EVALUATING METHODS FOR IMPROVING NITROGEN USE EFFICIENCY IN CORN AND HARD RED WINTER WHEAT

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EVALUATING METHODS FOR IMPROVING NITROGEN USE EFFICIENCY IN CORN AND HARD RED WINTER WHEAT

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INFLUENCE OF HYBRID, POPULATION, AND NITROGEN RATE ON SPECTRAL PREDICTION OF CORN GRAIN YIELD

ABSTRACT

With the escalation in environmental concern and cost of production, researchers have recently focused on investigating more efficient means of increasing grain yield while reducing fertilizer use. This study evaluated spectral reflectance, measuring the normalized difference vegetation index (NDVI) with a GreenSeeker™ Hand Held optical reflectance sensor as a function of corn (*Zea mays* L.) hybrid, plant population, and fertilizer N rate. A linear-plateau model existed between NDVI and plant population and the critical population at which NDVI was no longer affected occurred between 55,000 and 60,000 plants ha $^{-1}$ for the later maturing hybrids and closer to 70,000 plants ha $^{-1}$ for the earliest maturing hybrids. Vegetative response index (RI_{NDVI}) peaked between V8 and V9 at responsive locations each year and was highly correlated with RI at harvest ($RI_{HARVEST}$) in 2004. Regression analysis indicated that the V8 growth stage was most effective growth stage to predict grain yield, presumably because the highest variability in NDVI occurs at the V8 growth stage. Hybrid maturity did not effect grain yield prediction at V8, but reproductive growth stage yield prediction will require hybrid maturity categorization. Comparisons made between the GNDVI and RNDVI relationships with grain yield in 2004 showed no significant differences over three locations. However, separate yield prediction models for GNDVI and RNDVI will be required, since GNDVI values are about 10% lower than RNDVI and would underestimate yield potential using the same model.

INTRODUCTION

As environmental concerns continue to escalate and agriculture production becomes more scrutinized, new fertilizer application practices will continue to be researched with the goal of increasing fertilizer use efficiency. Currently, the Environmental Protection Agency (EPA) is reporting that watersheds in all 48 states of the continental U.S. tested for nitrate nitrogen (NO_3^-) groundwater contamination levels above the maximum contaminant level (MCL), of which Oklahoma is ranked 14th (EPA, 1999a). Production of cereal grains has largely been held responsible for this groundwater contamination, in particular corn (*Zea mays* L.) production, where high nitrogen (N) rates have been applied in high yielding environments. However, most of the corn-belt states have lower NO_3^- groundwater levels than surrounding states with minimal corn acreage. Excessive N applications to cereal grain crops continue to pollute the environment, increasing human health risk and costing farmers needless additional expense along with negative publicity. This exemplifies the need for continued research to improve fertilizer use efficiency. As a function of increasing nitrogen use efficiency (NUE) research, this study was conducted to evaluate the potential of using a spectral reflectance normalized difference vegetation index (NDVI) to determine N response and predict grain yield in corn. The effects of corn hybrid, plant population, and fertilizer N rate on NDVI were also evaluated to establish what adaptations might be necessary to use NDVI over a wide range of field conditions.

LITERATURE REVIEW

Nitrogen contamination of ground water has been linked to ill effects in humans. Short-term exposure to nitrate (NO_3^-) through ingestion can cause a serious illness in infants due to the conversion of NO_3^- to nitrite (NO_2^-) by the body, which can interfere with the oxygen-carrying capacity of the child's blood (EPA, 1999b). Most cases of infant methemoglobinemia (blue baby syndrome) are associated with exposure to NO_3^- in drinking water used to prepare infants' formula at levels >20 mg/L of nitrate-nitrogen (Bosch et al., 1950; Walton, 1951). With symptoms including shortness of breath and blueness of the skin, this can be an acute condition in which health deteriorates rapidly over a period of days (EPA, 1999b). Lifetime exposure at levels above the maximum contaminant level (MCL) of 10 mg L^{-1} nitrate-N results in: diuresis, increased starchy deposits, and hemorrhaging of the spleen (EPA, 1999b). Shallow groundwater unaffected by human activities usually contains less than 2 mg L^{-1} of nitrate-N (Mueller and Helsel, 1996).

Although N contamination of drinking water has the most direct impact on human health, N runoff from watersheds has had the greatest impact on the environment. Hypoxia and anoxia has severely stressed every major estuary and coastal marine ecosystem around the world to the point of threshold of change or collapse resulting in loss of fisheries, loss of biodiversity, and alteration of food webs (Diaz, 2001). While hypoxia (the condition of low dissolved oxygen, below 2 mg O_2 L^{-1}) and anoxia (complete absence of oxygen) have existed throughout geological time, their appearance in shallow coastal and estuary areas has been increasing, largely credited to the increase in eutrophication (Diaz, 2001). Excess nutrient loading has been linked to eutrophication, the production of excess organic matter (Nixon, 1995; Howarth et al., 1996). Howarth et al. (1996) concluded that the distribution of hypoxic zones around the world were clearly associated with developed watersheds or coastal population centers that deliver large quantities of nutrients, most notable being N, universally accepted as a major component of organic matter. Goolsby et al. (2001) reported that the annual total N flux to the Gulf of Mexico for 1980-1996 was 1,568,000 t yr^{-1}, which approximately tripled in the last 30 years, particularly increasing between 1970 and 1983. They went further to say that during wet years the N flux can increase as much as 50% due to flushing of NO_3^- accumulated in the soils, predominantly in southern Minnesota, Iowa, Illinois, Indiana, and Ohio (the Corn Belt), where the basins yield 1500 to more than 3100 kg N km^{-2} yr^{-1} to streams, several times the N yield outside of this region.

Raun and Johnson (1999) reported worldwide NUE estimates to be approximately 33%, with developing countries estimated at 29% and developed countries at 42%. As a result, N fertilizer losses were valued at about $15.9 billion dollars annually, which as of August of 2001 has increased to $20 billion dollars annually with the price of N fertilizer nearly doubling due to the shortages of natural gas (Raun et al., 2002). There are several paths in which N can be lost in the N cycle, dependent heavily on the crop and environmental conditions surrounding it. In corn for instance, the majority of the N lost has been attributed to the plant itself via ammonia (NH_3) loss through the leaves, ranging between 52 to 73% (Francis et al., 1993) as compared to wheat (*Triticum aestivum* L.), which typically loses only about 21% through the plant (Harper et al., 1987). Hilton et al. (1994) evaluated losses in corn from 10% in conventional tillage to 22% in no-till due to denitrification, which occurs in cool, wet soil environments that are typical of that in early spring of the major corn producing regions of the United States. Surface runoff losses have been reported to range from 1 to 13% depending on tillage system and application rate and method (Blevins et al., 1996; Chichester and Richardson, 1992). Drury et al. (1996) measured N losses up to 23 % of a 113 kg N ha^{-1} rate applied to their plots due to tile drainage, considerably lower for that region, and insinuated that even higher levels of N could be lost in the higher applications characteristic of that area.

Owens et al. (2000) and Kanwar et al. (1997) reported that using crop rotation with legume crops reduced nitrate leaching over continuous corn production, by reducing the amount of N needed to be supplied to maintain high yield production. Precipitation use efficiency was higher for corn grown in rotation rather than for continuous corn, leading to potentially increased NUE from higher yielding crops (Varvel, 1994). Wienhold et al. (1995) supported this principle by detecting that increased water use efficiency (WUE) brought forth by supplemental irrigation in semiarid regions increased NUE via greater N requirements of higher yielding crops. Eghball and Maranville (1991) agreed when they reported a positive correlation between WUE and NUE in corn production. Norwood and Currie (1996) reported higher grain yields in dryland corn production under no-till compared to conventional tillage and that no-till is essential for adequate yields in dry years and can still increase yields in more favorable climatic conditions. Furthermore, Eckert and Martin (1994) found that plant population had no influence on N uptake in no-till and that N uptake was directly related to yield in corn stressed by late planting.

Tillage comparisons showed that no-till enhanced N immobilization and reduced nitrification rates when compared to conventional-till (Doran, 1980; Stinner et al., 1983), often resulting in less nitrate leaching (Elliott et al., 1986; Lamb et al., 1985) and leaving less nitrate in the soil profile (Fenster and Peterson, 1979; Dowdell and Cannell, 1975). Although there are lower nitrate levels in soil profiles in no-till systems, studies have shown that nitrate has been found deeper in the profiles of no-till soils (Eck and Jones, 1992) agreeing with the findings of Edwards et al. (1990) that no-till improved soil drainage. This suggests that while no-till has the potential to increase N uptake from the soil, the improved drainage associated with no-till may actually increase N movement lower in the soil profile. Rice and Smith (1982) and Rodriguez and Giambiagi (1995) found that no-till enhances denitrification, because of the increase in soil water supply commonly occurring in no-till, reducing aerobic activity in the soil.

Banding N increased grain yield and grain N uptake as much as 21% in corn over broadcasting preplant N when both systems were followed by the same midseason N applications, suggesting that placement of N close to the seed could reduce the amount of preplant N needed to maintain high yields (Lehrsch et al., 2000). Diez et al. (1994) reduced nitrate leaching under irrigated corn using controlled release N fertilizers to improve NUE. Pan et al. (1984) stated that high-yielding genotypes were unable to absorb NO_3^- during ear development, which limited yields otherwise increased by supplies of ammonium (NH_4). Baker and Timmons (1994) along with Yadav (1997) found that splitting application of N throughout the season improved NUE. Crop rotation, tillage and N application methods have been generally accepted to improve NUE, but none of them have shown the potential of increasing NUE as effectively as in-season grain yield prediction. With accurate grain yield prediction, topdress N rates can be adjusted to maintain the predicted yield and maximize NUE. Raun et al. (2002) increased NUE greater than 15% (> 50% NUE) using an in-season yield prediction algorithm in dryland winter wheat production.

Traditionally, N application rates have been made based on grain yield goals determined from a recent 5-year crop yield average increased typically by 10 to 30% to assure adequate N for above average growing conditions (Johnson, 1991; Dahnke et al., 1988). However, setting unrealistic yield goals and not accounting for yield variation between fields and within a field has led to consistent, excessive N application. As a result, some fields have enough inorganic N in the soil in semi-arid regions to supply adequate N for multiple years of cereal crop production. Dryland winter wheat research has shown that the percent increase in grain yield goal over the 5-year average should be based on the amount of moisture available to the crop either at planting (Rehm & Schmitt, 1989), or the amount of stored soil water available at depths up to 1.5 m in areas where water is limiting (Black & Bauer, 1988).

As split applications of N became more popular, different methods have been used to measure early season fertilizer use, as a means of deciding how much more N fertilizer would be needed to meet the predetermined grain yield goal. Several researchers looked at in-season soil test of NO_3^-N at a depth of 30 cm, known as presidedress NO_3^-N test (PSNT). Research from Vermont showed that use of a PSNT reduced N rates without reducing grain yields in corn by setting a N application limit, with no N sidedress applications needed when the PSNT is above 25 mg kg^{-1} NO_3^-N (Magdoff et al., 1984; Durieux et al., 1995). While the PSNT worked well for the northeastern USA, some adjustments were made to the PSNT for the semi-arid regions under irrigation, particularly reducing the no N application limit to about 15 mg kg^{-1} NO_3^-N (Spellman et al., 1996). The PSNT test was further refined in corn production by Bundy and Andraski (1995), when they reported that classifying soils into two categories medium and high yield potential determined by: depth of root zone, water holding capacity, and length of growing season, when the test values were considered in the N responsive range. While the PSNT improved NUE, it could not produce these results consistently, even when other soil properties were evaluated in tandem with PSNT.

