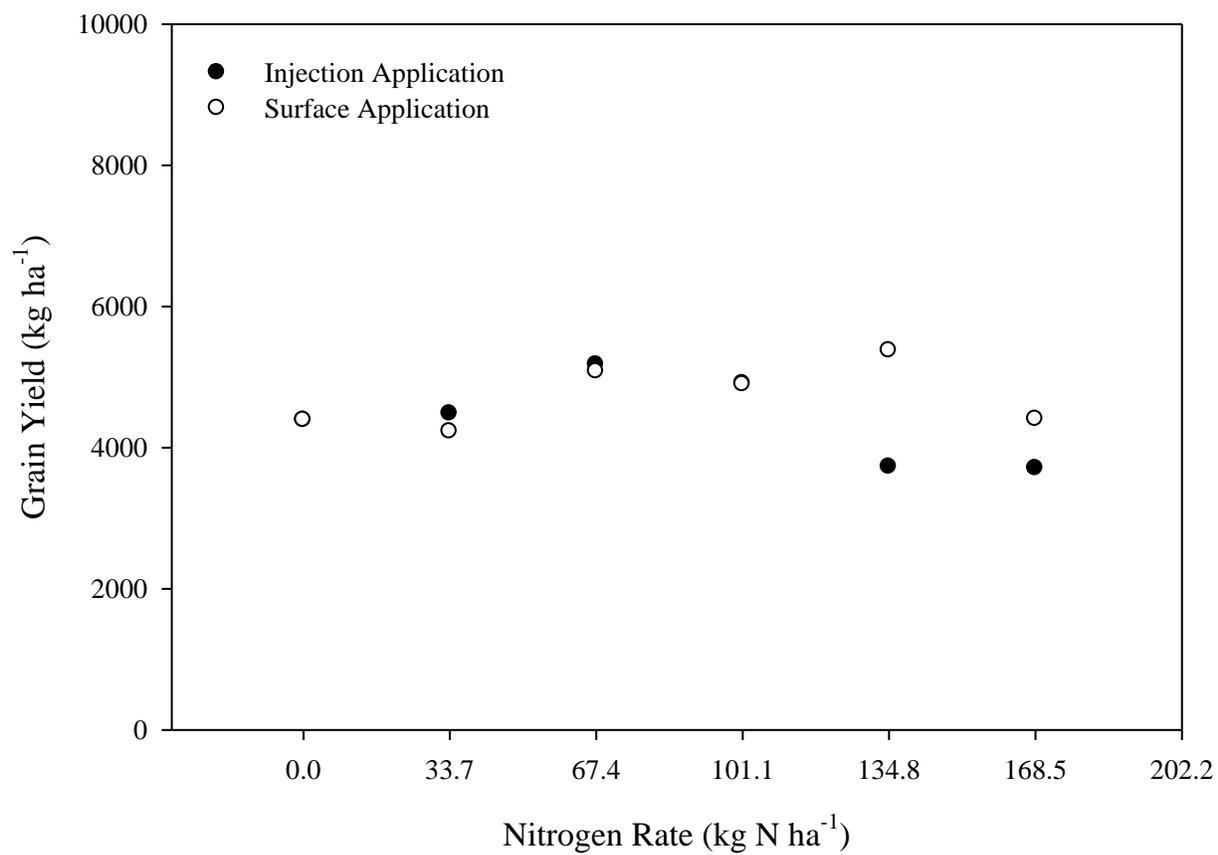
Appendix 4-B. Site TAR09 mean grain yield exhibiting no N rate response.



