# EVALUATION OF MIDSEASON UAN APPLICATION DEPTH IN WINTER WHEAT

By


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Bachelor of Science in Biological Science

Oklahoma Panhandle State University

Goodwell, Oklahoma

2015


Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2016

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# ACKNOWLEDGEMENTS

I would like to thank the Department of Plant and Soil Sciences at Oklahoma State University, the Oklahoma Agricultural Experiment Station and my advisor and committee members, Dr. William Raun, Dr. Hailin Zhang and Dr. Randy Taylor for their support and guidance throughout my time at Oklahoma State University. Additionally, I want to express my sincere thanks to the graduate and undergraduate students I have had the pleasure of working with, including Ethan Driver, Gwen Wehmeyer, Jaghman Dhillon, Bruno Morandin Figueiredo, Patrick Curl, Mariana Ramos Del Corso, Sulochana Dhital, Eva, Nambi, Melissa Golden, Daniel Aliddeki, Nicole Remondet, Fikayo Oyebiyi, Evan Hrbacek, Everett Hrbacek, Tyler Williams and Tyler Lynch. I would also like to thank Roger Edenborough, Dr. Justin Collins, and Dr. Curtis Bench for their guidance, advice and support. I would like to thank Shandy and Charles Brodhead, Natalya Weber, Chanda Reynolds, Jeremy and Ashley Collins, Shaylee Kelso, Scot Schwieterman and Trevor Johnson for being such supportive friends over the years. I would not be where am today without the love and support of my family, specifically my wonderful mother, Amy Bryant, grandparents David and Diane Bryant and brother, Tyler Bryant. Finally, I want to sincerely thank God for blessing me in so many ways, as I continue on the path He has in store for me.

Name: RYAN BRYANT-SCHLOBOHM

Date of Degree: DECEMBER, 2016

Title of Study: EVALUATION OF MIDSEASON UAN APPLICATION DEPTH IN WINTER WHEAT

Major Field: PLANT AND SOIL SCIENCES

Abstract:

Nitrogen Use Efficiency (NUE) is estimated to be only 33% for cereal production in the world. Providing producers with efficient methods to increase the effectiveness of their Nitrogen (N) applications is integral to agricultural sustainability and environmental quality. This study was conducted to evaluate the effect various subsurface placement depths of urea ammonium nitrate (UAN) has on grain yield, plant N uptake and NUE in winter wheat. Liquid UAN was applied in bands at depths of 5 and 10 cm, along with surface applications, all at various N rates at Feekes growth stage 5. Fields under conservation tillage at low N rates benefited from subsurface applications. No-till soils experience a shift in the active microbial zone compared to conventionally tilled fields, resulting in greater rates of N immobilization from N applied in the upper 6-7 cm of the soil profile. Conventional tillage generally benefits from subsurface applications, specifically when weather and environmental conditions are present that promote ammonia volatilization following fertilizer application. Nitrogen rates that provide the greatest economic returns are dependent on the environment, as yearly environmental variability is difficult to predict. Subsurface application depths of 10 cm provided notable increases in NUE compared to surface applications. Treatments at depths of 5 cm provided several instances of increased grain N. With a few instances of exception, UAN subsurface application depths had limited impact on grain yield, and were similar to that of surface applied N. Application depths of 10 cm had the greatest impact on grain yield in no-till cropping systems at low N rates.

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# CHAPTER I

## INTRODUCTION

Projected population growth demands further refinement from all facets of agriculture. Practices that maximize yield, while sustainably utilizing available resources are central to agriculture in this millennium. Nitrogen (N) is the most commonly deficient nutrient in global cereal grain production, leading to N fertilizer amendments occupying the highest tier of input costs for producers (Thomason et al., 2002).

Nitrogen plays a vital role in the physiology of life. It is found in protein forming amino acids, vitamins, energy systems, and genetic material of plants, along with being a key component of the chlorophyll molecule (Brady and Weil, 2002). High demand for N by the plant, coupled with the significant mobility of N compounds can lead to nutritional deficiencies. Signs of N deficiencies are chlorosis of the tips and margins of older leaves (IPNI, 2006).

Fertilizer N is required for optimum yields in the intensive agricultural systems of North America and around the world (Kucey and Schaalje, 1986). Mohammed et al. (2013) considered N as the single most abundant element in Earth's atmosphere. Further explaining that plants cannot readily use the atmospheric state of N; but through industrial fixation, fertilizer grade N is produced, allowing for the improvement of crop quality and performance. Work by Oberle and Keeney (1990) estimated that 3.5% of the soil organic N pool was mineralized throughout the duration of the growing season in an average year. On average, a 2.7 Mg/ha wheat crop will remove up to 95 kg/ha of N (Alberta, 2010). Under normal weather conditions, naturally supplied N would not be adequate to produce such yields, further demonstrating the importance of synthetically manufactured fertilizers.

Worldwide production of wheat exceeded 700,000,000 Mg in 2013 (FAO, 2015b), along with applications exceeding 90,000,000 Mg of N fertilizer (FAO, 2015a). Total N uptake of a plant, compared to the rate of application is the foundation for calculating Nitrogen-Use

Efficiency (NUE, Hardy and Havelka, 1975). Worldwide NUE is estimated at 33% by Raun and Johnson, 1999. The formula they described is {NUE = [(total cereal N removed) – (N coming from the soil + N deposited in the rainfall)]/(fertilizer N applied to crop). Increased NUE positively correlates with an increased return on investment. A 1% increase in worldwide NUE would result in greater than $1.1 billion in saved fertilizer costs (Raun and Johnson, 1999).

Low NUE is a result of several natural processes that can be inflated by producer practices, all while being subject to weather conditions. Ammonia volatilization, denitrificaiton, immobilization, and leaching are all major pathways of N loss and decreased NUE (Nielsen, 2006). The additional loss of ammonia from cereal crop tissue following anthesis has been documented (Harper et al., 1987). However, most often, low NUE can be attributed to the producer practice of applying insurance N, to safeguard from any unexpected events. This excessive use can be attributed to the inexpensive nature of most N fertilizers, and the opinion that slight over fertilization is less of an economic risk than yield reduction due to insufficient levels of N (Schepers et al., 1991). Providing the crop with excessive N not only decreases profits, but also can have significant impacts on the environment and human health (Boman et al., 1995; Sieling et al., 1998).

Schepers et al. (1991) identified producer practices as a major contributor to the degradation of groundwater quality. In their study, they observed a positive correlation between the land that received excess N and groundwater of the over fertilized land containing high levels of nitrate ($NO_3$-) N. Drinking water high in $NO_3$- has the potential to induce methemoglobinemia, a life-threatening condition in infants (Hegesh and Shiloah, 1982). Smil (1997) went on to discuss how major waterways are subject to surface run-off from production fields, often resulting in eutrophication. Further explanation was given on the adverse effects of soil N that escapes to the atmosphere, as nitrous oxide, where it reacts with excited oxygen, further degrading the ozone in the stratosphere, along with promoting the greenhouse effect in the troposphere.

The key concept to improving fertilizer utilization is to understand the routes N may take in exiting the field following application and correcting the production practices that contribute to these losses. Exploring new methods that possess the potential to increase NUE is integral to the long-term stability of the agriculture industry (Smil, 1997). This study reports the effects of application depth of urea ammonium nitrate (UAN) for side-dress applications on grain yield and NUE.

# CHAPTER II

## REVIEW OF LITERATURE

**Factors Contributing to Low NUE**

Management of fertilizer applications to achieve high NUE is proven to be profitable, as decreased NUE diminishes the economic contribution of nutrient application (Gauer et al., 1992). Several N loss mechanisms can be mitigated through improved production practices. Tomar and Soper (1981) identified fixation of N in soil organic and inorganic pools, microbial immobilization of N, denitrification, ammonia ($NH_3$) volatilization, and leaching as primary contributors to decreased fertilizer performance. To enact greater levels of NUE, fundamental knowledge of N cycling among soil-plant-atmosphere relationships is a necessity (Sharpe et al., 1988). Additionally, Raun and Johnson (1999) noted that although a practice may improve NUE, it could negatively affect the capability to sustain practical production.

**Ammonia Volatilization**

Increased utilization of urea and urea-based N fertilizers, along with the heightened popularity of no-till practices have contributed to $NH_3$ volatilization becoming a common problem challenging producers (McInnes et al., 1986). The N of many current fertilizers is either ammoniacal or enters an ammoniacal state following hydrolysis (Kresge and Satchell, 1960). Soil pH, cation exchange capacity (CEC), organic matter, residue, soil moisture, temperature, humidity, and fertilizer type all have heavy impacts on the quantity of N lost to volatilization (Jones et al., 2013a). Fowler and Brydon (1989) reported $NH_3$ losses of N in excess of 40% when urea was not incorporated into the soil.

Timely precipitation following broadcast applications of urea-N can greatly reduce, if not cease, ammonia volatilization by hydrolyzing and incorporating $NH_4$ into the soil profile (Keller and Mengel, 1986). A study designed by Oberle and Bundy (1987) to evaluate ammonia volatilization of N fertilizers surface applied in corn, produced results which indicated ammonia loss from surface-applied UAN was minimal if at least 2.5mm of precipitation occurred within 4 days of fertilization. It is recommended to avoid applications of urea-based fertilizers onto moist soil surfaces, unless an adequate rainfall is imminent (Jones et al., 2013b).