Since early research showed that cereal crops responded to N with favorable yield increases year after year, many scientists believed that plants responded to N the same every year and that environmental conditions only dictated which N sinks in the soil were predominately used and the amount used as effected by plant yield potential. This explains why yield goal has been the basis for N application over the years, even though seasonal environmental conditions are unpredictable. Although this theory is still largely accepted, one problem that has not been thoroughly addressed with this concept until recently is the response of plants to inorganic N fertilizer as reported by Liang and Mackenzie (1994) among others. Instead, many scientist have spent their time trying to determine how environmental conditions influence the N cycle in the soil and which N sinks are used by the plants, whether it is mineralized N from organic sources or readily-available inorganic sources from commercial fertilizer. Currently, the development of an N mineralization potential index has been futile, with the basic rationale that if N mineralization potential could be determined, N recommendations could be refined (Mullen et al., 2003). Further explaining why use of the PSNT is limited, given that the soil test for ammonium and/or nitrate before fertilizer application is accurate, is the fact that soil test information determined at a point in time is static and provides no prediction of mineralization and/or immobilization occurring throughout the growing season (Mullen et al., 2003).

Recent research has been directed towards using the crop to determine N usage and potential deficiencies by either direct plant analysis or indirect measures from optical sensors. Direct plant analysis has been used for some time, but has major drawbacks, some similar to PSNT. With any direct sampling method, laboratory analysis must be processed, which can become expensive with extensive sampling and of course the lag-time between sampling and return of laboratory analysis and fertilizer application (Fox et al., 1993 and Magdoff et al., 1990). With that in mind many scientists have turned to optical sensing instruments, which give real time indirect measurements of plant biomass and leaf chlorophyll concentration.

Chlorophyll meters (SPAD meters) have been successfully used to determine in-season N status, since chlorophyll content has been highly correlated with leaf N concentration (Wolfe et al., 1988; Schepers et al., 1992). With the chlorophyll meters, researchers developed an N Sufficiency index [(as-needed treatment/ well-fertilized treatment) * 100] from which recommendations were made for in-season N fertilizer applications when the index values fell below 95% (Blackmer and Schepers, 1995; Varvel et al., 1997). Varvel et al. (1997) reported that maximum grain yields in corn were attained when early season sufficiency indexes ranged between 90 and 100% up to the V8 growth stage, but if the sufficiency index fell below 90% at V8, maximum yields were not realized due to early season N deficiency resulting in lost yield potential. Peterson et al. (1993) indicated that variation in chlorophyll meter measurements can range up to 15% from plant to plant, requiring considerable measurements in order to maintain a representative average for the field at each sampling date. Nevertheless, the chlorophyll meter was not a viable tool for guiding N side-dress decisions for corn in the Southern Coastal Plain, undoubtedly because there was no variable-rate application determination in the sufficiency index used, either apply or don’t apply (Gascho and Lee, 2002). Another drawback of the chlorophyll meter is that by reading one leaf at a time, plant biomass cannot be determined as with the remote sensor.

Using a photodiode-based remote sensor measuring canopy radiance in the red (671nm) and near-infrared (NIR, 780nm) spectral bands, Stone et al. (1996) developed a plant N spectral index (PNSI) for correcting in-season wheat N deficiencies. This index, the absolute value of the inverse of the normalized difference vegetation index (NDVI), saved between 32 and 57 kg N ha $^{-1}$ compared to fixed N rates. Bausch and Duke (1996) developed an N Reflectance Index (NRI), using a canopy reflectance ratio of NIR (760-900nm)/ green (520-600nm) for the low N area to the NIR/ green for a well N-fertilized area, a very similar procedure to the sufficiency index differing only in how the measurement is taken. Johnson et al. (2000) presented an N response index ($RI_{Harvest}$) to calculate the actual crop response to applied N by dividing the highest mean yield N treatment by the mean yield check treatment. However, $RI_{Harvest}$ only explains the final yield response to fertilizer N, so an in-season RI estimate must be made in order for in-season N adjustment. Recent work has shown that in-season normalized difference vegetation index {NDVI = $[(NIR_{ref}/NIR_{inc}) – (Red_{ref}/Red_{inc})]/[(NIR_{ref}/NIR_{inc}) + (Red_{ref}/Red_{inc})]$} highly correlated with final grain N uptake (Lukina et al., 2001; Raun et al., 2002). Therefore, an in-season RI from NDVI, referred to as RI_{NDVI} (Highest mean NDVI N treatment/ Mean NDVI check treatment), was evaluated and determined to be a viable method for measuring the potential response to additional N (Mullen et al., 2003).

As mentioned above, one major drawback of the RI was that it only measured response to N and not how much N would be needed to sustain any deficiencies. Therefore, Raun et al. (2002) refined an in-season estimated grain yield (INSEY) equation by incorporating the RI_{NDVI}. They multiplied predicted yield potential times the RI_{NDVI} to obtain predicted yield with N fertilizer. They then worked backwards to determine N rate by subtracting estimated grain N removal in the unfertilized from the projected N uptake in the fertilized plot. This effectively improved NUE by over 15% when variable N rate topdress application was compared to traditional practices at uniform N rates in winter wheat. GopalaPillai and Tian (1999) reported that by using linear regression models on normalized intensity (NI) of a high-resolution color infrared (CIR) field image, they were able to predict grain yield with 55 to 91% accuracy, depending on the field and growing season. However, their work conceded that better correlation with yield was obtained when using CIR images taken after pollination, then those from earlier in the season, similar to the findings of work from Bartholome (1988) evaluating better correlation to grain yield with accumulated NDVI after booting in millet (*Panicum miliaceum* L.) and grain sorghum (*Sorghum bicolor* L.). With the goal of improving correlation of NDVI to grain yield, Rasmussen (1998) integrated the product of multitemporal NDVI with photosynthetically active radiation, but was not successful since no single regression line was valid for consecutive years. Other yield prediction models have been developed for corn, although they do not use in-season plant health evaluations as part of the equation. The crop environment resource synthesis (CERES)-Maize model simulates the major physiological processes, soil water movement processes, and N transformation and transport processes involved in plant growth and has been studied a great deal and has been determined to simulate grain N uptake (Pang et al., 1997). The artificial neural network (ANN) model was successful in predicting grain yield, designed to evaluate the following three aspects of 15 input factors: (1) yield trends with temperature, rainfall, soil texture, and soil pH, (2) interaction between N application and late July rainfall, and (3) optimization of the input factors with a genetic algorithm (Liu et al., 2001). However, both models use extensive evaluation of multiple factors to predict final grain yield by full season simulation, but were not accurate for mid-season grain prediction.

OBJECTIVE

This study was conducted to evaluate the influence of various corn hybrids, plant populations, and fertilizer N rates on the use of midseason NDVI measurements for predicting grain yield.

MATERIALS AND METHODS

Crop years 2002 and 2003

Two experimental sites were established in the spring of 2002, one near Stillwater, OK at the Lake Carl Blackwell Agronomy Research Farm (Pulaski fine sandy loam, course-loamy, mixed, nonacid, thermic Typic Ustifluvent), and one near Haskell, OK at the Eastern Oklahoma Research Station (Taloka silt loam fine, mixed, thermic Mollic Albaqiustoll). Initial soil test results are reported in Table 1. The experiment employed a factorial arrangement within a randomized complete block design with three replications. Individual plots measured 3.0 x 9.14 m. Ammonium nitrate (34-0-0) was surface-broadcasted by hand preplant at rates of 0, 56, and 112 kg N ha^{-1}.

Three _Bacillus_ _thuringiensis_ (bt) gene enhanced corn hybrids identified by their maturity date (105-day, 109-day, and 113-day) were planted at both sites in 2002, but three different hybrids with no bt gene enhancement (104-day, 107-day, 111-day) were planted at both sites in 2003 (planting, fertilizer, and harvest dates are reported on Table 2). Two different seeding rates were evaluated at both sites: at the Haskell site seeding rates of 44,460 (low) and 66,690 seeds ha^{-1} (high) in 2002 and 49,400 (low) and 71,630 seeds ha^{-1} (high) in 2003 and at the Lake Carl Blackwell (LCB) site seeding rates of 35,568 (low) and 51,870 seeds ha^{-1} (high). All site years were planted in 76.2 cm rows with conventional tillage. Each corn plot was sensed with a GreenSeeker™ Hand Held optical reflectance sensor (Ntech Industries, Ukiah, CA), measuring normalized difference vegetation index (NDVI) at different vegetative and reproductive growth stages at both sites each year (sensing dates and growth stages with description presented in Table 3) with the sensor nadir to the ground and approximately 70 cm above the crop canopy. Corn grain was harvested with a Massey Ferguson 8XP experimental combine, removing 2 rows x 9.14 m from the center of each plot. A Harvest Master yield-monitoring computer installed on the combine was used to record grain weight and moisture levels. Grain yield from each plot was determined by adjusting grain weight to 15.5% moisture and a grain sub-sample was taken for total N analysis.

Crop year 2004

In the spring of 2004 the experiment was reconfigured with the addition of a third site on the Greenlee Farm near Morris, OK (Taloka silt loam fine, mixed, thermic Mollic Albaqiustoll) and the relocation of the Haskell trial to an adjacent field at the same location with the same soil description. Furthermore, plant populations were increased from two populations to four and corn hybrids were reduced from three hybrids to two. Initial soil test results are also reported in Table 1. At the Greenlee Farm a P deficiency was corrected by [1]surface-boardcasting triple super phosphate (0-46-0) 45 kg P_2O_5 ha^{-1} at planting. Individual plot size was reduced to 3.0 x 6.10 m with the purpose of sustaining manageable labor requirements for the increased treatment size. In addition, ammonium nitrate (34-0-0) application rates were increased to 84 and 168 kg N ha^{-1} to assure N would not be a limiting factor in high N application treatments.

Two _Bacillus_ _thuringiensis_ (bt) gene enhanced corn hybrids identified by their maturity date (99-day and 113-day) were planted at all three sites (planting, fertilizer, and harvest dates are reported on Table 2). Four different seeding rates were evaluated at all three sites: 37050, 51870, 66690, and 81510 seeds ha^{-1}. The Haskell and Lake Carl Blackwell sites were planted in conventional tillage whereas the Greenlee Farm was planted in no-till, but all three sites were planted in 76.2 cm rows. With the availability of a green NDVI sensor, both GNDVI $\{GNDVI = [(NIR_{ref}/NIR_{inc}) – (Green_{ref}/Green_{inc})] / [(NIR_{ref}/NIR_{inc}) + (Green_{ref}/Green_{inc})]\}$ and RNDVI $\{RNDVI = [(NIR_{ref}/NIR_{inc}) – (Red_{ref}/Red_{inc})] / [(NIR_{ref}/NIR_{inc}) + (Red_{ref}/Red_{inc})]\}$ was measured at different vegetative and reproductive growth stages at all sites (sensing dates and growth stages presented in Table 3) with a GreenSeeker™ Hand Held optical reflectance sensor (Ntech Industries, Ukiah, CA). The center two rows of each corn plot were sensed separately with the sensor nadir to the ground and approximately 70 cm above the crop canopy. Corn grain was harvested (picked and shucked) by hand from the center two rows of each plot separately and ear weights were recorded for each row. Four random ears from each row were collectively weighed, dried in a forced air oven at 66^{o}C, and weighed again to determine moisture levels. Following the measurement of dry weights, the four ears were shelled by hand using a Root-Healey Manufacturing Company (Plymouth, OH) hand-crank corn sheller and the grain weight was taken to determine an average cob weight for each row. Finally, a grain yield from each row was calculated by adjusting grain weight to 15.5% moisture and a grain sub-sample was taken for total N analysis.

Data analysis

Grain samples were dried in a forced air oven at 66^{o}C, ground to pass a 140 mesh sieve (100 um), and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer (Schepers et al., 1989). Nitrogen use efficiency was determined using the difference method: dividing the difference between the grain N uptake of the N treatment and the grain N uptake of the check (0 N rate) by the N rate of the N treatment. Vegetative or In-season RI (RI_{NDVI}) was calculated dividing the highest mean NDVI N treatment by the mean NDVI check treatment. Grain or Harvest RI ($RI_{HARVEST}$) was calculated dividing the highest N treated grain yield average by the check average. Analyses of variance and single degree of freedom contrasts were performed using SAS (SAS, 1990). Linear and non-linear (linear-plateau) regression models were used to determined the relationships present between grain yield and NDVI as well as between NDVI and the treatment variables.