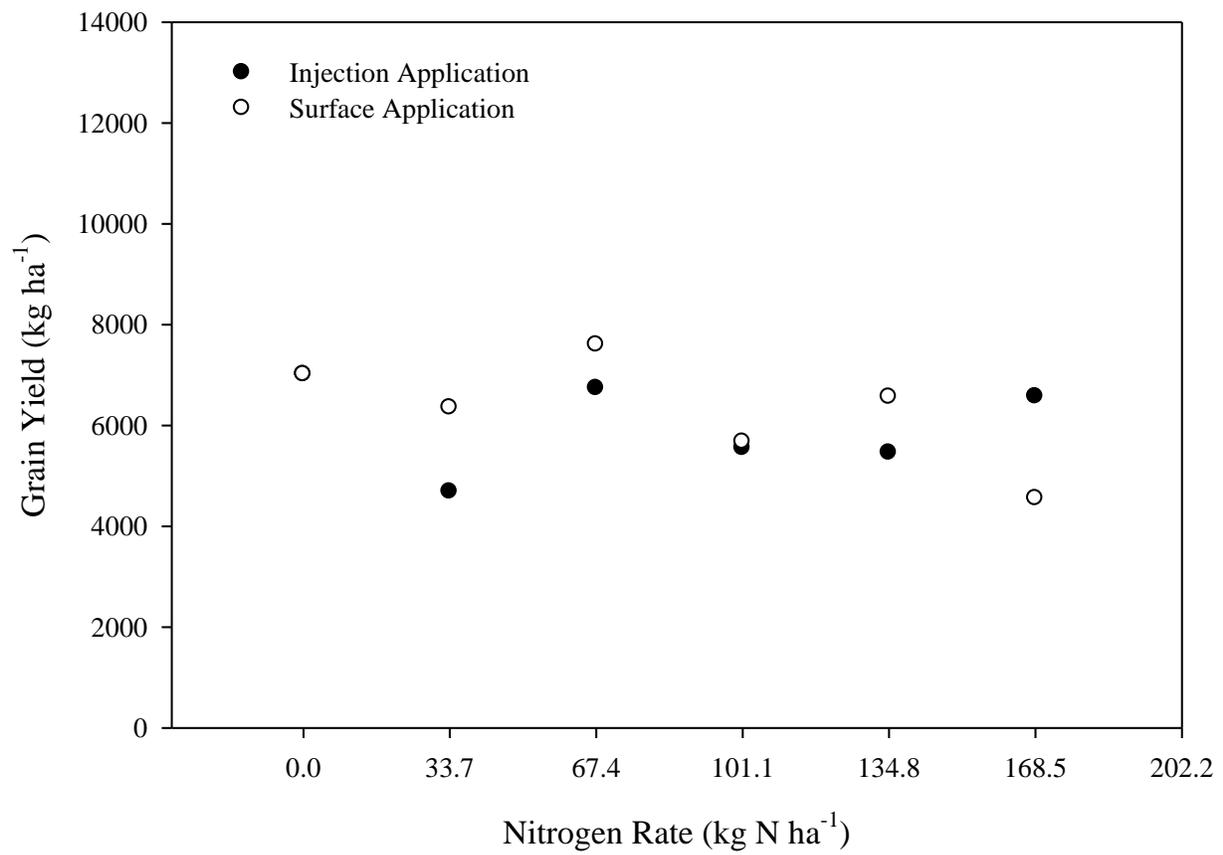
Appendix 4-C. Site AE09 mean grain yield exhibiting no N rate response.