**Denitrification**

No-till soils contain 1.23 to 1.77 times the normal population of facultative anaerobes and denitrifiers (Doran, 1980). This leads to an increased occurrence of denitrificaiton and immobilization in no-till fields. Doran (1980) explained that microbial population figures and the apparent abundance of various microbial species indicate the biochemical environment of no-till to promote heightened anaerobic activities of various microbial populations when compared to conventionally managed fields. Enhancing the microbial acquisition of $NO_3$, and the ultimate conversation to $N_2$ gas (Nielsen, 2006).

**Leaching**

The nitrification of $NH_4$ to $NO_3$ results in the loss of N’s ability to be adsorbed to cation exchange sites, thus increasing the solubility/mobility of N in the presence of soil water (Nielsen, 2006). Waterlogged soils have the potential to leach $NO_3$ deep below the root zone, into belowground water supplies, causing serious water quality concerns (Killpack and Buchholz, 1993). Urea ammonium nitrate fertilizers have the potential to leach as soon as they are applied (Nielsen, 2006).

**Fertilization Practices**

Production systems must take into account all possible sources of naturally supplied N, along with soil properties, nutrient demands, and weather patterns to efficiently evaluate the nutritional needs of the crop (Oberle and Keeney, 1990). Crop factors such as cultivar, seeding date, weed competition, disease pressure, and soil moisture all influence fertilizer recommendations (Alberta, 2010). Different practices vary in ranges of effectiveness, as such, it is important to gather knowledge of the production system when deciding on the source and application method of N fertilizer (Kucey and Schaalje, 1986).

**Surface vs. Subsurface Application**

Several studies have evaluated the effectiveness of various methods for fertilizer placement (Malhi and Nyborg, 1985; Mengel et al., 1982; Rao and Dao, 1996; Tomar and Soper, 1981; Varvel et al., 1989). Mengel et al. (1982) found that subsurface placement of N fertilizers improved grain yield in a conservation tillage system. It was reasoned that N was more readily available due to the bypassing of surface applications, which promote ammonia volatilization and immobilization under ideal weather conditions. Doran (1980) described no-till systems as having a greater microbial population in the upper 7.5cm of the soil profile. Further explaining the relationship of high rates of N immobilization with surface applied fertilizers in no-till fields. Additionally, increased soil water and an elevated presence of crop residues, compared to conventional till system, promote the higher rates of anaerobic metabolism and denitrification (Doran, 1980).

Placement of N in a subsurface band has proven to be more effective than broadcast applications on the surface (Rao and Dao, 1996; Bandel et al., 1980; Tomar and Soper, 1981). An experiment conducted by Rao and Dao (1996) illustrated a 32% and 15% increase in grain yield when N fertilizer was applied below the seed and between the rows, respectively, compared to the broadcast application. Differences between the below-the-seed and between-the-row treatments were not significant (Rao and Dao, 1996). They went on to comment that concentrated bands of N below the surface were less susceptible to volatilization and microbial immobilization.

Bandel et al. (1980) further emphasized the importance of subsurface placement, as surface residue leads to increased losses from volatilization and immobilization. A study conducted by Tomar and Soper (1981) provided supplemental demonstration to the advantages of subsurface bands of N. Their study compared fertilizer uptake among bands and broadcast applications with no surface residue, band and broadcast with surface residue, and band and broadcast with incorporated residue. They found fertilizer uptake efficiencies increased 24%, 69%, and 84% respectively, among the three treatments.

With sufficient soil moisture, little variation has been reported between band and broadcast N applications; however, under dry conditions, urea based fertilizers placed at depths of 10 cm are the most effective in enhancing cropping efficiency (Carter and Rennie, 1984). Additional work conducted by R.V. Olson (1987) produced results in agreement with previously mentioned studies. The study showed that banded depths of 5-10 cm enhanced fertilizer uptake when compared to bands and broadcast applications at the surface. Results of prior studies will prove to be fair comparison models for evaluating the application depths of 5 and 10 cm for UAN fertilizer.

**Crop Disturbance from Subsurface Application**

Carter and Rennie (1984) indicated that subsurface bands involve elevated soil disturbance in no-till systems. It incites added thought that midseason application of subsurface bands can generate damage to the crop. In a study evaluating spring-applied nitrogen fertilizer influence on winter wheat and residual soil nitrate, anhydrous ammonia (AA) was applied post emergence to the wheat crop at a 15.24 cm depth, perpendicular to the drilled rows (Boman et al., 1995). Application came from a 1.27 cm applicator knife following rolling coulters. This study reported no reduction in yield following the mid-season subsurface application to the established crop. Kelley and Sweeney (2007) mentioned that the initial cost of applying subsurface fertilizer will be larger than broadcast applications, but the economic gain from higher yields and lower N rates can be offset.

**Application Timing**

Many producers have adopted systems of applying split applications, with a portion of N at pre-plant, and the rest midseason. Early season N should be utilized to manipulate yield (Wuest and Cassman, 1992) and provide greater water use efficiency (Bushong et al., 2014), while late season additions focus more on improving grain quality (Wuest and Cassman, 1992). It is worthy to note that applying excess N to increase grain protein decreases overall NUE (Gauer et al., 1992). The timing of top-dress application is important, as there are several factors that contribute to lower NUE from N applied in the fall. Losses through denitrification and microbial immobilization overwinter months are common with fall-applied fertilizers, especially as a result of broadcast applications (Malhi and Nyborg, 1983).

Subsurface band applications are effective in combating denitrification and immobilization; however, spring applications ultimately prove to be the most effective between the two (Nyborg and Malhi, 1979). By evaluating methods to increase the efficiency of fall-applied urea, Nyborg and Malhi (1979) observed grain yields for barley receiving subsurface band treatments of 1520 kg/ha in the fall, compared to that of 2140 kg/ha in the spring. Olson (1986) concluded that fertilizer efficiency was optimized with spring applications due to less immobilization from late fall to early spring.

Freeze damage is another reason to stray from excess N in the fall. Luxury consumption in the fall can lead to overgrowth, diminishing the overwintering capacity of winter wheat (Needham, 2015). Excessive N can also lead to elevated insect, weed, and disease pressure (Needham, 2015). Overall, low rates of pre-plant N in the fall, along with sound estimations for in season spring N, and foliar N prior to flowering are proven to be the most efficient methods for supplying N throughout the growing season when grain yield is the ultimate metric (Thomason et al., 2002).

**Optical Sensing**

Soil N fluctuations are highly unpredictable (Johnson and Raun, 2003). Check plots in a long-term fertilization trial in Western Oklahoma produced near maximum yields after having received no fertilization for over 30 years. The reasoning for this was an unusually warm and wet winter, which allowed for increased N mineralization and N deposited in the rainfall to produce yields comparable to fertilized plots. Their experiment shows the need for conscious fertilizer management decisions, based on a combination of soil sampling and optical sensing. Compared to conventional farming methods, optical sensing can greatly reduce N rates, residual N, and apparent N loss without significantly reducing final grain yield (Li et al., 2009).

Stone et al. (1996) demonstrated spatial variation in forage and grain yield when variable N rates were applied based on plant N spectral indexes (PNSI). Raun et al. (2001) described the idea of yield goals, and the limitations they imposed. They went on to recommend the use of post dormancy spectral reflectance readings, in the form of normalized difference vegetation index (NDVI) collected at Feekes growth stage 4 and again at stage 5. Adding the two NDVI readings together and dividing by the growing degree days (GDD) between readings provided a reliable indication of potential grain yield (Raun et al., 2001). The additions of a calculated response index between N rich strips and normal producer practices for a field and a coefficient of variation to account for spatial variability within each 0.4 $m^2$ have been incorporated into a functional equation. This equation allows for improved estimations of seasonal N removal. Furthermore, it is predictive of the potential grain yield for each 0.4 $m^2$ with an adjustment for yearly variability in N response (Raun et al., 2005).

# CHAPTER III

## MATERIALS AND METHODS

Four trials were initiated to evaluate the appropriate depth to apply UAN in winter wheat with relevance to the depth's effect on grain yield, N uptake and NUE. Trials were located at Hennessey (no-till), Lahoma (conventional), Lake Carl Blackwell (conventional), and Perkins (no-till). The experiment sites at Hennessey, Lahoma, Lake Carl Blackwell, and Perkins were located on Bethany silt loam, a Grant silt loam, a Pulaski fine sandy loam and a Konawa and Teller fine sandy loam, respectively. The sites, alphabetically listed, were planted on October 28, 2015, October 9, 2015, October 19, 2015, and October 13, 2015 with the variety Iba from Oklahoma Foundation Seed. Seeding rates for Hennessey, Lahoma, Lake Carl Blackwell, and Perkins were 67, 82, 82 and 84 kg $ha^{-1}$, respectively. Planting was accomplished with a conventional grain drill, and a Great Plains no-till drill.

All sites received a preplant blanket application of 45 kg N $ha^{-1}$, with the exception of treatment 14 (0 N check). Pre-plant N was applied to the surface with a modified sprayer mounted on a four-wheeler, utilizing streamer nozzles. Midseason N applications were placed on the surface, 5 cm, and 10 cm beneath the soil surface at Feekes growth stage 5. Midseason N applications were made at Hennessey, Lahoma, Lake Carl Blackwell, and Perkins on February 22, 2016, February 23, 2016, February 17, 2016, and February 17, 2016, respectively. Nitrogen was applied with a coulter applicator (Figure 5) at rates of 34, 67, 101, and 134 kg N $ha^{-1}$. Coulters were spaced 43 cm apart.