RESULTS AND DISCUSION

Hybrid and Plant Population

Crop Year 2002

In the initial year, RNDVI was measured twice at both locations. The first reading at Haskell was taken at the 10-leaf (V10) growth stage (Table 3). The109-day hybrid had significantly lower RNDVI than the 105-day and 113-day hybrids. Plant population influenced RNDVI for the 109-day and 113-day hybrids with extensively higher RNDVI values in the higher plant population (Figure 1). However, at the second Haskell sensing (R1 growth stage, Table 3), the 105-day hybrid had significantly higher RNDVI values than both the 109-day and 113-day hybrids. Furthermore, plant population only influenced RNDVI in the 109-day hybrid at the second Haskell sensing, resulting in higher RNDVI values. Although plant biomass increased considerably between the first (V10) and second (R1) sensor readings, RNDVI values decreased extensively due to tassel development (Figure 1). The lighter color of the tassel decreased red light absorbance in the crop canopy. Therefore, separate grain yield prediction curves will be needed for the vegetative and reproductive growth stages. In addition, the 105-day hybrid, as a typical earlier maturing hybrid, was considerably smaller than the other two hybrids at the second RNDVI reading which may have led to the higher RNDVI values even though it did not produce the highest grain yield (Table 4).

The sensor measurements at LCB were taken at 7-leaf (V7) and silking (R1) growth stages (Table 3). The 109-day hybrid was consistently higher in RNDVI than the other two hybrids at both LCB sensor measurements followed by the113-day hybrid and then the 105-day which coincided with visual height observations. Plant population increased RNDVI in all three hybrids at the first sensing, with no effect on RNDVI at the second reading. Since the LCB site typically receives lower summer precipitation than Haskell, the site was considered to support lower grain yields and therefore lower plant populations were used. The LCB site resulted in considerably lower grain yields (Table 4) as well as lower RNDVI values. However the RNDVI trends differed from Haskell in that plant population did not affect RNDVI measured at the R1 growth stage at LCB, which may be attributed to apparent severe drought stress as revealed by the exceedingly low grain yields (Table 4).

Crop Year 2003

At the Haskell site nine sensor readings were taken, starting at the 6-leaf (V6) growth stage and ending at the dough (R4) growth stage (Table 3). Significant differences between the hybrids in RNDVI did not occur until the 8-leaf (V8) sensing, where the 104-day hybrid had greater RNDVI values over both the 107-day and 111-day hybrids and the 107-day hybrid had higher RNDVI values over the 111-day hybrid. The high plant population was significantly greater in RNDVI for all three hybrids at the first three sensor readings: V6, V7, and V8 (Figure 2). However, no differences were found at V10 between the 104-day and 107-day hybrids or within the plant populations and/or N rates of either hybrid. Also, no treatment differences were seen either between any of the hybrids or within the plant populations and/or N rates of any hybrid at the 16-leaf (V16) growth stage. Although significant treatment effects were visually present between V10 and V16 growth stages in all three hybrids, the effects could not be measured effectively at those stages due to complete absorbance in the red band that occurred (Figure 2). The 111-day hybrid had higher RNDVI values than both the 104-day and 107-day hybrids during the silking (R1) and dough (R4) reproductive growth stages and higher RNDVI values than the 107-day hybrid at the blister (R2) reproductive growth stage. The 104-day hybrid had significantly greater RNDVI values than did the 107-day hybrid at R2. The high plant population actually decreased RNDVI values in the 104-day hybrid at the R1, milk (R3), and R4 reproductive growth stages as well as the R4 sensing of the 107-day hybrid. However, the higher plant population increased RNDVI in the 111-day hybrid at the R1 and R2 growth stages. While the 111-day hybrid may have obtained significantly higher RNDVI values than either of the other two hybrids during the reproductive growth stages, it is conceivable that this event took place because of the maturity differences between the hybrids (as the hybrid matures RNDVI decreased due to hastened lower leaf senescence (Figure 2), since the 104-day and 107-day hybrids produced significantly higher grain yields (Table 5).

At the LCB site seven sensor readings were taken, starting at the V6 growth stage and ending at the R2 growth stage (Table 3). The 107-day hybrid was significantly lower in RNDVI than the 111-day hybrid throughout all sensor

(V6-R2) readings, but no statistical differences were observed between the 104-day and 107-day hybrids except at R2 when the 104-day hybrid showed higher RNDVI values (data not shown). The high plant population increased the RNDVI values of all three hybrids at all sensor (V6-R2) readings (data not shown). The red complete absorbance effect was not observed at LCB and consequently the decease in RNDVI did not occur at tassel development, but this was essentially due to the lower plant populations used. Plant stands were measured mid-season to further investigate the influence of plant population on RNDVI. The V8 and R2 sensor data revealed that a linear-plateau relationship existed between measured plant population and RNDVI for all three hybrids when combining both sites and excluding measurements from the 0 N treatments (Figures 3 & 4). The 0 N treatments typically had increased spatial variability most likely due to inadequate N resources, resulting in high variability in RNDVI that overshadowed the variability associated with plant population. Therefore plant population can influence RNDVI values at various growth stages, but as depicted in Figure 2 this influence can be either positive (increased RNDVI) or negative (decreased RNDVI).

Crop Year 2004

The 113-day hybrid was consistently higher than the 99-day hybrid in both green NDVI (GNDVI) and RNDVI at all locations after the V7 growth stage, which was consistant with grain yield. Grain yields were high in 2004 with the unusual timely rainfall throughout the growing season; as a result the later maturing 113-day hybrid was significantly higher in grain yield than the 99-day hybrid at all three locations (Table 6). A positive linear response to plant population in both GNDVI and RNDVI occurred for both hybrids at all nine (V5-R4) dates of sensing readings over all three sites (Figures 5 & 6). The quadratic response to plant population was variable between locations, hybrids, and NDVI bands, however linear plateau relationships were seen for both hybrids at the V8 growth stage (Figures 7 & 8). Similar effects were seen in grain yield with quadratic responses to plant population as well (Table 6). As a result the maximum effective plant population for grain yield was 66,690 plants ha^{-1} for the 113-day hybrid at all three locations and the 99-day hybrid at the Greenlee Farm and Haskell locations. However, the 99-day hybrid at the LCB site showed that the 81,510 plants ha^{-1} population produced the highest grain yield. Significant factors were site, hybrid, and band specific, indicating that the influence of plant population on both GNDVI and RNDVI is dependant upon environmental conditions.

Nitrogen Response

Crop Year 2002

At Haskell a positive linear response to N was seen for RNDVI in the 113-day hybrid at the V10 reading (Figure 9), but N response was limited in the other hybrids. While visual differences were observed in the trial at the R1 reading, no significant trends were determined from RNDVI measurements (Figure 9). However there was no linear response to N in grain yield for any of the three hybrids at either plant population (Table 4). Since there was no response to N at Haskell, poor NUE resulted with a slightly significant advantage for the 109-day hybrid over the 113-day (Table 7). A positive linear response to N was observed at LCB for the high plant population of the 109-day and 113-day hybrids at the first (V7) sensing (as shown by the 113-day hybrid in Figure 9). At the second (R1) LCB reading, a positive linear response was observed for the high plant populations of all three hybrids and for the low population of the 105-day hybrid (as shown by the 113-day hybrid in Figure 9). In grain yield a positive linear response to N was observed at LCB for the 105-day and the 113-day hybrids at the low plant population and for all three hybrids at the high population (Table 4). There were no significant differences found in NUE between the hybrids at LCB (Table 7).

In-season RI (RI_{RNDVI}) was determined (highest mean RNDVI N treatment/ mean RNDVI check treatment) at both sensor readings and compared to final grain yield response ($RI_{Harvest}$). In-season RI data from the first sensor reading indicated that growth stage was important in estimating $RI_{Harvest}$ (Figure 10). The Haskell data shows that $RI_{Harvest}$ was predicted well by the RI_{RNDVI} taken at V10 with little to no change in RI_{RNDVI} taken at R1, but the data also shows that a small N response was seen at Haskell as mentioned previously. The LCB RI_{RNDVI} taken at V7 underestimated $RI_{Harvest}$ for all three hybrids (Figure 10). However, LCB RI_{RNDVI} taken at R1 did not predict $RI_{Harvest}$ effectively (data not shown).

Crop Year 2003

A positive linear RNDVI response to N occurred at Haskell in both plant populations of all three hybrids at the V6, V7, and V8 sensor readings (as indicated in Figure 11) and for both plant populations of the 111-day hybrid at the

10-leaf (V10) sensing. As mentioned beforehand canopy closure occurred between V10 and V16 at Haskell resulting in complete red absorbance and the inability to distinguish visually observable N deficiencies (Figure 11). Furthermore negative linear NDVI responses to N were evaluated in the reproductive growth stages, particularly after the R1 growth stage, for both plant populations of all three hybrids at Haskell. Generally, if complete red absorbance is observed an inverse occurs in the treatment effect on NDVI values due to tassel development. At tassel development NDVI values decline as stated earlier (Figure 11), however the NDVI values of the lower fertility treatments decline less since tassel development is seemingly associated with plant health. At LCB a positive linear NDVI response to N occurred in the low plant population of the 107-day hybrid for all sensor (V6-R2) readings, but no N response was observed in the 104-day and 111-day hybrids or in the high plant population of the 107-day hybrid (data not shown). Nitrogen response in grain yield was merely observed for the 104-day hybrid in both plant populations at Haskell and no N response was seen at LCB resulting in poor NUE (Table 8). At Haskell there was a significant advantage for the 104-day hybrid over both the 107-day and 111-day in NUE, while at LCB the 107-day hybrid was significantly higher in NUE over both the 104-day and the 111-day hybrids (Table 8). At the LCB site, the higher plant populations required more N than the residual N could provide. However, the greater plant biomass produced needed more soil moisture than available during grain fill to maintain grain yield, therefore the lower plant population produced greater grain yields since there was less competition for moisture.

In-season RI was determined at all sensing dates and compared to final grain yield response ($RI_{Harvest}$). The V8 sensor data produced the highest RI_{RNDVI} values and were therefore compared to the $RI_{Harvest}$ data (Figure 12). The Haskell data shows that V8 RI_{RNDVI} overestimated $RI_{Harvest}$, but the LCB V8 RI_{RNDVI} generally predicted $RI_{Harvest}$ well (Figure 12). Similar to the 2002 Haskell RI data, the LCB V8 RI_{RNDVI} showed a small response to N and therefore a better relationship with $RI_{Harvest}$ than the 2003 Haskell data. As alluded to above and concluded in previous research, mid-season N response may not result in higher grain yield if environmental stress is great during grain fill and an associated overestimates of $RI_{Harvest}$.

Crop Year 2004

A highly significant interaction for NDVI between plant population and N rate occurred in 2004 at all three locations. Positive linear GNDVI responses to N at the Greenlee Farm were sporadic within the hybrids and growth stages, particularly at the lower plant populations (37,050 & 51,870 plants ha^{-1}). Conversely, positive linear RNDVI responses to N at the Greenlee Farm were a little more rational with mid-season (V8, V9, V12-VT) N responses in all plant populations but the lowest (37,050 plants ha^{-1}) of the 99-day hybrid and the lowest and highest (81,510 plants ha^{-1}) populations of the 113-day hybrid. Similar results were noted in grain yield at the Greenlee Farm with the 99-day hybrid showing no response to N at the lowest plant population; nevertheless a quadratic response was noted at the 51,870 population and a positive linear response at the 66,690 and 81,510 populations (Table 6). On the contrary, the

113-day hybrid at the Greenlee Farm showed a positive linear response to N at the 66,690 population and a quadratic response at the 81,510 population, but no N response was seen in the two lower populations (Table 6). Nitrogen response was potentially underestimated for the 66,690 population and overestimated in the 37,050 population in the 113-day hybrid.