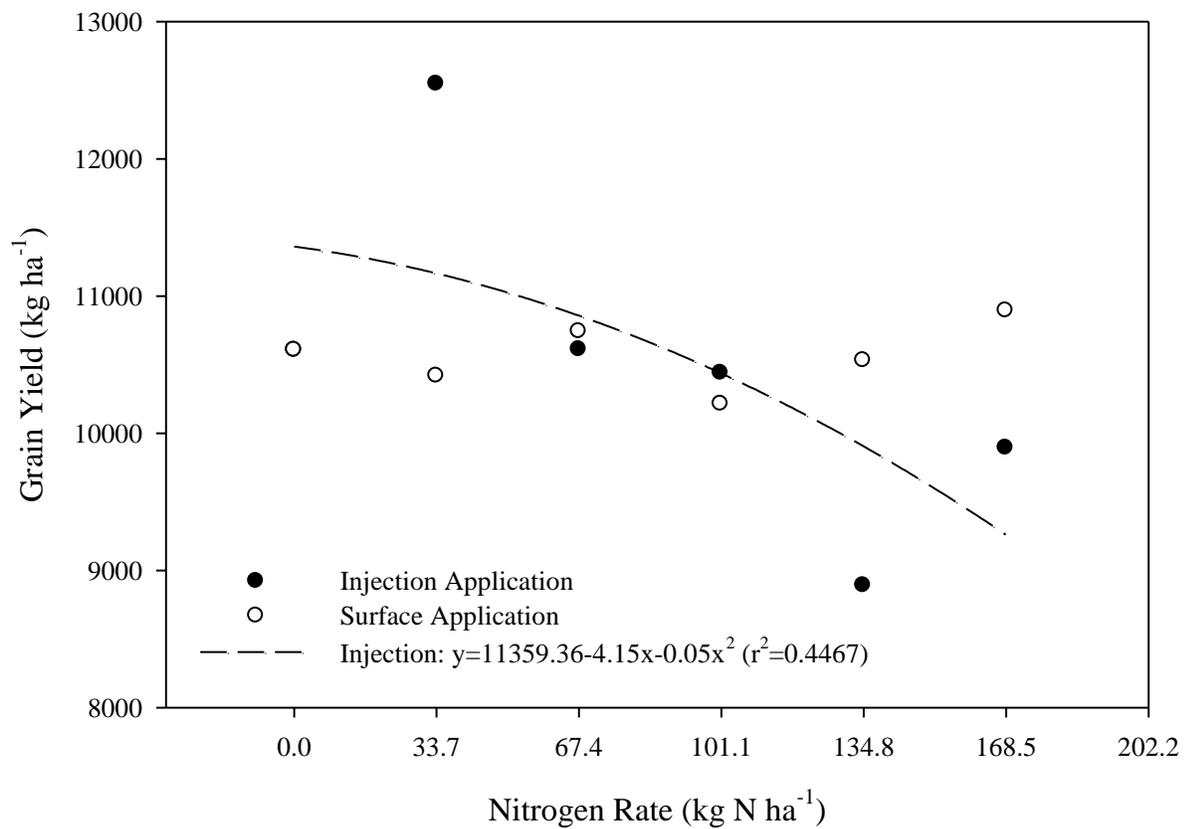
Appendix 4-D. Site VD10 mean grain yield exhibiting no N rate response.



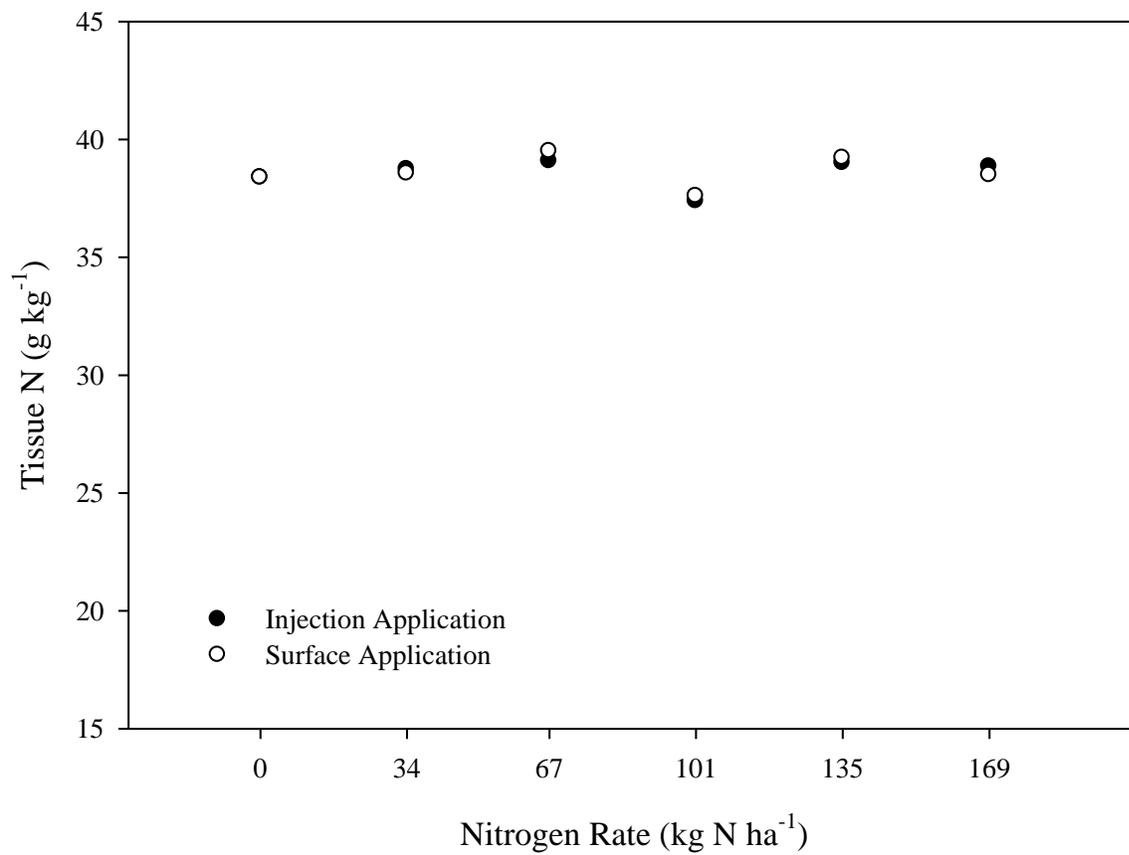
Appendix 4-E. Site PD10 mean grain yield exhibiting no N rate response.