A randomized complete block experimental design with three replications, and 14 treatments was used at all sites (Table 1). Total trial size measured 42.7 m by 24.4 m. Each treatment plot size measured 6.1 m by 3.0 m. Replications were separated by 3.0 m x 42.7 m allies, which contributed to the total width and length of the trial measurements.

Weekly Greenseeker™ readings were taken throughout the spring growing season leading up to head emergence. Commercial herbicides were applied as needed to control weed competition both pre and post emergence. The center 1.8 m was harvested the length of each plot with a Massey Ferguson self-propelled combine. At physiological maturity, harvest occurred at Hennessey, Lahoma, Lake Carl Blackwell, and Perkins on June 7, 2016, June 11, 2016, June 13, 2016, and June 8, 2016, respectively.

Grain subsamples were collected from each plot immediately after harvest. Grain subsamples were then placed in a drier at 60°C for 24 hours. Subsamples were then ground down and processed to fine flour. Sampling grinding was conducted with a Wiley Grinding Mill. Ground samples were then, individually, placed in glass sample bottles with three metal rods. These bottles were then placed on rollers for 24 hours. Next, 150mg of each sample was weighed out and analyzed to determine total N using a LECO Combustion Carbon/Nitrogen Analyzer.

Nitrogen Use Efficiency (NUE) was determined using the formula [(Grain N uptake treated-Grain N uptake check)/N rate applied]. Statistical analysis was conducted with SAS utilizing the PROC GLM procedure, mean separations using LSD alpha=0.05, and single degree of freedom contrasts (SAS Institute Inc., 2008).

# CHAPTER IV

# FINDINGS

**Hennessey – Grain Yield**

At the Hennessey location, grain yields ranged from 2.92 – 5.22 Mg $ha^{-1}$ (Table 2). Statistical differences between treatments were small. Treatment 12 (134 kg N $ha^{-1}$ applied at 5 cm) was significantly lower than treatment 1 (45 kg N $ha^{-1}$ as preplant) and 4 (34 kg N $ha^{-1}$ applied at 10 cm). Plots that received only preplant N at 45 kg N $ha^{-1}$ had the highest yield, with a mean of 5.22 Mg $ha^{-1}$. These yields were not statistically different from the 0 N check, treatment 14, which had a mean yield of 3.95 Mg $ha^{-1}$. Numerically, the 10 cm application depth at N rates of 34, 67, and 101 kg $ha^{-1}$ (treatments 4, 7 and 10) outperformed the surface application. Further comparison between the 5 and 10 cm application depths showed that yields from the 10 cm depth were higher than the 5 cm depth. Although numeric differences were evident, the lack of statistical significance prohibits a sound conclusion from being drawn at this location. Non-orthogonal contrasts produced no significant differences when comparing surface to subsurface treatments at alpha=0.05 (Table 3). Excessive standing water in plots throughout the growing season, contributed to the limited differences detected for the main effect of treatment in this trial. Furthermore, it is likely that the above average temperatures and precipitation led to heightened rates of N mineralization. High levels of naturally supplied N explains the lack of treatment response when comparing varying N rates/depths to the 0 N check.

**Hennessey – Grain N**

At the Hennessey location, grain N levels ranged from 1.32 – 2.14%, with treatment 12 (134 kg N $ha^{-1}$ applied at 5 cm) occupying the high end of the range and treatment 14 (0 N check) at the lower end (Table 2). All treatments, with the exception of treatment 1 (45 kg $ha^{-1}$ of preplant N), were significantly higher than the 0 N check, treatment 14. No conclusive statistical difference was present when evaluating application depths at different N rates. However, trends for higher grain N from subsurface treatments were noticed. Treatments 3 and 4 (34 kg N $ha^{-1}$ at 5 and 10 cm, respectively) were numerically higher than their surface counterpart, treatment 2. Similar numeric results were present at N rates of 101 and 134 kg $ha^{-1}$, where treatments 9 and 10 (101 kg N $ha^{-1}$ at 5 and 10 cm, respectively) were numerically higher than treatment 8 (surface application of 101 kg N $ha^{-1}$) and treatments 12 and 13 (subsurface application of 134 kg N $ha^{-1}$ at 5 and 10 cm, respectively) being numerically superior to treatment 11 (134 kg N $ha^{-1}$ applied to the surface). There was a positive trend for grain N as N rates increased. Non-orthogonal contrasts produced results that agree with noted data trends (Table 3). Contrasts among surface and both 5 and 10 cm depths were significant for the subsurface treatments at alpha=0.05. Contrasts between 5 and 10 cm application depths were not significant at alpha=0.05, implying no statistical difference in grain N content at the two depths. Various contrasts between N rates were significant (alpha=0.05), which further illustrates the positive trend seen for increased grain N at higher N rates. Results suggest that subsurface treatments provided the best grain N content and 3 of the 4 tiers of N rates. The data implies that there is no difference between the 5 and 10 cm depths. However, due to the high environmental variability seen at this location, statistical significance was limited.

**Hennessey – NDVI Feekes 7**

At this location, NDVI values collected at Feekes 7 ranged from 0.47 – 0.73 (Table 2). Statistical differences were limited. Treatments 1 – 13 were all statistically higher than the 0 N check, treatment 14. Treatment 5 (67 kg N $ha^{-1}$ applied to the surface) was significantly superior to treatment 6 (67 kg N $ha^{-1}$ at 5 cm), yet both treatments were not statistically different than treatment 7 (67 kg N $ha^{-1}$ at 10 cm). Numerically, 3 of the 4 treatments receiving midseason N at the 5 cm application depth (3, 8 and 12) had the highest NDVI values in their respective N rate tiers. Non-orthogonal contrasts were used to evaluate differences among surface, 5 cm, and 10 cm application depths (Table 3). Contrasts among surface and 5 and 10 cm application depths were not significant (p=0.33 and p=0.36, respectively). Further contrasts between 5 and 10 cm application depths were not significant. When correlating NDVI collected at Feekes 7 with final grain yield (Figure 1), no conclusive correlation was achieved ($R^2$=0.01). The continued lack of statistical significance at the Hennessey location does not allow for firm conclusions to be drawn, however, the consistent numerical trends of the data imply that subsurface applications of midseason N provide competitive results.

**Hennessey – NUE**

At the Hennessey location, the NUE values ranged from 6% (treatment 12, 134 kg N $ha^{-1}$ at 5 cm) –64% (treatment 1, 45 kg $ha^{-1}$ of preplant N) (Table 4). At N rates of 34, 67 and 101 kg $ha^{-1}$, subsurface treatments achieved higher levels of NUE. Of all the treatments that received midseason N, treatment 4 (34 kg N $ha^{-1}$ at 10 cm) experienced the highest NUE value of 39%. These results mirror trends seen with the grain N concentrations of the treatments. Subsurface applications at 10 cm provided the highest NUE for N rates of 34, 67 and 101 kg $ha^{-1}$. Due to the above average temperatures and favorable soil moisture throughout the growing season, treatment 1 (45 kg $ha^{-1}$ of preplant N) likely experienced high NUE due to the heightened levels of naturally mobilized N combined with a single preplant N application. These factors produced the highest mean yields in the trial and were not significantly different from the treatments that received midseason N, with the exception of treatment 12 (134 kg N $ha^{-1}$ applied at 5 cm). This location clearly demonstrates the need for midseason N management, as maximum yields were achieved with a single preplant N application.

**Lahoma – Grain Yield**

At the Lahoma location, grain yields ranged from 1.29 – 3.97 Mg $ha^{-1}$ (Table 5). At 34 kg N $ha^{-1}$, treatments 3 and 4 (5 and 10 cm application depths, respectively), were significantly lower than the surface application, treatment 2. There was no statistical difference between treatments 3 and 4. Treatment 7 (67 kg N $ha^{-1}$ applied at 10 cm) was not different when compared to the same N rate applied to the surface, treatment 5. A significant difference was present between the two subsurface treatments at 67 kg N $ha^{-1}$, where treatment 7 achieved a higher yield. Both subsurface application depths at 101 kg N $ha^{-1}$ (treatments 9 and 10) were significantly higher than the surface application (treatment 8). No difference was present between the surface (treatment 11) and subsurface (treatments 12 and 13) application methods at 134 kg N $ha^{-1}$. All treatments that received midseason N, treatments 2-13, produced significantly higher yields than the 0 N check, treatment 14. This showcased the positive impact provided by midseason N. No statistical difference was present between treatment 14 and treatment 1 (45 kg $ha^{-1}$ of preplant N). At N rates of 67, 101 and 134 kg $ha^{-1}$, subsurface treatments 7, 12 and 13 were statistically similar to surface treatments 5 and 11. The lone exception was treatment 6 (67 kg N $ha^{-1}$ at 5 cm), which was significantly lower than the surface and 10 cm application depth at 67 kg N $ha^{-1}$. Non-orthogonal contrasts were used to evaluate cumulative differences in application depths (Table 6). A contrast between surface and 5 cm application depths was significant ($p=0.02$). However, a contrast between surface and 10 cm depths was not significant ($p=0.77$). Yields for the surface treatments were numerically higher than the 10 cm treatments at N rates of 67 and 134 kg $ha^{-1}$ and statistically superior at 34 kg N $ha^{-1}$. A significant difference was highlighted in contrasts between treatments with 5 and 10 cm application depths (p=0.03), with favor given to the 10 cm depths when evaluating numeric trends. Overall, subsurface treatments were reliable in maintaining competitive yields with the surface applications at midseason N rates of 67, 101 and 134 kg N $ha^{-1}$. Application depths of 10 cm had higher yields than treatments with 5 cm application depths.