At Haskell positive linear GNDVI and RNDVI responses to N were observed for both hybrids in all plant populations during mid (V6-V9) and late (R4-R5) season sensor readings, but not at V11 or R1 growth stages except for in the low plant populations due to canopy closure (Figures 13 & 14). The Haskell site showed a large grain yield response to N by means of a positive linear response at the 37,050 population and a positive quadratic response at the 51,870, 66,690, and 81,510 populations (Table 6). Positive linear GNDVI responses to N observed at LCB were inconsistent within the 113-day hybrid with sporadic responses occurring in the 37,050 and 66,690 plant populations and consistent responses occurring in the 51,870 and 81,510 plant populations between V7 and R4 growth stages except for V12-VT in the 81,510 population. Positive linear GNDVI responses to N in the 99-day hybrid were not seen for the 37,050 population the entire season or the other plant populations until the reproductive growth stages. Similar positive linear RNDVI responses to N results were seen for the 113-day hybrid with responses to the 51,870 and 81,510 plant populations between V7 and R4 growth stages except for V12-VT in the 81,510 population. However the 51,870 population of the 99-day hybrid shown mid-season positive linear RNDVI responses to N as well, otherwise the 99-day hybrid along with the 37,050 and 66,690 plant populations of the 113-day hybrid N responses were not evaluated until the reproductive stages. At the LCB site, an N response in grain yield was noticed only for the highest plant population (81,510 plants ha^{-1}) with a positive linear response in the 113-day hybrid and a positive quadratic response in the 99-day hybrid (Table 6).

At the Haskell site NUE was significantly higher for the 113-day hybrid over the 99-day, but at the Greenlee Farm and LCB there was no difference between the hybrids (Table 9). At all sites the highest plant populations required the most additional N in 2004 (a positive linear response in plant population to NUE) since more competition from plant biomass production requires more N wither or not this increased plant biomass portrays greater grain yield per unit area. Following the same procedure as in 2003, in-season RI was determined at all sensor readings and compared to $RI_{Harvest}$. As seen in 2003 the V8 data produced the highest RI_{GNDVI} (from GNDVI) and RI_{RNDVI} (from RNDVI) values and was compared to the $RI_{Harvest}$ (Figures 15 & 16). Similar trends were seen in the high linear relationships between RI_{GNDVI} and $RI_{Harvest}$ and between RI_{RNDVI} and $RI_{Harvest}$. Both in-season RI's (green and red) consistently underestimated $RI_{Harvest}$ in both hybrids at all three locations. While the coefficients of determination (R^2) of the two relationships were identical, the slope was higher in the RI_{GNDVI} relationship with $RI_{Harvest}$ than that of the RI_{RNDVI}, indicating that the RNDVI estimated $RI_{Harvest}$ better than GNDVI by underestimating $RI_{Harvest}$ to a smaller extent (Figures 15 & 16). The extent of the underestimation may be attributed to the high grain yields observed in 2004. Nitrogen response increased beyond the V8 growth stage and was maintained throughout grain fill as a result of moderate air temperatures and timely rainfall and since detection of treatment differences declines with canopy closure the increased N response was not recognized by later sensor readings.

Grain Yield Prediction

Crop Year 2002

Linear regression was evaluated between grain yield and RNDVI measurements and between grain yield in 2002 (Figure 17). Although the sensor measurements may have some inaccuracy due to not maintaining proper height above the crop canopy (i.e. holding the sensor too close to the canopy) some very pronounced relationships were found. While comparisons between grain yield and RNDVI at early growth stages (V7 at LCB, V10 at Haskell) resulted in poor relationships at both sites (data not shown), comparisons made at the later reading (R1 growth stage) showed a very good relationship existed between grain yield and RNDVI (Figure 17). This suggests that late-season (reproductive stage) sensor readings could predict grain yield effectively. Furthermore, separating the hybrids improved the relationship between grain yield and RNDVI, but not significantly since the combined hybrid model already had a very pronounced relationship. The R1 sensor readings may have been more effective since tassel development was observed to be profoundly affected by plant health and therefore narrowing the sensing field of view by holding the sensor too close to the crop canopy would not greatly affect the RNDVI measurement from a plant health prospective. Where as at earlier growth stages before tassel development, RNDVI measurements would need to measure plant biomass which potentially could not be done effectively if the sensor is held too close to the crop canopy, resulting in less variability between treatments and inflated RNDVI readings. In addition, a very profound negative linear relationship was also found between grain yield and CV (RCV) derived from RNDVI (RCV= RNDVI standard deviation / RNDVI mean) at the R1 sensor reading; however a comparison between RNDVI and RCV showed a very pronounced negative linear relationship (Figure 18). The RNDVI relationship with grain yield showed a slight (insignificant) advantage over RCV with grain yield and as a result of the high relationship between RNDVI and RCV no benefit would be anticipated by combining both RNDVI and RCV to predict grain yield. Therefore mid-season RNDVI can be utilized very effectively to predict grain yield.

Crop Year 2003

Linear regression analysis revealed that the best relationship between grain yield and RNDVI over three hybrids occurred at the V8 growth stage in 2003 (Figure 19). These data indicate that early season grain yield prediction is achievable and therefore side-dress N application based on grain yield prediction is practical. Although lower than the V8 relationship, the R2 growth stage comparison between grain yield and RNDVI also showed a well-defined relationship supporting the 2002 results that late season yield prediction is possible though not practical for side-dress N application (Figure 20). However, a closer look at the R2 model (Figure 20) showed that each hybrid has a separate linear relationship with grain yield corresponding to 2002 results. While the combined model explains a considerable amount of variation, the model was improved significantly to that of the V8 data when the hybrids were fitted with separate curves (data not shown). Separating out the hybrids in the early season model did not improve the relationship with grain yield, confirming that while significant differences in NDVI occurred between the hybrids at V8 these differences existed in grain yield as well. Consistent with 2002 data, RCV related with grain yield very similarly to that of RNDVI at both growth stages (V8 & R2) and like 2002 RNDVI was highly related with RCV (Figures 21 & 22). Therefore, using RCV in grain yield prediction either combined with RNDVI or separately had no benefit in 2003 as well. Mid-season grain yield prediction can be achieved not only in the reproductive stages as supported by the 2002 data, but also in earlier vegetative growth stages, particularly at V8 when side-dress N applications can be used to maximize NUE.

Crop Year 2004

In 2004, the V8 data showed the highest positive linear relationship between both GNDVI and RNDVI with grain yield, consistent with RNDVI in 2003. There were no significant differences between the GNDVI and RNDVI relationships with grain yield at V8. However, the NDVI (both GNDVI & RNDVI) relationship with grain yield was considerably higher in the 99-day hybrid compared to the 113-day hybrid (Figures 23 & 24). Therefore developing separate yield prediction lines for these two hybrids would have been necessary to maintain accurate grain yield prediction. Little rationale can be given as to why grain yield prediction was extensively enhanced in the 99-day hybrid, since the difference in visible plant height among other hybrid characteristics was minimum at V8 due to the fact that the growth patterns of the shorter season (early maturing) hybrids did not typically separate from the longer season hybrids in this study (over 3 years) until the reproductive stages. The most plausible explanation could be that the 99-day hybrid was not as well suited for the dry-land environment as anticipated and was under substantial stress throughout the growing season that limited yield potential early and resulted in dramatically reduced plant response to the post-sensing (late-season) environment contrary to the 113-day hybrid.

The strongest relationship between NDVI collected in the reproductive growth stages and grain yield occurred at R4 (dough), but this relationship was considerably less than that of the V8 reading in the GNDVI of 99-day hybrid and slight improvement in the RNDVI of the 113-day (Figures 25 & 26). In the 99-day hybrid the RNDVI relationship with grain yield was significantly higher than the GNDVI and in the 113-day hybrid the RNDVI relationship with grain yield improved between V8 and R4 while the GNDVI relationship did not change. Since GNDVI reflectance was negatively affected by tassel development, an advantage occurred in grain yield prediction for the RNDVI over the GNDVI in the reproductive stages. Furthermore, poor relationships resulted from grain yield and the NDVI measurements taken in the reproductive growth stages (R1-R3) prior to R4. A violent thunderstorm with damaging hail and very strong winds that occurred between the V9 and V10 growth stages (June 2) nearly destroyed the trials with severe plant damage from torn leaves and stunned plants due to lodging. This plant damage, as proven by the low RNDVI values at V11, resulted in underestimation and variation in grain yield prediction during these growth stages. However, the NDVI relationship with grain yield improved at R4 presumably due to variation in lower leave senescence associated with plant health.

As in the preceding years, CV (both GCV & RCV) was correlated with grain yield, but to a lesser degree than NDVI at both growth stages. NDVI was correlated with CV as well, but not at the level of the two previous years (Figures 27 & 28). Regardless of the lower relationship between NDVI and CV, the analysis resulted in the same findings as the preceding years that CV (GCV or RCV) did not improve the relationship between grain yield and NDVI. Even though the grain yield relationship with GNDVI declined significantly between V8 and R4 in the 99-day hybrid, the 2004 RNDVI data corresponds with the previous two years that grain yield could be predicted effectively during both the vegetative (V8) and reproductive stages.

CONCLUSIONS

The critical population at which the NDVI plateau occurred, ranged between 55,000 and 60,000 plants ha $^{-1}$ in the later maturing hybrids and closer to 70,000 in the earliest maturing hybrids. Therefore, plant population did not affect NDVI at populations commonly used in corn production (between 55,000 and 70,000 plants ha $^{-1}$), and should not be a major concern when using NDVI to predict grain yield unless an early maturing hybrid is used in a low plant population. Although post-sensing environmental conditions did cause radical changes in N response between vegetative measurements (RI_{NDVI}) and final yield ($RI_{HARVEST}$) at some site years, determining N response (RI) mid-season has been proven possible at the V8 growth stage.

NDVI data from the V8 growth stage predicted grain yield most accurately in both 2003 and 2004, presumably because the highest variability in NDVI occurred at the V8 growth stage both years. Later vegetative growth stages may actually contain more plant variability than V8 and could have stronger relationships with grain yield, but canopy closure occurs shortly after V8 (V10 to V12) and vegetative stage NDVI data collected thereafter miscues plant variability. Well-defined relationships between NDVI and grain yield also occurred in the reproductive growth stages, but at different growth stages each year: R1 in 2001, R2 in 2003, and R4 in 2004. Although late-season yield prediction is not useful for N management and limited due to temporal variability, the potential is there for other uses.

Separating the hybrids vastly improved these reproductive relationships with grain yield all three years, but only improved the V8 relationship with grain yield in 2004. Hybrid maturity did not effect grain yield prediction at V8, but reproductive growth stage yield prediction will require hybrid maturity categorization. Finally, comparisons made between the GNDVI and RNDVI relationships with grain yield in 2004 showed no significant differences over three locations. Separate yield prediction models for GNDVI and RNDVI will be required, since GNDVI values are about 10% lower than RNDVI and would underestimate yield potential using the same model.

REFERENCES

Aase, J.K., and J.L. Pikul. 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87:652-656.

Baker, J.L. and D.R. Timmons. 1994. Fertilizer management effects on leaching of labeled nitrogen for no-till corn in field lysimeters. J. Environ. Qual. 23:305-310.

Bartholome, E. 1988. Radiometric measurements and crop yield forecasting; Some observations over millet and sorghum experimental plots in Mali. Int. J. Remote Sens. 9:1539-1552.

Bausch, W.C. and H.R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Trans. ASAE 39(5):1869-1875.

Blevins, D.W., D.H. Wilkison, B.P. Kelly, and S.R. Silva. 1996. Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. J. Environ. Qual. 25:584-593.

Black, A.L. and A. Bauer. 1988. Setting winter wheat yield goals. P. 24-34. In J.L. Havlin (ed) Proc. Workshop Central Great Plains Profitable Wheat Management, Wichita, KS. 17-20 Aug. 1988. Potash and Posphate Inst., Altanta, GA.

Blackmer, T.M. and J.S. Schepers. 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. J. Prod. Agric. 8(1):56-60.

Blumenthal, J.M. and M.P. Russelle. 1996. Subsoil nitrate uptake and symbiotic dinitrogen fixation by alfalfa. Agron. J. 88:909-915.

Bosch, H.M., A.B. Rosefield, R. Huston, H.R. Shipman and F.L. Woodward. 1950. Methemoglobinemia and Minnesota well supplies. J. Am. Water Works Assoc. 42: 161-170.

Bundy, L.G. and T.W. Andraski. 1995. Soil yield potential effects on performance of soil nitrate tests. J. Prod. Agric. 8:561-568.

Chichester, F.W. and C.W. Richardson. 1992. Sediment and nutrient loss from clay soils as affected by tillage. J. Environ. Qual. 21:587-590.

Dahnke, W.C., L.J. Swenson, R.J. Goos, and A.G. Leholm. 1988. Choosing a crop yield goal. SF-822. North Dakota State Ext. Serv., Fargo.