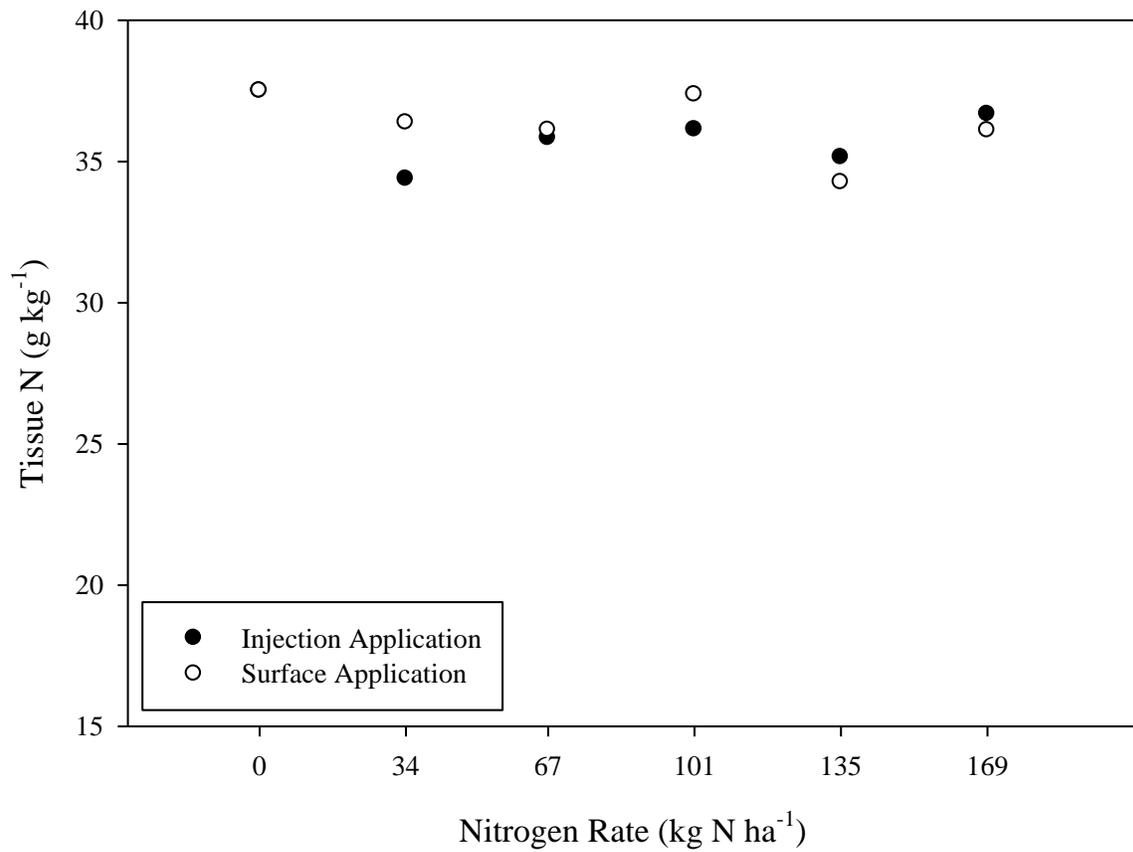
Appendix 4-F. Site KBB10 mean grain yield exhibiting no N rate response.