**Lahoma – Grain N**

At the Lahoma location, grain N levels ranged from 1.43 – 2.23% (Table 5) with treatment 14 (0 N check) occupying the low end of the range and treatment 12 (134 kg N $ha^{-1}$ applied at 5 cm) representing the high end. With the exception of treatments 1 (45 kg $ha^{-1}$ of preplant N) and 2 (34 kg N $ha^{-1}$ surface applied), all treatments were significantly higher than the 0 N check. No statistical difference was detected among the three application methods at the 34 kg $ha^{-1}$ N rate. At 67 kg N $ha^{-1}$, the 5 cm application depth, treatment 6, was significantly higher than the surface and 10 cm application depth, treatments 5 and 7, respectively. Furthermore, no statistical difference was found between the surface and 10 cm depth at 67 kg N $ha^{-1}$. Treatment 12 (134 kg N $ha^{-1}$ at 5 cm) was significantly greater than treatment 11 (134 kg N $ha^{-1}$ surface applied), yet statistically similar to treatment 13 (134 kg N $ha^{-1}$ at 10 cm). A positive trend occurred with elevated grain N at increased N rates. Non-orthogonal contrasts were used in evaluating cumulative differences between surface and subsurface application methods (Table 6). Contrasts between surface and 5 and 10 cm depths were highly significant (p=0.0002 and p=0.002, respectively) for both subsurface methods. Additionally, a contrast between 5 and 10 cm treatments was not significant (p=0.33). Overall, subsurface treatments outperformed surface applications with a combination of numeric and statistical advantages in various treatment comparisons.

**Lahoma – NDVI Feekes 7**

At this location, NDVI values collected at Feekes growth stage 7 (second stem node visible) ranged from 0.31 – 0.53 (Table 5). Treatments 1 – 13 were all significantly higher than the 0 N check, treatment 14. At midseason N rates of 34 and 67 kg $ha^{-1}$, surface treatments 2 and 5, respectively, were significantly higher than the subsurface treatments 3/4 and 6/7. No difference was detected between treatments 3 (34 kg N $ha^{-1}$ at 5 cm) and 4 (34 kg N $ha^{-1}$ at 10 cm). Furthermore, there was no significant difference in surface and subsurface treatments at the 101 kg N $ha^{-1}$ grouping, although the subsurface treatments were numerically higher at this rate.

At 134 kg N $ha^{-1}$, there was no statistical difference between the surface and 10 cm application depth, along with no detectable difference between the 5 and 10 cm depths. However, at 134 kg N $ha^{-1}$, the surface treatment was significantly higher than the 5 cm depth. Non-orthogonal contrasts were significant for differences between surface and subsurface treatments at both 5 and 10 cm depths ($p<0.0001$ and $p=0.02$, respectively) (Table 6). The added contrast between 5 and 10 cm application depths was significant ($p=0.02$). Linear regression between NDVI values collected at Feekes 7 and final grain yield produced a strong correlation ($R^2=0.88$) (Figure 2). Surface treatments outperformed subsurface treatments at N rates of 34 and 67 kg $ha^{-1}$. No difference was seen between surface and 10 cm depths at 101 and 134 kg N $ha^{-1}$. These results suggest that 10 cm application depths for midseason N were competitive with surface applications at higher N rates. However, surface applications were more effective at producing higher NDVI values at the two lower midseason N rates.

**Lahoma – NUE**

At the Lahoma location, NUE values ranged from 14 – 48% (Table 7). At N rates of 34 and 67 kg $ha^{-1}$, surface treatments 2 and 5 had higher NUE values than the subsurface treatments. Midseason N rates of 101 and 134 kg $ha^{-1}$ produced the inverse, as the subsurface treatments witnessed greater levels of NUE. Treatment 10 (101 kg N $ha^{-1}$ at 10 cm) had the highest NUE for subsurface treatments at 44.85%. Treatments that had midseason N applied at depths of 10 cm (4, 7, 10 and 13) achieved higher NUE values than the 5 cm counterparts, treatments 3, 6, 9 and 12. Treatment 2 (34 kg N $ha^{-1}$ surface applied) held the highest NUE for all treatments at 47.94%. Subsurface N applications were most effective at increasing NUE at higher N rates (101 and 134 kg $ha^{-1}$). Among subsurface treatments, the 10 cm application depth accounted for higher levels of NUE when compared to that produced by 5 cm application depths. Lower midseason N rates of 34 and 67 kg $ha^{-1}$ showed that surface applications had the higher NUE's. Within this location, subsurface treatments at high midseason N rates were most effective in providing the highest levels of NUE.

**Lake Carl Blackwell – Grain Yield**

At the Lake Carl Blackwell location, grain yields ranged from 2.31 (treatment 1, 45 kg $ha^{-1}$ of preplant N) – 4.18 Mg $ha^{-1}$ (treatment 9, 101 kg N $ha^{-1}$ at 5 cm) (Table 8). Treatment 5 (67 kg N $ha^{-1}$ surface applied) and treatment 9 (101 kg N $ha^{-1}$ at 5 cm) were the only treatments that were significantly different from the 0 N check, treatment 14. Heavy weed pressure from Italian Ryegrass limited the observable response from independent variables. Although statistical differences were small, numeric trends were evident. At N rates of 34, 101, and 134 kg $ha^{-1}$, the

10 cm application depth provided numerically higher yields to the surface applications of midseason N. Furthermore, the 10 cm application depth outperformed the 5 cm treatments at N rates of 34, 67 and 101 kg $ha^{-1}$. Non-orthogonal contrasts were employed to evaluate differences among surface and subsurface applications (Table 9). Contrasts comparing surface to 5 cm and surface to 10 cm depths yielded no significant results (p=0.97 and p=0.96, respectively). A further contrast between the two subsurface depths of 5 and 10 cm was not significant. Due to the lack of statistical significance, it is not possible to draw a sound conclusion from the grain yield data at this location. Although, slight numeric trends of the data do suggest that the 10 cm application depth has the potential to be the most efficient at providing superior yields.

**Lake Carl Blackwell – Grain N**

At the Lake Carl Blackwell location, treatment 12 (134 kg N $ha^{-1}$ at 5 cm) achieved the highest grain N content of 2.29%, while treatment 11 (134 kg N $ha^{-1}$ surface applied) recorded the lowest grain N concentration at 1.40% (Table 8). At N rates of 34, 67 and 101 kg $ha^{-1}$, no statistical difference was present among the surface, 5 and 10 cm application depths within each set of N rates. However, treatments 12 (134 kg N $ha^{-1}$ at 5 cm) and 13 (134 kg N $ha^{-1}$ at 10 cm) were significantly higher than treatment 10 (134 kg N $ha^{-1}$ surface applied). There was no significant difference present between treatments 12 and 13. Numerically, there was a slight trend in favor of the subsurface treatments, as treatments 6 (67 kg N $ha^{-1}$ at 5 cm) and 7 (67 kg N $ha^{-1}$ at 10 cm) had higher yields than treatment 5 (67 kg N $ha^{-1}$ surface applied). Treatment 3 (34 kg N $ha^{-1}$ at 5 cm) had higher yields compared to treatment 2 (34 kg N $ha^{-1}$ surface applied), yet treatment 2 achieved a numerically higher yield than treatment 4 (34 kg N $ha^{-1}$ at 10 cm). Furthermore, treatment 10 (101 kg N $ha^{-1}$ at 10 cm) was the highest when compared to other treatments at the same rate. Treatment 8 (101 kg N $ha^{-1}$ surface applied) contributed a slight yield advantage to treatment 9 (101 kg N $ha^{-1}$ at 5 cm). Non-orthogonal contrasts were performed between surface and subsurface treatments (Table 9). The Contrast comparing surface applications and 5 cm depths was highly significant (p=0.004). Another contrast between surface applications and 10 cm treatments was significant for the 10 cm application depth (p=0.01). However, a contrast between 5 and 10 cm depths was insignificant (p=0.65). Due to the high variation in treatment response induced by weed pressure, concise conclusions are not possible from the grain N data at this site. Although, slight numeric trends and contrast results suggest that there is a benefit from subsurface N applications. Subsurface applications did not decrease grain N content. Higher concentrations were observed from at least one of the two depths in each tier of N rates when compared to the surface treatments.

**Lake Carl Blackwell – NDVI Feekes 7**

At the Lake Carl Blackwell location, NDVI data collected at Feekes growth stage 7 (second stem node visible) produced no significant results (Table 8). Treatment NDVI values ranged from 0.55, treatment 14 (0 N check), to 0.73, treatment 12 (134 kg N $ha^{-1}$ at 5 cm). With the exception of treatment 10 (101 kg N $ha^{-1}$ at 10 cm) and 12 (134 kg N $ha^{-1}$ at 5 cm), there were no significant differences among treatments compared to the 0 N check, treatment 14. Limited numeric trends were observed. Non-orthogonal contrasts were used to evaluate combined differences between surface and subsurface treatments (Table 9). A contrast between surface applications and 5 cm depths was not significant as. When contrasting the 5 and 10 cm depths, it produced no significant results (p=0.69). A linear regression was performed to evaluate the relationship between NDVI data from Feekes 7 and grain yield (Figure 3). The observed regression resulted in no correlation ($R^2$=0.05). As seen with the grain N and yield data, no firm conclusion could be drawn.