Daliparthy, J., S.J. Herbert, and P.L.M. Veneman. 1994. Dairy manure applications to Alfalfa: crop response, soil nitrate, and nitrate in soil water. Agron. J. 86:927-933.

Dao, T.H. 1993. Tillage and winter wheat residue management effects on water infiltration and storage. Soil Sci. Am. J. 57:1586-1595.

Diaz, R.J. 2001. Overview of Hypoxia around the World. J. Environ. Qual. 30:275-281.

Diez, J.A., R. Roman, M.C. Cartagena, A. Vallejo, A. Bustos, and R. Caballero. 1994. Controlling nitrate pollution of aquifers by using different nitrogenous controlled release fertilizers in maize crop. Agric. Ecosys. and Environ. 48:49-56.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Dowdell, R.J., and R.Q. Cannell. 1975. Effect of ploughing and direct drilling on soil nitrate content. J. Soil. Sci. 26:53-61.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya, and T.W. Welacky. 1996. Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss. J. Environ. Qual. 25:317-324.

Durieux, R.P., H.J. Brown, E.J. Stewart, J.Q. Zhao, W.E. Jokela, and F.R. Magdoff. 1995. Implications of nitrogen management strategies for nitrate leaching potential: Roles of nitrogen source and fertilizer recommendations system. Agron. J. 87:884-887.

Eck, H. V., and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Eckert, D.J. and V.L. Martin. 1994. Yield and nitrogen requirement of no-tillage corn as influenced by cultural practices. Agron. J. 86:1119-1123.

Edwards, W.M., M.J. Shipitalo, L.B. Owens, and L.D. Norton. 1990. Effect of *Lumbricus terrestris* L. burrows on hydrology of continuous no-till corn fields. Geoderma 46:73-84.

Eghball, B. and J.W. Maranville. 1991. Interactive effects of water and nitrogen stresses on nitrogen utilization efficiency, leaf water status and yield of corn genotypes. Commun. Soil. Sci. Plant Anal., 22(13&14):1367-1382.

Elliott, E.T., P.W. Tracy, G.A. Peterson, and C.V. Cole. 1986. Leaching of mineralized N is less under no-till cultivation. P. 53-54. *In* Trans. Int. Congr. Soil Sci. 13th, Hamburg, Germany. Vol. 6. Congr. Centurum, Hamburg.

Esala, Martti and Aku Leppanen. 1998. Leaching of ^{15}N-labeled fertilizer nitrate in undisturbed soil columns after simulated heavy rainfall. Commun. Soil Sci. Plant Anal. 29:1221-1238.

Francis, D.D., J.S. Schepers, and M.F. Vigil. 1993. Post-anthesis nitrogen loss from corn. Agron J. 85:659-663.

Fenster, C.R., and G.A. Peterson. 1979. Effects of no-tillage fallow compared to conventional tillage in a wheat-fallow system. Nebraska Agic. Exp. Bull. 289.

Fox, R.H., J.S. Shenk, W.P. Piekielek, M.O. Westerhaus, J.D. Toth, and K.E. Macneal. 1993. Comparsion of near-infrared spectroscopy and other soil nitrogen availability quick tests for corn. Agron. J. 85:1049-1053.

Gascho, G.J. and R.D. Lee. 2002. Determining side-dress nitrogen requirements of corn following broiler litter in the Southern Coastal Plain. J. Plant Nutr. 11:2361-2371.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen Input to the Gulf of Mexico. J. Environ. Qual. 30:329-336.

GopalaPillai, S. and L. Tian. 1999. In-field variability detection and spatial yield modeling for corn using digital aerial imaging. Trans. ASAE 42(6):1911-1920.

Harper, L.A., R.R. Sharpe, G.W. Langdale, and J.E. Giddens. 1987. Nitrogen cycling in a wheat crop: Soil, plant, and aerial nitrogen transport. Agron. J. 79:965-973.

Hilton, B.R., P.E. Fixen, and H.J. Woodward. 1994. Effects of tillage, nitrogen placement, and wheel compaction on denitrification rates in the corn cyle of a corn-oats rotation. J. Plant Nutr. 17:1341-1357.

Holland, J.F., and W.L. Felton. 1989. Effect of tillage practice on grain sorghum production in northern New South Wales. Aust. J. Exp. Agric. 29:843-848.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Z. Zhao-Liang. 1996. Regional nitrogen budgets and reverine N & P fluxes for the drainage to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35:75-139.

Johnson, G.V. 1991. General model for predicting crop response to fertilizer. Agron. J. 83:367-373.

Johnson, G.V., W.R. Raun, and R.W. Mullen. 2000. Nitrogen use efficiency as influenced by crop response index. P. 291. In Agronomy abstracts. ASA, CSSA, and SSSA, Madison, WI.

Jones, O.R., and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the southern high plains. Agron. J. 89:222-232.

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. J. Prod. Agric. 10:227-234.

Kessavalou, A., J.W. Doran, W.L. Powers, T.A. Kettler, and J.H. Qian. 1996. Bromide and nitrogen-15 tracers of nitrate leaching under irrigated corn in central Nebraska. J. Environ. Qual. 25:1008-1014.

Kirkegaard, J.A., R. Munns, R.A. James, P.A. Gardner, and J.F. Angus. 1995. Reduced growth and yield of wheat with conservation cropping: II. Soil biological factors limit growth under direct drilling. Aust. J. Agric. Res. 46:75-88.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Wheat-fallow tillage systems 'effect on newly cultivated grassland soils' nitrogen budget. Soil Sci. Soc. Am. J. 49:352-356.

Lehrsch, G.A., R.E. Sojka, and D.T. Westermann. 2000. Nitrogen placement, row spacing, and furrow irrigation water positioning effects on corn yield. Agron. J. 92:1266-1275.

Liang, B.C., M. Remillard, and A.F. MacKenzie. 1991. Plant and environment interactions. J. Environ. Qual. 20:123-128.

Liang, B.C. and A.F. MacKenzie. 1994. Corn yield, nitrogen uptake and nitrogen use efficiency as influenced by nitrogen fertilization. Can. J. Soil Sci. 74:235-240.

Liu, J., C.E. Goering, and L. Tian. 2001. A neural network for setting target corn yields. Trans. ASAE 44(3):705-713.

Lopez-Bellido, L., M. Fuentes, J.E. Castillo, F.J. Lopez-Garrido, and E.J. Fernandez. 1996. Long-term tillage, crop rotation and nitrogen fertilizer effects on wheat yield under rainfed Mediterranean conditions. Agron. J. 88:783-791.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, A.R. Klatt, G.V. Johnson, R.L. Elliott, M.L. Stone, J.B. Solie, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885-898.

Magdoff, F.R., D. Ross, and J. Amadon. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1301-1304.

Magdoff, F.R., W.E. Jokela, R.H. Fox, and G.F. Griffin. 1990. A soil test for nitrogen availability in the northeastern United States. Commun. Soil Sci. Plant Anal. 21:1103-1115.

Menezes, R.S.C., G.J. Gascho, W.W. Hanna, M.L. Cabrera, and J.E. Hook. 1997. Subsoil nitrate uptake by grain pearl millet. Agron. J. 89:189-194.

Merrill, S.D., A.L. Black, and A. Bauer. 1996. Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci. Am. J. 60:575-583.

Mueller, D.K. and D.R. Helsel. 1996. Nutrients in the nation’s waters: Too much of a good thing? U.S. Geological Survey Circular 1136. National Climatic Data Center. 1994. Asheville, North Carolina.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. Ophelia 41:199-219.

Norwood, C.A. 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86:558-563.

Norwood, C.A., and R.S. Currie. 1996. Tillage, planting date, and plant population effects on dryland corn. J. Prod. Agric. 9:119-122.

Owens, L.B., R.W. Malone, M.J. Shipitalo, W.M. Edwards, and J.V. Bonta. 2000. Lysimeter study of nitrate leaching from a corn-soybean rotation. J. Environ. Qual. 29:467-474.

Pan, W.L., E.J. Kamprath, R.H. Moll, and W.A. Jackson. 1984. Prolificacy in corn: Its effects on nitrate and ammonium uptake and utilization. Soil Sci. Soc. Am. J. 48:1101-1106.

Pang, X.P., J. Letey, and L. Wu. 1997. Yield and nitrogen uptake prediction by CERES-Maize model under semiarid conditions. Soil Sci. Soc. Am. J. 61:254-256.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. NebGuide G93-1171-A. Cooperative Extension, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln.

Phillips, S.B., W.R. Raun, and G.V. Johnson. 1997. Seasonal and long-term changes in nitrate-nitrogen content of well water in Oklahoma. J. Environ. Qual. 26:1632-637.

Randall, G.W., D.R. Huggins, D.J. Fuchs, D.D. Buhler, M.P. Russelle, W.P. Koskinen, and J.L. Anderson. 1994. Cropping system effects on water, nitrate, and pesticide losses through tile drainage. Minnesota Water '94 Conf., April 1994.

Rasmussen, M.S. 1998. Developing simple, operational, consistent NDVI-vegetation models by applying environmental and climatic information. Part II: Crop yield assessment. Int. J. Remote Sensing 19(1):119-139.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815-820.

Rehm, G. and M. Schmitt. 1989. Setting realistic crop yield goals. Minnesota Ext. Serv. Ag-FS-3873. Univ. of Minnesota.

Rice, C.W., and M.S. Smith. 1982. Denitrification in no-till and plowed soils. Soil Sci. Soc. Am. J. 46:1168-1173.

Rodriguez, M.B., and N. Giambiagi. 1995. Denitrification in tillage and no-tillage Pampean soils: relationships among soil water, available carbon, and nitrate and nitrous oxide production. Commun. Soil. Sci. Plant Anal. 26:3205-3220.

SAS Institute. 1990. SAS/STAT user's guide. Release 6.03 ed. SAS Inst., Cary, NC.

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N, and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. 20:949-959.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil Sci. Plant Anal. 23(17-20):2173-2187.

Schuman, G.E. and L.F. Elliott. 1978. Cropping an abandoned feedlot to prevent deep percolation of nitrate-nitrogen. Soil Sci. 126:237-243.

Shrestha, R.K. and J.K. Ladha. 1998. Nitrate in groundwater and integration of nitrogen-catch crop in rice-sweet pepper cropping system. Soil Sci. Soc. Am. J. 62:1610-1619.

Schuh, W.M., D.L. Klinkebiel, J.C. Gardner, and R.F. Meyer. 1997. Tracer and nitrate movement to groundwater in the Northern Great Plains. J. Environ. Qual. 26:1335-1347.

Smika, D.E., and P.W. Unger. 1986. Effect of surface residues on soil water storage. Adv. Soil. Sci. 5:111-138.

Spellman, D.E., A. Rongni, D.G. Westfall, R.M. Waskom, and P.N. Soltanpour. 1996. Pre-sidedress nitrate soil testing to manage nitrogen fertility in irrigated corn in a semi-arid environment. Commun. Soil Sci. Plant Anal. 27:561-574.

Stinner, B.R., G.D. Hoyt, and R.L. Todd. 1983. Changes in soil chemical properties following a 12-year fallow: A 2-year comparison of conventional tillage and no-tillage agroecosystems. Soil Tillage Res. 3:277-290.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE. 39(5):1623-1631.

U.S. Environmental Protection Agency (EPA). 1999a. National Primary Drinking Water Regulations Technical Fact Sheets. Washington, D.C.: Office of Water, Office of Ground Water and Drinking Water. http://www.epa.gov/OGWDW/hfacts.html. March

U.S. Environmental Protection Agency. 1999b. Risk of Groundwater Nitrate Contamination. Watershed Information Network. Available at http://www.epa.gov/iwi/1999april/iii21usmap.html. April

Varvel, G.E. 1994. Monoculture and rotation system effects on precipitation use efficiency in corn. Agron. J. 86:204-208.

Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 61:1233-1239.

Waddell, J.T., and R.R. Weil. 1996. Water distribution in soil under ridge-till and no-till corn. Soil Sci. Soc. Am. J. 60:230-237.

Walton, G. 1951. Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. Am. J. Public Health. 41: 986-996.