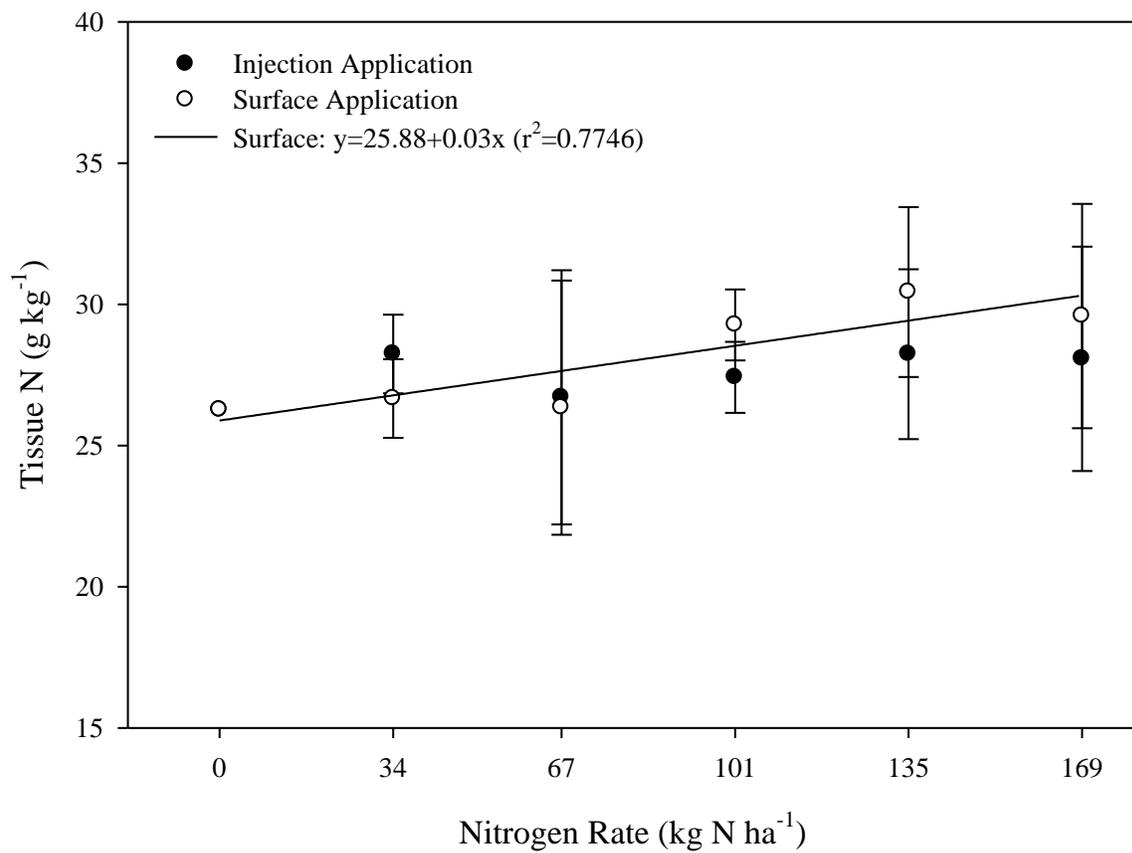
Appendix 4-G. Site KB08 mean grain yield: injection application method exhibited significant response to N rate; however, the relationship is inverse and no comparison between methods can be made.