**Lake Carl Blackwell – NUE**

At the Lake Carl Blackwell location, NUE values were low (Table 10). Treatment 1 (45 kg N $ha^{-1}$ at preplant) had the lowest NUE (<0) while treatment 9 (101 kg N $ha^{-1}$ at 5 cm) held the highest at 25%. Within all of the N rates, at least one of the two subsurface treatments had the greatest NUE. Treatments that received midseason N at 10 cm had an NUE higher than the surface treatments in all tiers of N rates. At 67 kg N $ha^{-1}$, treatment 6 (5 cm) was lower than treatment 5 (surface). This gives a slight advantage to the treatments that received midseason N at the 10 cm depth. Overall, subsurface applications of midseason N had higher NUE when compared to surface applications.

**Perkins – Grain Yield**

At the Perkins location, grain yields ranged from 2.58 – 5.94 Mg $ha^{-1}$ (Table 11). Treatment differences were not present at N rates of 67, 101 and 134 kg $ha^{-1}$. However, treatments 1-13 were significantly higher than the 0 N check, treatment 14. Treatment 4 (34 kg N $ha^{-1}$ at 10 cm) was significantly greater than treatment 2 (34 kg N $ha^{-1}$ surface applied). Furthermore, treatment 3 (34 kg N $ha^{-1}$ at 5 cm) was not statistically different than treatments 2 or 4. Yield differences were small at N rates of 67, 101, and 134 kg $ha^{-1}$. This suggests no additional benefit from N applications beyond 67 kg $ha^{-1}$. Non-orthogonal contrasts were used to evaluate differences among surface, 5 cm, and 10 cm application depths (Table 12). Contrasts among surface and 5 cm depths and surface and 10 cm depths were not significant (p=0.88 and p=0.39, respectively). A further contrast between 5 and 10 cm application depths was not significant (p=0.47). Based off of the results from 34 kg N $ha^{-1}$, the 10 cm application depth was the most efficient at providing competitive yields when N was limited. No identifiable difference was seen between surface and subsurface yields at N rates of 67, 101 and 134 kg N $ha^{-1}$.

**Perkins – Grain N**

At this location, grain N content ranged from 1.5% within treatment 1 (45 kg $ha^{-1}$ preplant N) to 2.2% in treatment 12 (134 kg N $ha^{-1}$ at 5 cm) (Table 11). All treatments within N rates of 67, 101, and 134 kg N $ha^{-1}$ were significantly higher than the 0 N check, treatment 14. No significant differences were present at 34 kg N $ha^{-1}$, however both 5 and 10 cm application depths (treatments 3 and 4, respectively) provided numerically higher yields than the surface application (treatment 3). At 101 kg N $ha^{-1}$, treatments 9 (5 cm depth) and 10 (10 cm depth) were significantly greater than treatment 8 (surface). Treatment 12 (134 kg N $ha^{-1}$ at 5 cm) was statistically superior to treatment 11 (134 kg N $ha^{-1}$ surface applied). There was no significant difference among treatments 11 and 13 (134 kg N $ha^{-1}$ at 10 cm) or 12 and 13. Non-orthogonal contrasts were used to evaluate differences among surface and subsurface application depths (Table 12). A significant difference was present between surface and 5 cm application depths (p=0.003). Trends favored the 5 cm application depth. A further contrast between surface and 10 cm application depths was significant (p=0.03). Again, data trends suggest that the 10 cm depth was better. A final contrast was employed between the two subsurface depths but was not significant (p=0.32). Subsurface midseason N applications provided various statistical and numeric advantages to the surface treatments. No clear difference was present between 5 and 10 cm application depths. Results did imply that subsurface N applications were effective in maintaining, if not increasing grain N content.

**Perkins – NDVI Feekes 7**

At this location, NDVI values collected at Feekes growth stage 7 (second stem node visible) ranged from 0.36 (treatment 14; 0 N check) to 0.64 (treatment 8; 101 kg N $ha^{-1}$ surface applied) (Table 11). Treatments 1 – 13 were all significantly greater than treatment 14. Within each group of N rates, there were no significant differences among surface, 5 cm, and 10 cm application depths. At 34 kg N $ha^{-1}$, both subsurface applications depths of 5 and 10 cm (treatments 3 and 4, respectively) were numerically higher than the surface application (treatment 2). Non-orthogonal contrasts were used to evaluate differences among surface, 5 cm, and 10 cm application depths (Table 12). Contrasts between surface and 5 and 10 cm application depths were significant (p=0.003 and p=0.03, respectively). A further contrast between 5 and 10 cm application depths was not significant (p=0.32). When correlating Feekes 7 NDVI sensor data with final grain yield (Figure 4), correlation was high ($R^2$=0.90). Firm conclusions cannot be drawn from the NDVI sensor data collected at Feekes 7. Although, numeric trends at 34 kg N $ha^{-1}$ suggest that subsurface treatments had higher NDVI values.

**Perkins – NUE**

At this location, NUE values ranged from 28% (treatment 1; 45 kg N $ha^{-1}$ at preplant) to 54% (treatment 4; 34 kg N $ha^{-1}$ at 10 cm) (Table 13). At 34 kg N $ha^{-1}$, treatments 3 (5 cm) and 4 (10 cm) provided notably higher levels of NUE at 48.13 and 54%, respectively, compared to the 34% achieved by treatment 2 (surface). Treatment 7 (67 kg N $ha^{-1}$ at 10 cm) had a higher NUE than treatment 5 (67 kg N $ha^{-1}$ surface applied). Subsurface treatments 9 and 10 provided higher levels of NUE than the surface applications in treatment 8 at N rates of 101 kg $ha^{-1}$. The same trend was witnessed at 134 kg N $ha^{-1}$, where treatments 12 and 13 (5 and 10 cm, respectively) had greater NUE's than treatment 11 (surface). The trends of this data show the positive effect subsurface N applications have on NUE, specifically from the 10 cm application depth. Midseason N applied at 10 cm consistently produced the highest NUE across N rates of 34, 67 and 101 kg $ha^{-1}$.

# CHAPTER V

## CONCLUSIONS

The objective of this study was to evaluate the effect of midseason UAN application depth on grain yield. Perkins was the only site where subsurface N placement increased wheat grain yields. At 34 kg N $ha^{-1}$, subsurface applications of 10 cm had the highest yields, exceeding 5.9 Mg $ha^{-1}$. Bypassing the active microbial zone as mentioned by Doran (1980), coupled with the N limited nature of the treatment grouping at 34 kg $ha^{-1}$, were considered to be key factors that helped explain this response. No till cropping systems in N limited environments benefitted the most from 10 cm application depths of UAN.

For NDVI sensor data collected at Feekes growth stage 7, no treatment differences were observed. However, the lack of statistical differences among surface and subsurface treatments suggests the ability of subsurface treatments to maintain yields and crop performance compared to traditional methods of N placement.

Positive trends for increased grain N content at elevated N rates were seen. Limited statistical differences were present at Hennessey and Lake Carl Blackwell. At the Lahoma site, the 5 cm application depth had higher grain N content than the surface treatments at N rates of 67 and 134 kg $ha^{-1}$. The 5 and 10 cm application depths at Perkins resulted in higher yields when compared to the surface treatments at 101 kg $ha^{-1}$ . Furthermore, 5 cm application depth had higher yields compared to surface treatments at 134 kg N $ha^{-1}$. There was no statistical difference between the 5 and 10 cm application depths at 134 kg N $ha^{-1}$ at the Perkins location. These results suggest that subsurface treatments were more efficient at providing elevated grain N concentrations at higher midseason N rates, specifically 5 cm application depths.

Subsurface treatments were consistent in providing higher levels of NUE at all four locations, with the exception of 34 and 67 kg N $ha^{-1}$ at Lahoma and 134 kg N $ha^{-1}$ at Hennessey. Overall, 10 cm application depths had higher NUE's, yet there were a few instances where the 5 cm depth had the highest NUE. With how predominant the trend was throughout most of the experiment, subsurface treatments, specifically 10 cm application depths, were the most successful in achieving increased NUE.

Although statistical differences were small the best subsurface depth (10 cm) largely agrees with previous literature in showcasing the beneficial impact of subsurface N applications (Bandel et al., 1980; Carter and Rennie, 1984; Mengel et al., 1982; Olson, 1987; Rao and Dao, 1996; Tomar and Soper, 1981). Further replications of this study would be required to conclusively evaluate the differences between 5 and 10 cm application depths and reduce the environmental influence. Although data trends were not conclusive, 10 cm application depths did not reduce grain yield, grain N, NDVI or NUE. Subsurface applications of 5 cm were not as consistent as 10 cm application depths when compared to surface treatments concerning yield. This data suggests that 10 cm application depths could be beneficial for producers hoping to maximize yields, and grain N.