Weil, R.R., R.A. Weismiller, and R.S. Turner. 1990. Nirate contamination of groundwater under irrigated Coastal Plain soils. J. Environ. Qual. 19:441-448.

Wienhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the Northern Great Plains. Agron. J. 87:842-846.

Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive water and nitrogen effects on senescence of maize: II. Photosynthetic decline and longevity of individual leaves. Agron. J. 80:865-870.

Yadav, S.N. 1997. Formulation and estimation of nitrate-nitrogen leaching from corn cultivation. J. Environ. Qual. 26:808-814.

Table 1. Initial surface (0-15cm) soil test results prior to experiment initiation at Greenlee Farm, Haskell, and LCB, OK.

	NH_4-N	NO_3-N	P	K	
Sample	------------------- mg kg^{-1}			-------------------	pH
Haskell 2002-03 (0-15 cm)	7.65	2.66	48	136	6.18
LCB (0-15 cm)	14.28	1.63	23	239	6.13
Haskell 2004 (0-15 cm)	NA	20.00	112	218	6.70
Greenlee Farm (0-15 cm)	2.65	6.26	13	147	5.67

NH_4-N and NO_3-N – 2 M KCL extract; P and K – Mehlich-3 extraction; pH – 1:1 soil:deionized water; NA- not available

Table 2. Planting, fertilizer, and harvest dates at Greenlee Farm, Haskell, and LCB, OK, 2002-04.

Location	Crop Year	Planting	Fertilizer Application	Grain Harvest
Haskell	2002	4-18-2002	4-16-2002	9-11-2002
LCB	2002	4-23-2002	4-23-2002	8-28-2002
Haskell	2003	4-03-2003	4-03-2003	8-20-2003
LCB	2003	4-01-2003	4-08-2003	8-07-2003
Greenlee Farm	2004	3-31-2004	3-31-2004	8-17-2004
Haskell	2004	4-01-2004	4-01-2004	8-31-2004
LCB	2004	4-03-2004	4-03-2004	8-28-2004

Table 3. Sensing dates by growth stage at Greenlee Farm, Haskell, and LCB, OK, 2002 to 2004.

Growth Stage	Physiological Description	2002		2003		2004		
		Haskell	LCB	Haskell	LCB	Greenlee	Haskell	LCB
V5	Ear and shoot development complete	---	---	---	---	5-17-04	5-17-04	5-15-04
V6	Third whorl elongated, growing point above surface	---	---	5-22-03	5-21-03	5-22-04	5-22-04	5-18-04
V7		---	6-15-02	5-26-03	5-24-03	5-27-04	---	5-23-04
V8	Fourth whorl elongated, nutrient deficiencies appear	---	---	5-30-03	6-02-03	5-31-04	5-27-04	5-29-04
V9		---	---	---	6-07-03	---	5-31-04	6-01-04
V10	Rapid biomass growth, new leaves occur every 2-3 days	6-19-02	---	6-6-03	---	6-08-04	---	---
V11		---	---	---	---	---	6-08-04	---
V12	Brace roots develop, ear size and kernel number determined	---	---	---	---	6-15-04	---	6-08-04
V15-V16		---	---	6-15-03	6-14-03	---	---	---
VT (Tasseling)	Tassel development, maximum plant height, pollen shed begins	---	---	---	---	---	---	---
R1 (Silking)	Silks develop and pollination occurs, kernel fill begins	7-11-02	7-09-02	6-21-03	6-20-03	6-29-04	6-15-04	6-16-04
R2 (Blister)	Silks darken and dry, kernels white and blister shaped, starch develops	---	---	6-27-03	6-25-03	---	6-29-04	6-26-04
R3 (Milk)	Kernels turn yellow externally, but milking internal fluid	---	---	7-7-03	---	7-10-04	---	---
R4 (Dough)	Kernels thicken to a paste, 50% kernel dry weight	---	---	7-18-03	---	7-16-04	7-09-04	7-09-04
R5 (Dent)	Kernels have dented at top, the milk line appears	---	---	---	---	---	7-16-04	7-17-04

Vegetative growth stages (V#) determined by number of collared leaves. Depending on hybrid and environmental conditions plants produce between 11 to 20 collared leaves (V11-V20), in 2004 only 12 collared leaves were observed before tasseling.

Table 4. Corn grain yield treatment means by location, Haskell and Lake Carl Blackwell, OK, 2002.

Treatment		Haskell			Lake Carl Blackwell		
Plant pop.	N rate (kg ha^{-1})	105-day	109-day	113-day	105-day	109-day	113-day
		---------------------------- Mg ha^{-1} ---------------------------					
Low	0	5.49	4.32	5.64	1.49	1.54	2.01
	56	5.25	5.07	5.47	1.71	2.07	2.54
	112	5.22	4.57	5.47	2.00	1.57	2.81
	Hybrid Avg.	5.32	4.65	5.53	1.73	1.73	2.45
High	0	4.85	5.54	5.71	0.97	1.11	1.58
	56	5.19	5.02	5.44	1.57	1.98	2.16
	112	5.01	5.64	5.68	1.86	2.96	2.72
	Hybrid Avg.	5.02	5.40	5.61	1.47	2.02	2.15
SED		0.15	0.52	0.38	0.24	0.36	0.25

SED is the standard error of the difference between two equally replicated means.
Haskell population (pop) was: 44,460 seeds ha^{-1} (low) and 66,690 seeds ha^{-1} (high).
LCB (Lake Carl Blackwell) population was: 35,568 seeds ha^{-1} (low) and 51,870 seeds ha^{-1} (high).

Table 5. Corn grain yield treatment means by location, Haskell and Lake Carl Blackwell, OK, 2003.

Treatment		Haskell			Lake Carl Blackwell		
Plant pop.	N rate (kg ha^{-1})	104-day	107-day	111-day	104-day	107-day	111-day
		------------------------------- Mg ha^{-1} ------------------------------					
Low	0	6.37	6.41	5.89	4.26	2.49	3.30
	56	6.74	6.23	5.79	3.95	2.77	3.49
	112	6.94	6.50	5.91	3.51	3.96	3.35
	Hybrid Avg.	6.68	6.38	5.86	3.91	3.07	3.38
High	0	6.16	6.21	5.63	3.85	3.82	3.88
	56	6.92	6.17	5.50	4.88	4.89	3.18
	112	6.67	6.62	5.75	4.64	4.02	3.66
	Hybrid Avg.	6.58	6.33	5.63	4.46	4.24	3.57
SED		0.22	0.406	0.218	0.62	0.83	0.34

SED is the standard error of the difference between two equally replicated means.
Haskell population (pop) was: 49,400 seeds ha^{-1} (low) and 71,630 seeds ha^{-1} (high).
LCB (Lake Carl Blackwell) population was: 35,568 seeds ha^{-1} (low) and 51,870 seeds ha^{-1} (high).

Table 6. Effect of hybrid, plant population, and N rate on grain yield by location, Greenlee Farm, Haskell, and Lake Carl Blackwell, OK, 2004.

Treatment		Greenlee Farm		Haskell		Lake Carl Blackwell	
Plant pop. (Plant ha^{-1})	N rate (kg ha^{-1})	99-day	113-day	99-day	113-day	99-day	113-day
		------------------------------ Mg ha^{-1} ------------------------------					
37,050	0	3.01	6.89	6.11	6.85	6.68	7.70
	84	3.18	6.69	7.30	8.50	6.93	8.23
	168	3.43	5.82	7.47	9.27	7.34	8.67
	Hybrid Avg.	3.30	6.25	6.96	8.21	7.25	8.20
51,870	0	5.58	7.44	7.37	7.27	8.08	8.50
	84	4.47	8.34	9.04	9.62	7.99	10.57
	168	6.04	8.43	8.48	9.88	8.95	10.20
	Hybrid Avg.	5.26	8.38	8.29	8.92	8.34	9.73
66,690	0	5.21	8.18	7.33	6.95	8.75	10.50
	84	6.06	9.46	10.05	10.89	9.50	9.97
	168	7.11	9.41	10.05	11.43	8.94	10.87
	Hybrid Avg.	6.58	9.43	9.14	9.75	9.04	10.44
81,510	0	4.81	6.99	7.46	6.89	8.81	8.74
	84	6.11	9.91	10.23	10.78	10.49	10.48
	168	6.42	9.99	10.24	11.56	9.08	11.67
	Hybrid Avg.	6.26	9.96	9.31	9.74	9.65	10.30
SED		0.87	1.00	0.51	0.57	1.02	1.46

SED is the standard error of the difference between two equally replicated means.

Table 7. Nitrogen Use Efficiency treatment means by location, Haskell and Lake Carl Blackwell, OK, 2002.

Treatment		Haskell			Lake Carl Blackwell		
Plant pop.	N rate (kg ha^{-1})	105-day	109-day	113-day	105-day	109-day	113-day
		%					
Low	56	0	22	1	16	23	22
	112	2	3	0	20	7	15
	Hybrid Avg.	0	13	0	18	15	18
High	56	7	0	0	30	29	19
	112	1	10	0	25	29	19
	Hybrid Avg.	4	2	0	27	29	19
SED		6	12	9	13	7	5

NUE= (Grain N uptake of N treatment – Grain N uptake of check) / Nrate
SED is the standard error of the difference between two equally replicated means.
Haskell population (pop) was: 44,460 seeds ha^{-1} (low) and 66,690 seeds ha^{-1} (high).
LCB (Lake Carl Blackwell) population was: 35,568 seeds ha^{-1} (low) and 51,870 seeds ha^{-1} (high).

Table 8. Nitrogen Use Efficiency treatment means by location, Haskell and Lake Carl Blackwell, OK, 2003.

Treatment		Haskell			Lake Carl Blackwell		
Plant pop.	N rate (kg ha^{-1})	104-day	107-day	111-day	104-day	107-day	111-day
		%					
Low	56	22	9	8	10	6	11
	112	16	9	6	0	20	5
	Hybrid Avg.	19	9	7	3	17	8
High	56	21	7	9	26	60	5
	112	13	8	1	14	20	8
	Hybrid Avg.	17	7	4	20	40	2
SED		7	10	5	12	13	8

NUE= (Grain N uptake of N treatment – Grain N uptake of check) / Nrate
SED is the standard error of the difference between two equally replicated means.
Haskell population (pop) was: 49,400 seeds ha^{-1} (low) and 71,630 seeds ha^{-1} (high).
LCB (Lake Carl Blackwell) population was: 35,568 seeds ha^{-1} (low) and 51,870 seeds ha^{-1} (high).

Table 9. Effect of hybrid, plant population, and N rate on NUE by location, Greenlee Farm, Haskell, and Lake Carl Blackwell, OK, 2004.

Treatment		Greenlee Farm		Haskell		Lake Carl Blackwell	
Plant pop. (Plant ha^{-1})	N rate (kg ha^{-1})	99-day	113-day	99-day	113-day	99-day	113-day
		---------------------------------- % ----------------------------------					
37,050	84	8	13	43	48	10	18
	168	6	0	21	36	5	15
	Hybrid Avg.	7	3	32	42	8	17
51,870	84	0	27	49	71	14	31
	168	10	23	24	39	26	22
	Hybrid Avg.	0	25	37	55	20	25
66,690	84	16	25	79	89	33	5
	168	25	25	45	58	14	14
	Hybrid Avg.	21	25	62	74	22	10
81,510	84	23	39	76	94	55	48
	168	17	33	41	61	11	39
	Hybrid Avg.	20	36	59	78	40	44
SED		14	20	9	12	22	20

NUE= (Grain N uptake of N treatment – Grain N uptake of check) / Nrate

SED is the standard error of the difference between two equally replicated means.

Figure 1. Effect of plant population on RNDVI for two sensor readings in three hybrids at Haskell and LCB, OK, 2002.