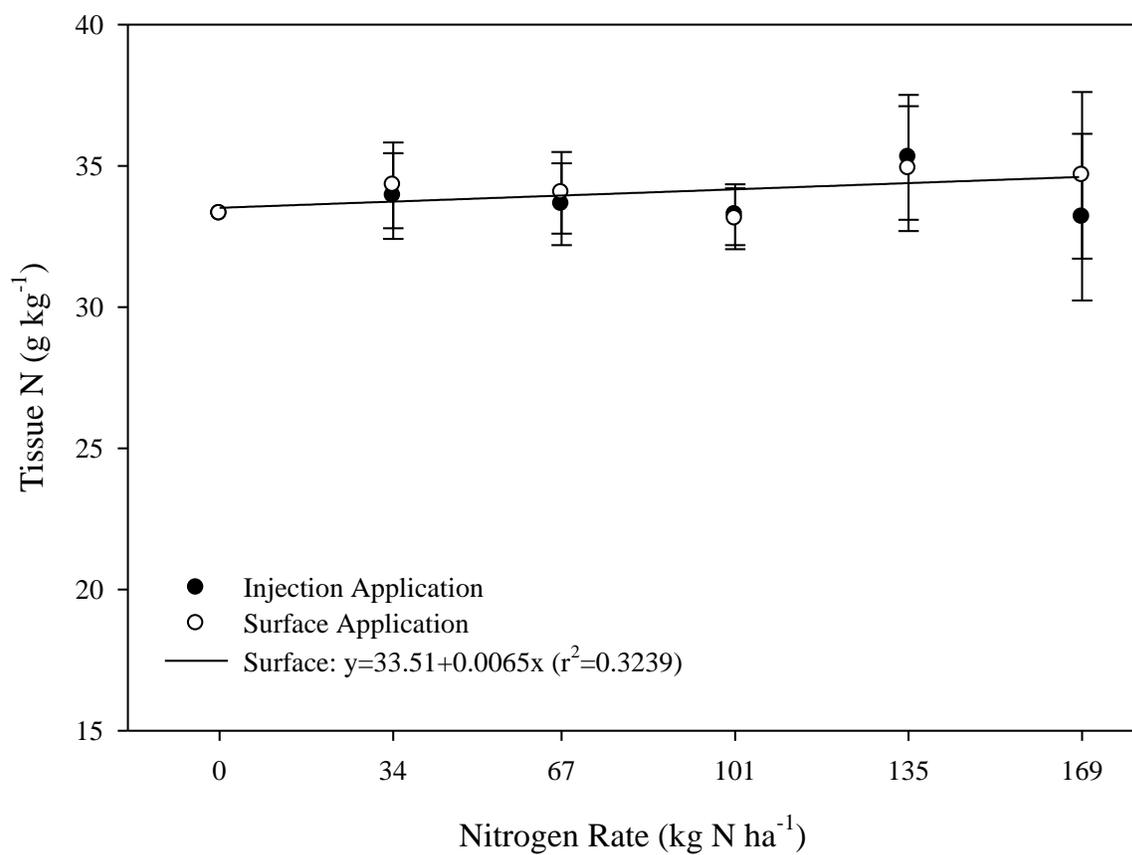
Appendix 4-H. Site KB08 mean ear leaf tissue N content for injection and surface application of UAN



Appendix 4-I. Site KCS08 mean ear leaf tissue N content for injection and surface application of UAN



Appendix 4-J. Site TAR09 mean ear leaf tissue N content for injection and surface application of UAN.



Appendix 4-K. Site AE09: ear leaf tissue N content from surface application of UAN increased significantly to increasing N rate; however, injection application did not increase tissue N content.

5 SUMMARY AND CONCLUSION

Management of N is a major concern for many corn producers because of increasing N fertilizers costs and public pressure associated with N movement into the environment. Ammonia volatilization can be a major source of N-loss from surface-applied urea-containing fertilizers in many production systems. However, no-tillage crop production may exaggerate $\text{NH}_3\text{-N}$ losses because of the plant residue left on the surface of the soil. Plant residues can increase NH_3 volatilization in a number of ways: (1) higher urease activity compared to the mineral soil; (2) increased surface area for urease activity to occur; (3) promotion of slow drying periods; and (4) formation of a physical barrier between the N source and the soil (Al-kanani and Mackenzie, 1992; Dick, 1984; and Hargrove, 1988).

Placing the fertilizer below the residue into the mineral soil eliminates NH_3 volatilization from the residue and may increase the potential for NH_4^+ adsorption due to increased CEC of the mineral soil. Injection of UAN solution has been proposed as an application method that places the fertilizer below the plant residue, which should reduce potential $\text{NH}_3\text{-N}$ losses compared to surface-applied UAN. Urea ammonium-nitrate injection application may be best utilized during sidedress application to corn. In the Mid-Atlantic region, UAN is commonly applied in a band between rows onto the soil or residue surface. This method of application has the potential for significant $\text{NH}_3\text{-N}$ losses (Al-kanani and Mackenzie, 1992; Oberle and Bundy, 1987; Keller and Mengel, 1986).