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# APPENDICES

**Table 1.** Treatment structure employed at all locations to evaluate the effects of preplant N, sidedress N and mid-season application depth.

| Treatment | Preplant N (kg N/ ha) | Sidedress N (kg N/ ha) | Midseason Application Depth (cm) |
|---|---|---|---|
| 1 | 45 | 0 | N/A |
| 2 | 45 | 34 | 0 |
| 3 | 45 | 34 | 5 |
| 4 | 45 | 34 | 10 |
| 5 | 45 | 67 | 0 |
| 6 | 45 | 67 | 5 |
| 7 | 45 | 67 | 10 |
| 8 | 45 | 101 | 0 |
| 9 | 45 | 101 | 5 |
| 10 | 45 | 101 | 10 |
| 11 | 45 | 134 | 0 |
| 12 | 45 | 134 | 5 |
| 13 | 45 | 134 | 10 |
| 14 | 0 | 0 | N/A |

**Table 2.** Treatment structure, NDVI, grain N % and grain yield as influenced by UAN application depth (0, 5 and 10 cm) and N rate (34, 67, 100 and 134 kg ha$^{-1}$). All sites received 45 kg ha$^{-1}$ of pre-plant N except for treatment 14, Hennessey, OK 2015-2016.

| Treatment | Application Depth, cm | Midseason N Rate, kg ha$^{-1}$ | NDVI, Feekes 7 | Grain N Content, % | Grain Yield, Mg ha$^{-1}$ |
|---|---|---|---|---|---|
| **1** | N/A | 0 | 0.70$^{BA}$ | 1.56$^{FE}$ | 5.22$^{A}$ |
| **2** | 0 | 34 | 0.72$^{BA}$ | 1.59$^{E}$ | 4.46$^{BA}$ |
| **3** | 5 | 34 | 0.72$^{BA}$ | 1.74$^{DEC}$ | 4.23$^{BA}$ |
| **4** | 10 | 34 | 0.70$^{BA}$ | 1.75$^{DEC}$ | 4.77$^{A}$ |
| **5** | 0 | 67 | 0.73$^{A}$ | 1.90$^{BDAC}$ | 3.66$^{BA}$ |
| **6** | 5 | 67 | 0.63$^{B}$ | 1.71$^{DE}$ | 4.62$^{BA}$ |
| **7** | 10 | 67 | 0.69$^{BA}$ | 1.73$^{DEC}$ | 4.65$^{BA}$ |
| **8** | 0 | 100 | 0.66$^{BA}$ | 1.88$^{BDC}$ | 4.00$^{BA}$ |
| **9** | 5 | 100 | 0.69$^{BA}$ | 1.97$^{BAC}$ | 4.50$^{BA}$ |
| **10** | 10 | 100 | 0.65$^{BA}$ | 1.98$^{BAC}$ | 4.68$^{BA}$ |
| **11** | 0 | 134 | 0.65$^{BA}$ | 1.94$^{BDAC}$ | 4.53$^{BA}$ |
| **12** | 5 | 134 | 0.69$^{BA}$ | 2.14$^{A}$ | 2.93$^{B}$ |
| **13** | 10 | 134 | 0.64$^{BA}$ | 2.08$^{BA}$ | 4.00$^{BA}$ |
| **14** | N/A | 0 | 0.47$^{C}$ | 1.33$^{F}$ | 3.95$^{BA}$ |
| **MSE** | | | 0.004 | 0.022 | 1.184 |
| **SED** | | | 0.049 | 0.123 | 0.920 |
| **CV** | | | 8.98 | 8.32 | 25.32 |

SED – Standard error of the difference between two equally replicated means, CV – coefficient of variation, %, MSE – mean square error from analysis of variance. Means followed by the same letter were not significantly different at the 5% probability level.

**Table 3.** Treatment differences from non-orthogonal contrasts, winter wheat N study under conservation tillage, Hennessey, OK, 2015-2016.

| Non-orthogonal contrast | Grain Yield | Grain N Content | NDVI, Feekes 7 |
|---|---|---|---|
| Depth 0 vs 5 cm | NS | NS | NS |
| Depth 0 vs 10 cm | NS | NS | NS |
| Depth 5 vs 10 cm | NS | NS | NS |
| Midseason N 34 vs 67 | NS | NS | NS |
| Midseason N 34 vs 101 | NS | ** | @ |
| Midseason N 34 vs 134 | NS | ** | @ |
| Midseason N 67 vs 101 | NS | * | NS |
| Midseason N 67 vs 134 | NS | ** | NS |
| Midseason N 101 vs 134 | NS | NS | NS |

NS, not significant

@, *, **, significant at the 0.10, 0.05 and 0.01 probability levels, respectively

**Table 4.** Wheat NUE means as influenced by application depth (0, 5 and 10 cm) and midseason N rate (34, 67, 101 and 134 kg $ha^{-1}$). Hennessey, OK, 2015-2016.

| Treatment, description | NUE, % |
|---|---|
| 1, 45 kg N $ha^{-1}$ preplant N | 64 |
| 2, 34 kg N $ha^{-1}$ at 0 cm | 23 |
| 3, 34 kg N $ha^{-1}$ at 5 cm | 26 |
| 4, 34 kg N $ha^{-1}$ at 10 cm | 39 |
| 5, 67 kg N $ha^{-1}$ at 0 cm | 15 |
| 6, 67 kg N $ha^{-1}$ at 5 cm | 24 |
| 7, 67 kg N $ha^{-1}$ at 10 cm | 25 |
| 8, 101 kg N $ha^{-1}$ at 0 cm | 16 |
| 9, 101 kg N $ha^{-1}$ at 5 cm | 25 |
| 10, 101 kg N $ha^{-1}$ at 10 cm | 27 |
| 11, 134 kg N $ha^{-1}$ at 0 cm | 20 |
| 12, 134 kg N $ha^{-1}$ at 5 cm | 6.0 |
| 13, 134 kg N $ha^{-1}$ at 10 cm | 17 |
| 14, 0 N check | N/A |

**Table 5.** Treatment structure, NDVI, grain N % and grain yield as influenced by UAN application depth (0, 5 and 10 cm) and N rate (34, 67, 100 and 134 kg $ha^{-1}$). All sites received 45 kg $ha^{-1}$ of pre-plant N except for treatment 14, Lahoma, OK 2015-2016.

| Treatment | Application Depth, cm | Midseason N Rate, kg $ha^{-1}$ | NDVI, Feekes 7 | Grain N Content, % | Grain Yield, Mg $ha^{-1}$ |
|---|---|---|---|---|---|
| **1** | N/A | 0 | $0.38^{E}$ | $1.43^{G}$ | $1.74^{DE}$ |
| **2** | 0 | 34 | $0.51^{BA}$ | $1.51^{GF}$ | $3.73^{A}$ |
| **3** | 5 | 34 | $0.40^{ED}$ | $1.67^{EF}$ | $2.47^{C}$ |
| **4** | 10 | 34 | $0.43^{EDC}$ | $1.70^{EF}$ | $2.72^{BC}$ |
| **5** | 0 | 67 | $0.51^{BA}$ | $1.70^{EF}$ | $3.65^{A}$ |
| **6** | 5 | 67 | $0.39^{E}$ | $2.11^{BAC}$ | $2.33^{DC}$ |
| **7** | 10 | 67 | $0.45^{DC}$ | $1.86^{ED}$ | $3.28^{BA}$ |
| **8** | 0 | 100 | $0.43^{EDC}$ | $2.01^{DC}$ | $2.70^{BC}$ |
| **9** | 5 | 100 | $0.46^{BC}$ | $2.09^{BAC}$ | $3.78^{A}$ |
| **10** | 10 | 100 | $0.48^{BAC}$ | $2.13^{BAC}$ | $3.94^{A}$ |
| **11** | 0 | 134 | $0.53^{A}$ | $2.03^{BDC}$ | $3.97^{A}$ |
| **12** | 5 | 134 | $0.46^{BDC}$ | $2.23^{A}$ | $3.71^{A}$ |
| **13** | 10 | 134 | $0.48^{BAC}$ | $2.22^{BA}$ | $3.91^{A}$ |
| **14** | N/A | 0 | $0.31^{F}$ | $1.43^{G}$ | $1.29^{E}$ |
| **MSE** | | | 0.001 | 0.014 | 0.175 |
| **SED** | | | 0.025 | 0.096 | 0.341 |
| **CV** | | | 7.33 | 6.22 | 13.55 |

SED – Standard error of the difference between two equally replicated means, CV – coefficient of variation, %, MSE – mean square error from analysis of variance. Means followed by the same letter were not significantly different at the 5% probability level.