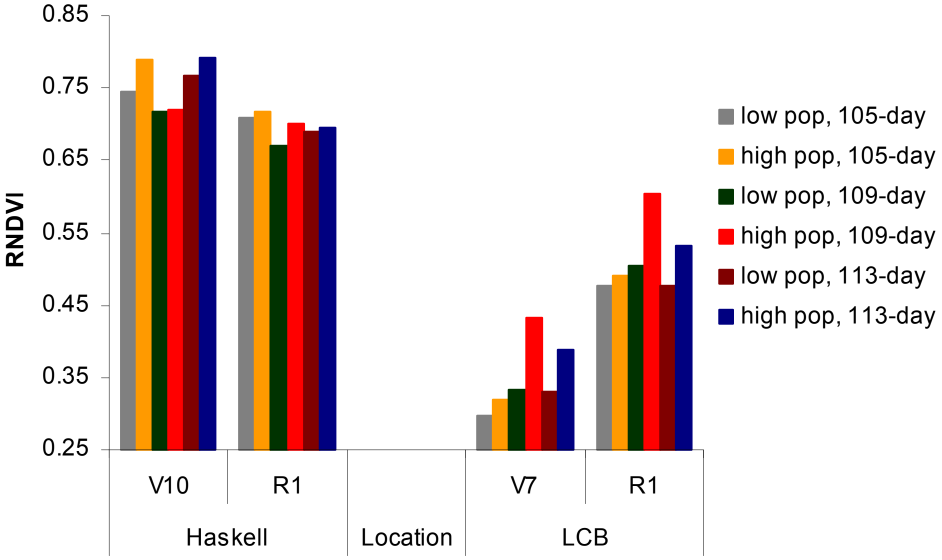


Figure 2. Effect of plant population on RNDVI over time in three hybrids at Haskell, OK, 2003.

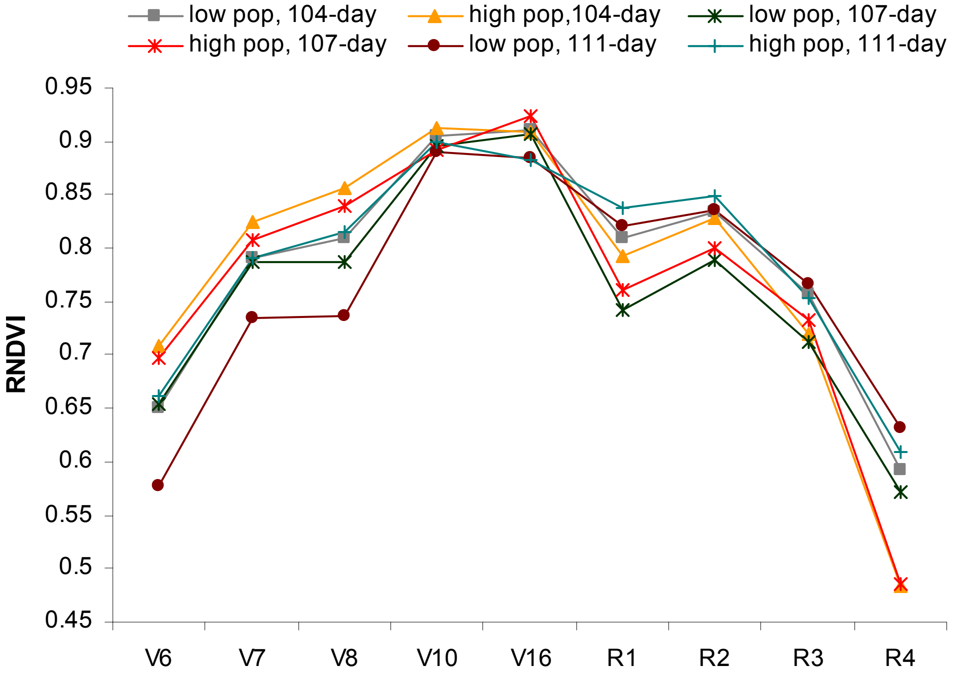


Figure 3. Relationship between RNDVI and plant population of three hybrids at the V8 growth stage over two locations with 0 N treatments removed fitted to a linear-plateau model, 2003.

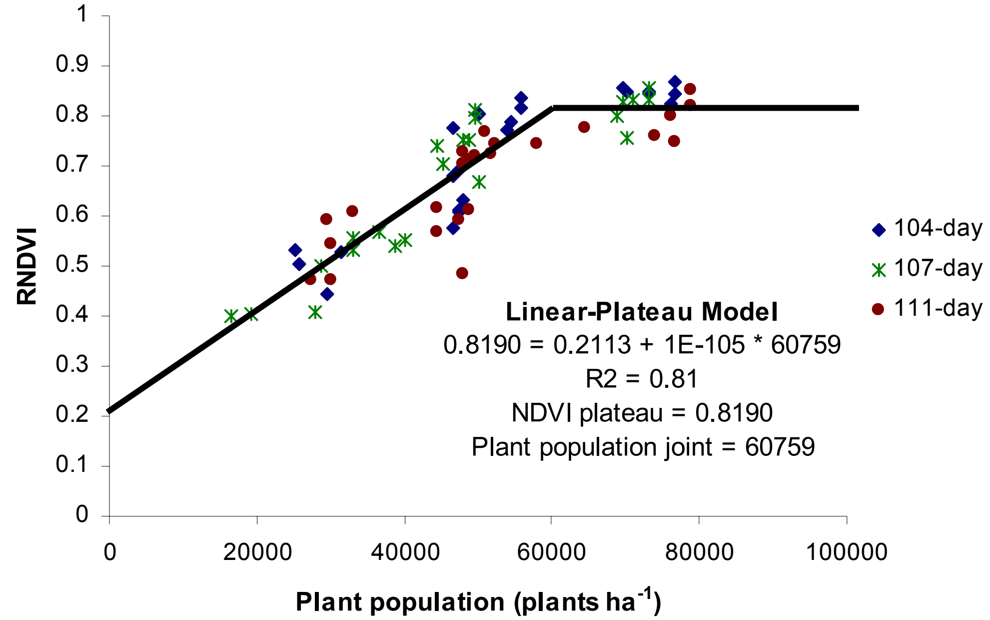


Figure 4. Relationship between RNDVI and plant population of three hybrids at the R2 growth stage over two locations with 0 N treatments removed fitted to a linear-plateau model, 2003.

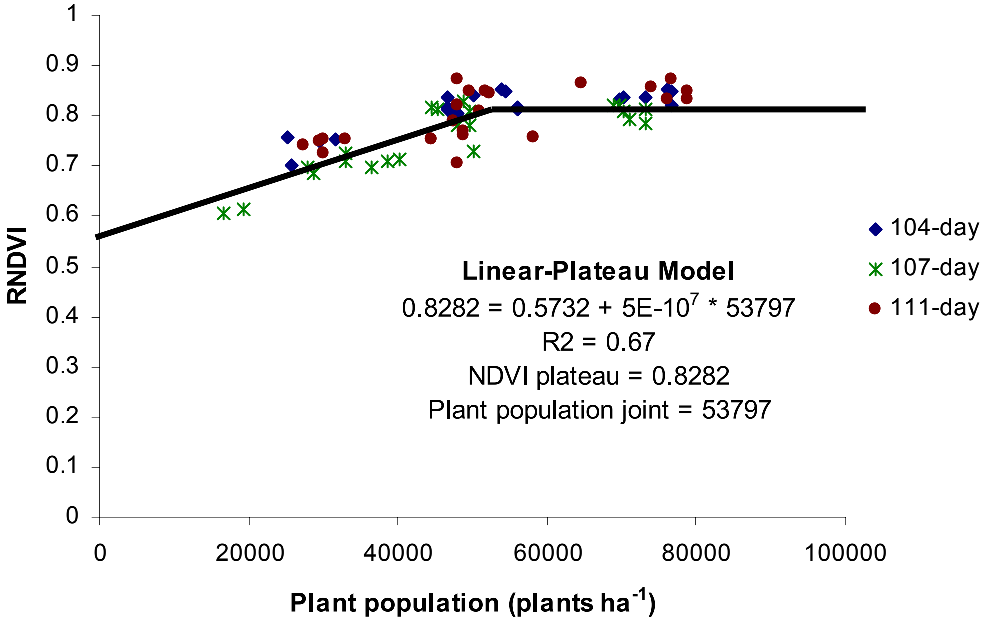


Figure 5. Effect of plant population on GNDVI over time in the 168 kg N ha^{-1} pre-plant treatment of the 113bt-day hybrid at Haskell, OK, 2004.

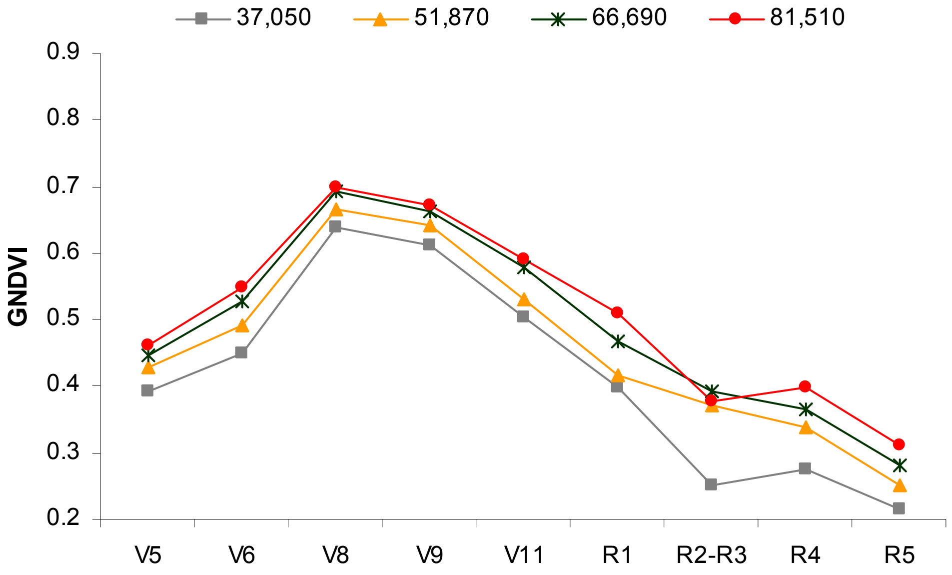


Figure 6. Effect of plant population on RNDVI over time in the 168 kg N ha^{-1} pre-plant treatment of the 113bt-day hybrid at Haskell, OK, 2004.

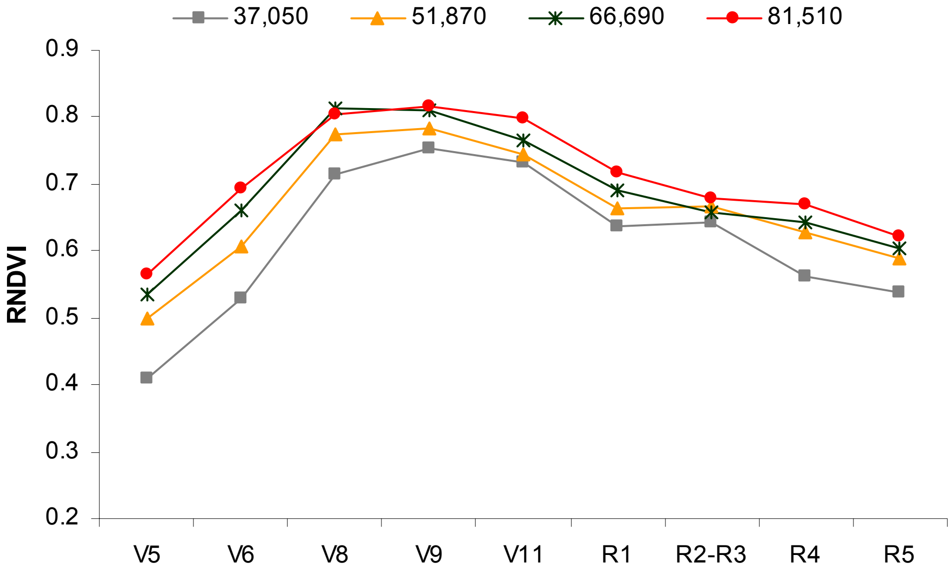


Figure 7. Relationship between plant population and RNDVI at V8 with 0 N treatments removed for the 99-day hybrid over three locations, 2004.