This study sought to evaluate the injection and surface-banding of UAN in two ways: (1) the measurement of $\text{NH}_3\text{-N}$ losses from surface-applied and injected UAN onto varying soil surface conditions using a laboratory system; and (2) to evaluate the effects of sidedress application of UAN surface-banded and injected at varying N rates on corn grain yield, ear leaf tissue N content, and stalk NO_3 . The laboratory system was designed by Whitehurst Associates Inc. (New Bern, NC) and was shown to provide reliable and rapid results throughout a range of N rates, temperatures, air flow, and trapping acid volumes.

Injection of UAN was found to essentially eliminate $\text{NH}_3\text{-N}$ losses when applied through all surface residue covers; $\text{NH}_3\text{-N}$ losses were <1% of applied N for injected UAN at both N rates. Ammonia-N losses from surface-applied UAN ranged from 15.3 to 32.4% of applied N. UAN surface-applied to corn residue at an N rate of 125 kg N ha^{-1} produced $\text{NH}_3\text{-N}$ losses nearly

twice as high as UAN surface-applied to wheat straw and bare soil at the same rate. This may be due to heightened microbial activity and a priming effect resulting from the addition of N, which could have encouraged the release of NH_3 during decomposition and mineralization processes (Westerman and Kurtz, 1973).

Overall, injection of UAN greatly reduced NH_3 -N losses, and the presence of plant residues on the soil surface seemed to increase NH_3 -N losses when UAN was surface-applied. However, it must be noted that conditions during the trials were optimal for NH_3 volatilization and remained so for 3 wk. Realistically, a rainfall event is likely to occur that leaches the fertilizer through the residue into the mineral soil within 3 wk of application in the Mid-Atlantic region. Based on the results, NH_3 -N losses from surface-applied UAN would be greatly reduced if an adequate rainfall event occurred within 2 days after application. This may explain the inconsistencies in results from studies observing the effects of injection and surface-application of UAN on corn growth responses and N uptake (Bandel et al., 1984; Eckert, 1987; and Touchton and Hargrove, 1982).

There are numerous explanations for the lack of differences between injection and surface-application of UAN throughout many field studies. Fox et al. (1986) proposed there was no or very little NH_3 volatilization loss from the surface-applied UAN, or the injection method failed to prevent NH_3 -N losses or caused a comparable loss by some other pathway. Based on the results from the laboratory study, we can say that the lack of difference is probably due to negligible NH_3 -N losses from surface-applied UAN in many field studies. However, many of the studies evaluating the injection and surface-banding of UAN took place in conventionally-tilled systems where NH_3 -N losses are typically less than when UAN is applied onto plant residues (Al-kanani and Mackenzie, 1992). This warranted the re-consideration and evaluation of the injection method for UAN in no-tillage systems under field settings.

Fifteen sites were established between 2008 and 2010 in Virginia to evaluate the effects of injection and surface-banding of UAN on grain yield, ear leaf tissue N content, and stalk NO_3 . A portion of the sites were found to be unresponsive to N primarily due to lack of moisture and subsequent drought stress. Injection of UAN was found to produce higher grain yield, ear leaf tissue N content, and stalk NO_3 at a number of sites and N rates; however, results were very inconsistent. The reasoning for this may be best explained by the theory proposed by Fox et al. (1986) in the previous paragraph. Most differences were observed in ear leaf tissue N content,

which may be due to the prolonged influence of climatic conditions on grain yield and stalk NO_3 concentrations. Plant stresses during the growing season could mask the differences, and therefore, would not be detected in post-mortem plant measurements.

When evaluating the optimal N rate where ear leaf tissue N content or grain yield reached a maximum for both application methods, injection of UAN was found to reduce the amount of N needed at most sites. Injection of UAN reduced the N required to reach maximum yield or ear leaf tissue N by 25 kg N ha^{-1} compared to surface-banding when results from all N responsive sites were combined. This suggests that the benefits of injecting UAN are readily obtained from the adoption of this practice on many sites and through multiple years.

The injection of UAN has been proven to reduce $\text{NH}_3\text{-N}$ losses in a controlled environment compared to surface-applications; however, this difference could not be consistently identified under field conditions when grain yield, ear leaf tissue N content, and stalk NO_3 were the dependent variables. In many situations, surface-banding of UAN may be as efficient as the injection method in terms of NH_3 volatilization, but it should be acknowledged that injection of UAN consistently reduces the potential for $\text{NH}_3\text{-N}$ losses under all conditions. Therefore, the injection method may be a viable management strategy.

5.1 REFERENCES

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