**Table 6.** Treatment differences from non-orthogonal contrasts, winter wheat N study under conventional tillage, Lahoma, OK, 2015-2016.

| Non-orthogonal contrast | Grain Yield | Grain N Content | NDVI, Feekes 7 |
|---|---|---|---|
| Depth 0 vs 5 cm | * | NS | ** |
| Depth 0 vs 10 cm | NS | NS | * |
| Depth 5 vs 10 cm | * | NS | * |
| Midseason N 34 vs 67 | NS | NS | NS |
| Midseason N 34 vs 101 | * | ** | NS |
| Midseason N 34 vs 134 | ** | ** | * |
| Midseason N 67 vs 101 | @ | * | NS |
| Midseason N 67 vs 134 | ** | ** | * |
| Midseason N 101 vs 134 | @ | NS | @ |

NS, not significant

@, *, **, significant at the 0.10, 0.05 and 0.01 probability levels, respectively

**Table 7.** Wheat NUE means as influenced by application depth (0, 5 and 10 cm) and midseason N rate (34, 67, 101 and 134 kg ha$^{-1}$). Lahoma, OK, 2015-2016.

| **Treatment, description** | **NUE, %** |
|---|---|
| 1, 45 kg N ha$^{-1}$ preplant N | 14 |
| 2, 34 kg N ha$^{-1}$ at 0 cm | 48 |
| 3, 34 kg N ha$^{-1}$ at 5 cm | 29 |
| 4, 34 kg N ha$^{-1}$ at 10 cm | 35 |
| 5, 67 kg N ha$^{-1}$ at 0 cm | 39 |
| 6, 67 kg N ha$^{-1}$ at 5 cm | 27 |
| 7, 67 kg N ha$^{-1}$ at 10 cm | 38 |
| 8, 101 kg N ha$^{-1}$ at 0 cm | 26 |
| 9, 101 kg N ha$^{-1}$ at 5 cm | 41 |
| 10, 101 kg N ha$^{-1}$ at 10 cm | 45 |
| 11, 134 kg N ha$^{-1}$ at 0 cm | 35 |
| 12, 134 kg N ha$^{-1}$ at 5 cm | 36 |
| 13, 134 kg N ha$^{-1}$ at 10 cm | 38 |
| 14, 0 N check | N/A |

**Table 8.** Treatment structure, NDVI, grain N % and grain yield as influenced by UAN application depth (0, 5 and 10 cm) and N rate (34, 67, 100 and 134 kg ha$^{-1}$). All sites received 45 kg ha$^{-1}$ of pre-plant N except for treatment 14, Lake Carl Blackwell, OK 2015-2016.

| **Treatment** | **Application Depth, cm** | **Midseason N Rate, kg ha$^{-1}$** | **NDVI, Feekes 7** | **Grain N Content, %** | **Grain Yield, Mg ha$^{-1}$** |
|---|---|---|---|---|---|
| **1** | N/A | 0 | 0.59$^{BA}$ | 1.66$^{BEDC}$ | 2.31$^{B}$ |
| **2** | 0 | 34 | 0.69$^{BA}$ | 1.61$^{EDC}$ | 2.98$^{BA}$ |
| **3** | 5 | 34 | 0.62$^{BA}$ | 1.63$^{EDC}$ | 3.23$^{BA}$ |
| **4** | 10 | 34 | 0.64$^{BA}$ | 1.58$^{ED}$ | 3.33$^{BA}$ |
| **5** | 0 | 67 | 0.65$^{BA}$ | 1.45$^{ED}$ | 4.16$^{A}$ |
| **6** | 5 | 67 | 0.61$^{BA}$ | 1.69$^{BEDC}$ | 3.05$^{BA}$ |
| **7** | 10 | 67 | 0.64$^{BA}$ | 1.71$^{BEDC}$ | 3.73$^{BA}$ |
| **8** | 0 | 100 | 0.67$^{BA}$ | 1.81$^{BDC}$ | 2.83$^{BA}$ |
| **9** | 5 | 100 | 0.67$^{BA}$ | 1.80$^{BDC}$ | 4.18$^{A}$ |
| **10** | 10 | 100 | 0.71$^{A}$ | 1.96$^{BAC}$ | 2.84$^{BA}$ |
| **11** | 0 | 134 | 0.65$^{BA}$ | 1.40$^{E}$ | 3.15$^{BA}$ |
| **12** | 5 | 134 | 0.73$^{A}$ | 2.29$^{A}$ | 2.69$^{B}$ |
| **13** | 10 | 134 | 0.70$^{BA}$ | 2.00$^{BA}$ | 3.27$^{BA}$ |
| **14** | N/A | 0 | 0.55$^{B}$ | 1.67$^{BEDC}$ | 2.36$^{B}$ |
| **MSE** | | | 0.009 | 0.048 | 0.743 |
| **SED** | | | 0.077 | 0.179 | 0.703 |
| **CV** | | | 14.40 | 12.67 | 27.35 |

SED – Standard error of the difference between two equally replicated means, CV – coefficient of variation, %, MSE – mean square error from analysis of variance. Means followed by the same letter were not significantly different at the 5% probability level.

**Table 9.** Treatment differences from non-orthogonal contrasts, winter wheat N study under conventional tillage, Lake Carl Blackwell, OK, 2015-2016.

| **Non-orthogonal contrast** | **Grain Yield** | **Grain N Content** | **NDVI, Feekes 7** |
|---|---|---|---|
| Depth 0 vs 5 cm | NS | ** | NS |
| Depth 0 vs 10 cm | NS | * | NS |
| Depth 5 vs 10 cm | NS | NS | NS |
| Midseason N 34 vs 67 | NS | NS | NS |
| Midseason N 34 vs 101 | NS | * | NS |
| Midseason N 34 vs 134 | NS | ** | NS |
| Midseason N 67 vs 101 | NS | * | NS |
| Midseason N 67 vs 134 | NS | * | NS |
| Midseason N 101 vs 134 | NS | NS | NS |

NS, not significant
@, *, **, significant at the 0.10, 0.05 and 0.01 probability levels, respectively

**Table 10.** Wheat NUE means as influenced by application depth (0, 5 and 10 cm) and midseason N rate (34, 67, 101 and 134 kg $ha^{-1}$). Lake Carl Blackwell, OK, 2015-2016.

| **Treatment, description** | **NUE, %** |
|---|---|
| 1, 45 kg N $ha^{-1}$ preplant N | <0 |
| 2, 34 kg N $ha^{-1}$ at 0 cm | 11 |
| 3, 34 kg N $ha^{-1}$ at 5 cm | 17 |
| 4, 34 kg N $ha^{-1}$ at 10 cm | 17 |
| 5, 67 kg N $ha^{-1}$ at 0 cm | 19 |
| 6, 67 kg N $ha^{-1}$ at 5 cm | 11 |
| 7, 67 kg N $ha^{-1}$ at 10 cm | 22 |
| 8, 101 kg N $ha^{-1}$ at 0 cm | 8 |
| 9, 101 kg N $ha^{-1}$ at 5 cm | 2511 |
| 10, 101 kg N $ha^{-1}$ at 10 cm | 3.0 |
| 11, 134 kg N $ha^{-1}$ at 0 cm | 12 |
| 12, 134 kg N $ha^{-1}$ at 5 cm | 15 |
| 13, 134 kg N $ha^{-1}$ at 10 cm | N/A |
| 14, 0 N check | |

**Table 11.** Treatment structure, NDVI, grain N % and grain yield as influenced by UAN application depth (0, 5 and 10 cm) and N rate (34, 67, 100 and 134 kg $ha^{-1}$). All sites received 45 kg $ha^{-1}$ of pre-plant N except for treatment 14, Perkins, OK 2015-2016.

| Treatment | Application Depth, cm | Midseason N Rate, kg $ha^{-1}$ | NDVI, Feekes 7 | Grain N Content, % | Grain Yield, Mg $ha^{-1}$ |
|---|---|---|---|---|---|
| **1** | N/A | 0 | $0.45^{C}$ | $1.53^{F}$ | $3.54^{E}$ |
| **2** | 0 | 34 | $0.53^{B}$ | $1.61^{FE}$ | $4.24^{ED}$ |
| **3** | 5 | 34 | $0.57^{BA}$ | $1.70^{DE}$ | $4.68^{DC}$ |
| **4** | 10 | 34 | $0.56^{B}$ | $1.68^{FE}$ | $5.02^{BC}$ |
| **5** | 0 | 67 | $0.58^{BA}$ | $1.86^{C}$ | $5.37^{BAC}$ |
| **6** | 5 | 67 | $0.58^{BA}$ | $1.86^{C}$ | $5.34^{BAC}$ |
| **7** | 10 | 67 | $0.56^{B}$ | $1.83^{DC}$ | $5.55^{BA}$ |
| **8** | 0 | 100 | $0.64^{A}$ | $1.88^{C}$ | $5.85^{A}$ |
| **9** | 5 | 100 | $0.59^{BA}$ | $2.08^{BA}$ | $5.43^{BAC}$ |
| **10** | 10 | 100 | $0.59^{BA}$ | $2.03^{B}$ | $5.75^{BA}$ |
| **11** | 0 | 134 | $0.64^{A}$ | $2.02^{B}$ | $5.81^{A}$ |
| **12** | 5 | 134 | $0.60^{BA}$ | $2.19^{A}$ | $5.94^{A}$ |
| **13** | 10 | 134 | $0.64^{A}$ | $2.17^{BA}$ | $5.61^{BA}$ |
| **14** | N/A | 0 | $0.36^{D}$ | $1.61^{FE}$ | $2.58^{F}$ |
| **MSE** | | | 0.002 | 0.008 | 0.216 |
| **SED** | | | 0.037 | 0.071 | 0.380 |
| **CV** | | | 8.05 | 4.66 | 9.20 |

SED – Standard error of the difference between two equally replicated means, CV – coefficient of variation, %, MSE – mean square error from analysis of variance. Means followed by the same letter were not significantly different at the 5% probability level.

**Table 12.** Treatment differences from non-orthogonal contrasts, winter wheat N study under conservation tillage, Perkins, OK, 2015-2016.

| Non-orthogonal contrast | Grain Yield | Grain N Content | NDVI, Feekes 7 |
|---|---|---|---|
| Depth 0 vs 5 cm | NS | ** | NS |
| Depth 0 vs 10 cm | NS | * | NS |
| Depth 5 vs 10 cm | NS | NS | NS |
| Midseason N 34 vs 67 | ** | ** | NS |
| Midseason N 34 vs 101 | ** | ** | * |
| Midseason N 34 vs 134 | ** | ** | ** |
| Midseason N 67 vs 101 | NS | ** | NS |
| Midseason N 67 vs 134 | NS | ** | * |
| Midseason N 101 vs 134 | NS | ** | NS |

NS, not significant

@, *, **, significant at the 0.10, 0.05 and 0.01 probability levels, respectively

**Table 13.** Wheat NUE means as influenced by application depth (0, 5 and 10 cm) and midseason N rate (34, 67, 101 and 134 kg $ha^{-1}$). Perkins, OK, 2015-2016.

| **Treatment, description** | **NUE, %** |
|---|---|
| 1, 45 kg N $ha^{-1}$ preplant N | 28 |
| 2, 34 kg N $ha^{-1}$ at 0 cm | 34 |
| 3, 34 kg N $ha^{-1}$ at 5 cm | 48 |
| 4, 34 kg N $ha^{-1}$ at 10 cm | 54 |
| 5, 67 kg N $ha^{-1}$ at 0 cm | 52 |
| 6, 67 kg N $ha^{-1}$ at 5 cm | 52 |
| 7, 67 kg N $ha^{-1}$ at 10 cm | 54 |
| 8, 101 kg N $ha^{-1}$ at 0 cm | 47 |
| 9, 101 kg N $ha^{-1}$ at 5 cm | 49 |
| 10, 101 kg N $ha^{-1}$ at 10 cm | 52 |
| 11, 134 kg N $ha^{-1}$ at 0 cm | 42 |
| 12, 134 kg N $ha^{-1}$ at 5 cm | 49 |
| 13, 134 kg N $ha^{-1}$ at 10 cm | 45 |
| 14, 0 N check | N/A |

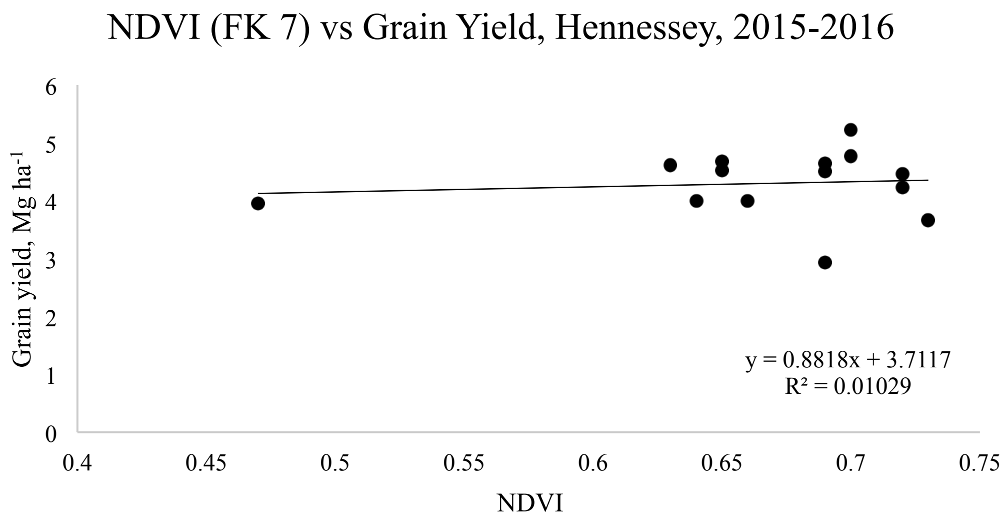


**Figure 1.** NDVI (FK 7) vs wheat grain yield, winter wheat, Hennessey, OK, 2015-2016.

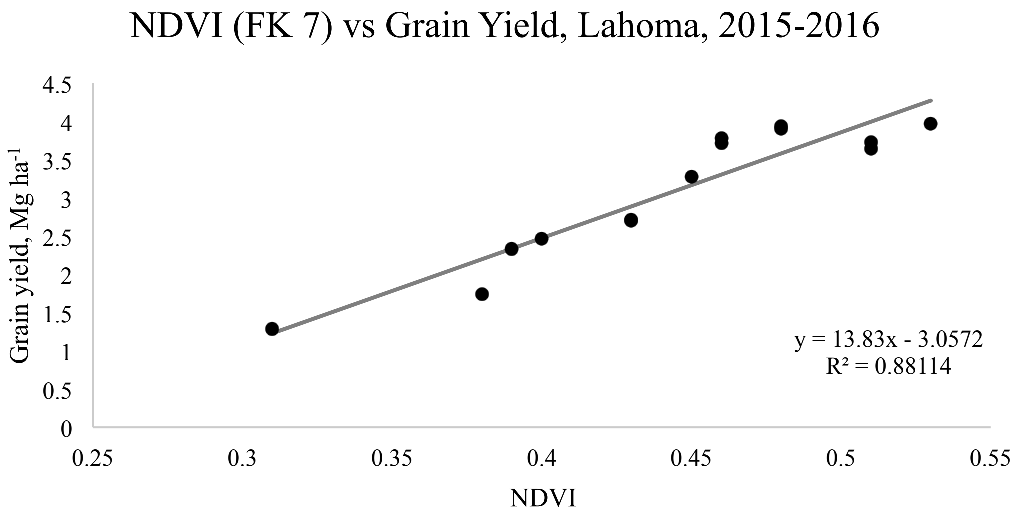


**Figure 2.** NDVI (FK 7) vs winter wheat grain yield, Lahoma, OK, 2015-2016.

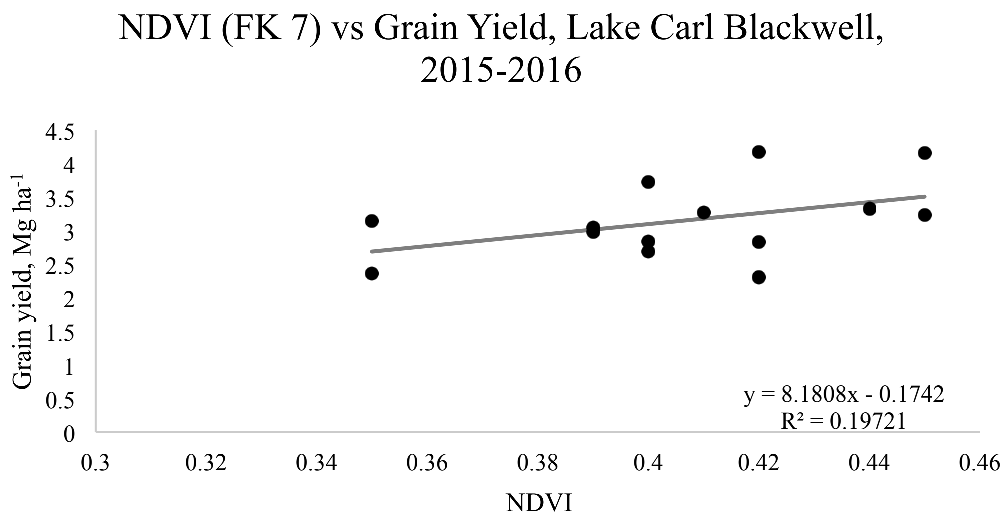


**Figure 3**. NDVI (FK 7) vs winter wheat grain yield, Lake Carl Blackwell, OK, 2015-2016.

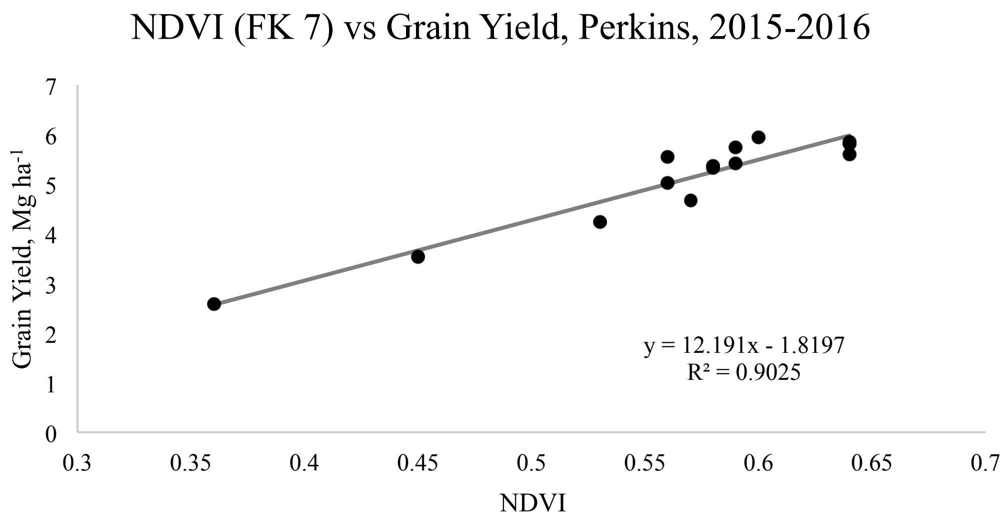


**Figure 4.** NDVI (FK 7) vs winter wheat grain yield, Perkins, OK, 2015-2016.

**Figure 5.** Coulter applicator used for midseason N applications.

VITA

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