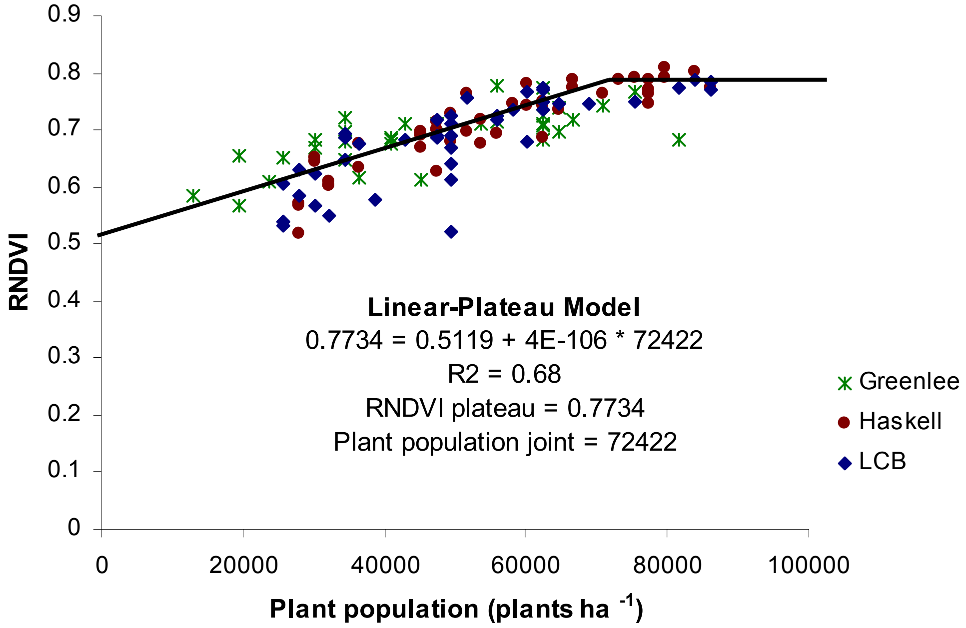


Figure 8. Relationship between plant population and RNDVI at V8 with 0 N treatments removed for the 113-day hybrid over three locations, 2004.

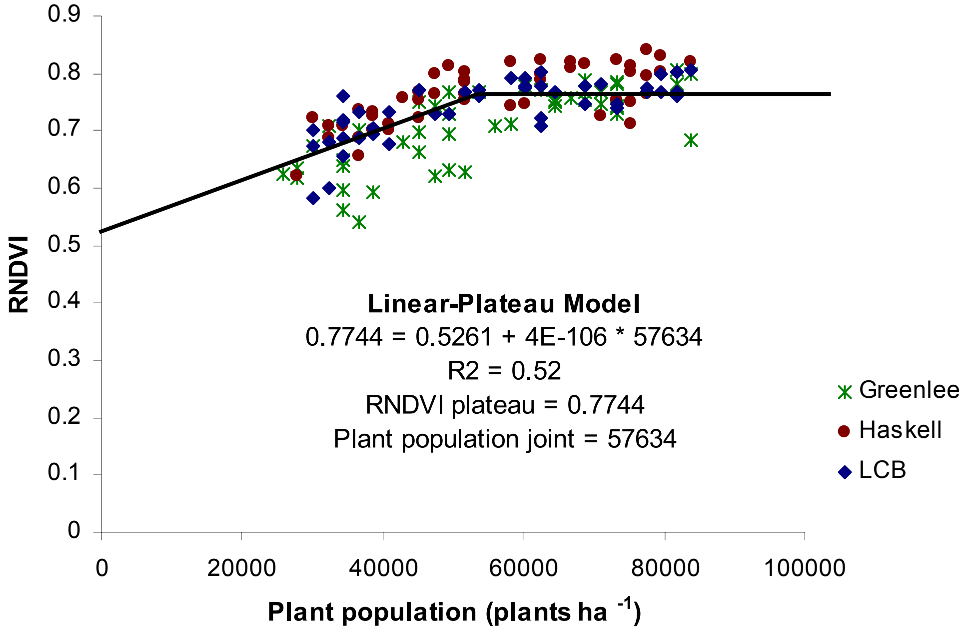


Figure 9. Effect of N rate on RNDVI for two sensor readings in the high plant population of the 113-day hybrid at Haskell and LCB, OK, 2002.

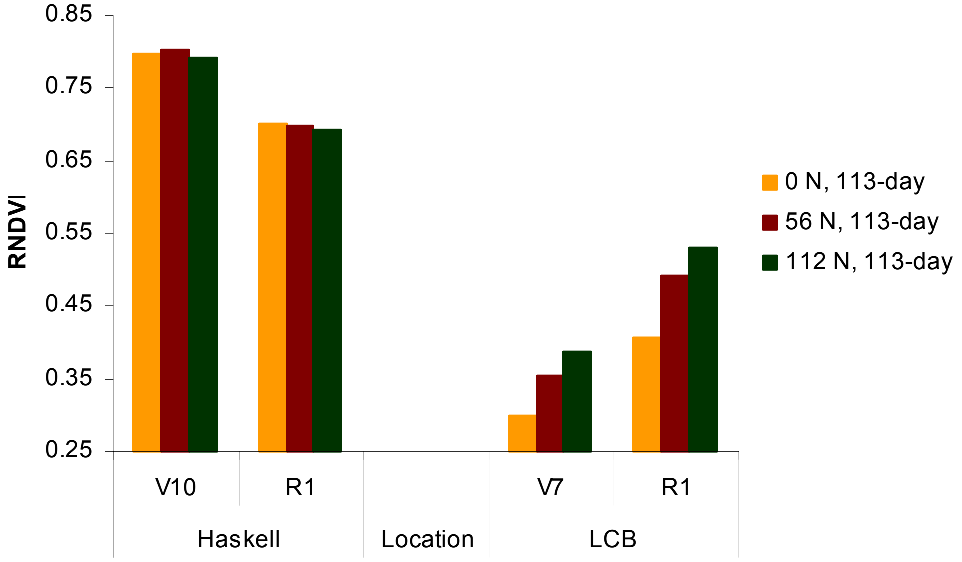


Figure 10. Relationship between RI_{RNDVI} measured at the R1 growth stage and $RI_{HARVEST}$ over two locations, 2002.

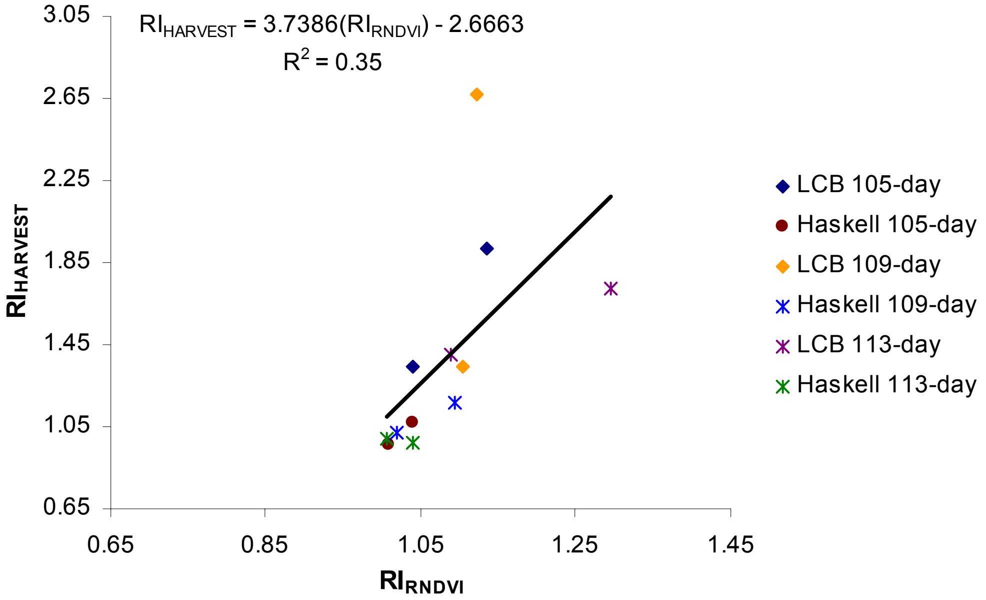


Figure 11. Effect of N rate on RNDVI over time in the high plant population of the 104-day hybrid at Haskell, OK, 2003.

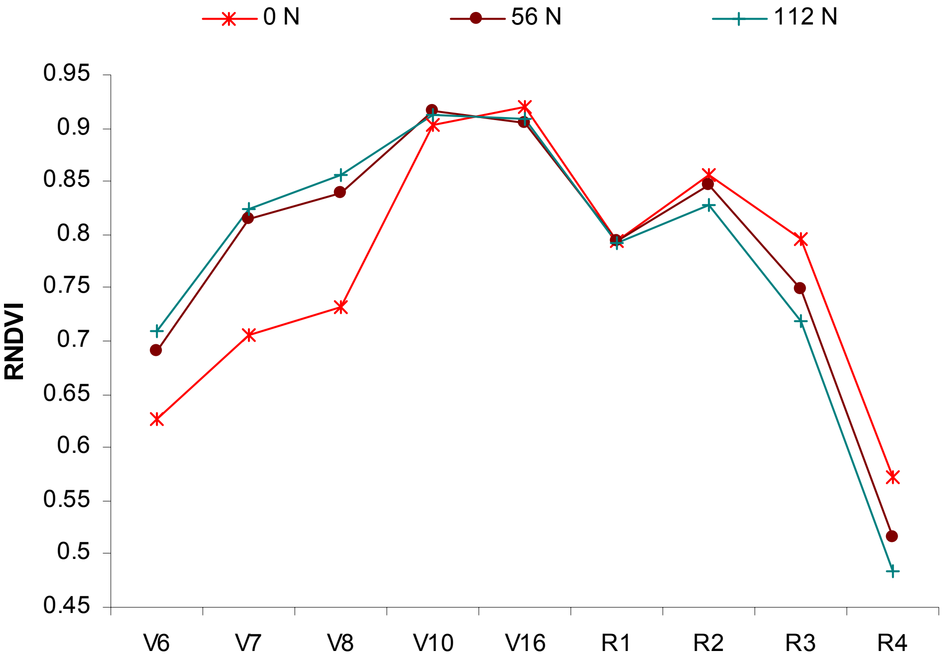


Figure 12. Relationship between RI_{RNDVI} measured at the R2 growth stage and $RI_{HARVEST}$ over two locations, 2003.

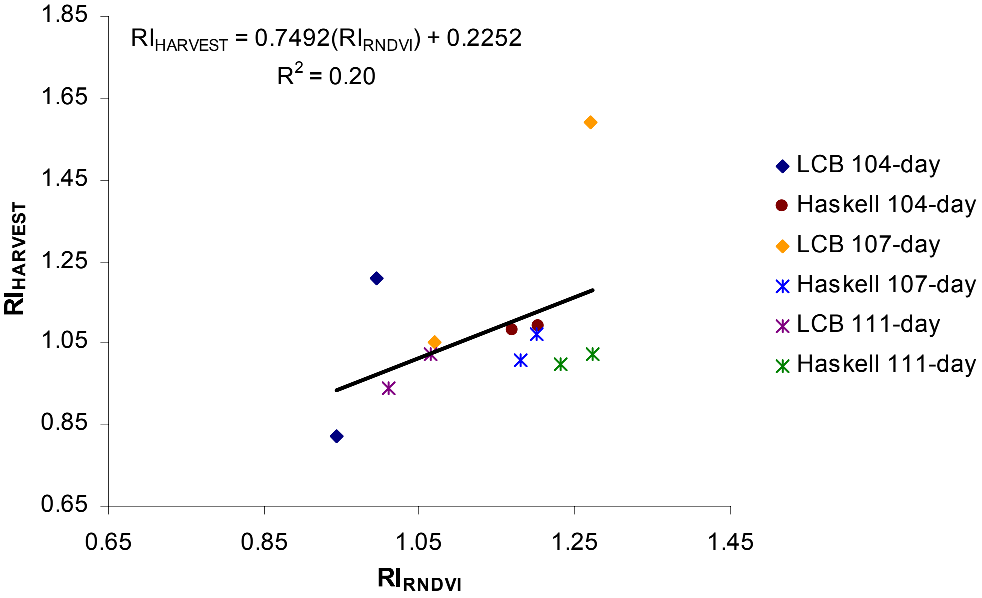


Figure 13. Effect of N rate on GNDVI over time in the 66,690 plants ha $^{-1}$ plant population of the 113-day hybrid at Haskell, OK, 2004.

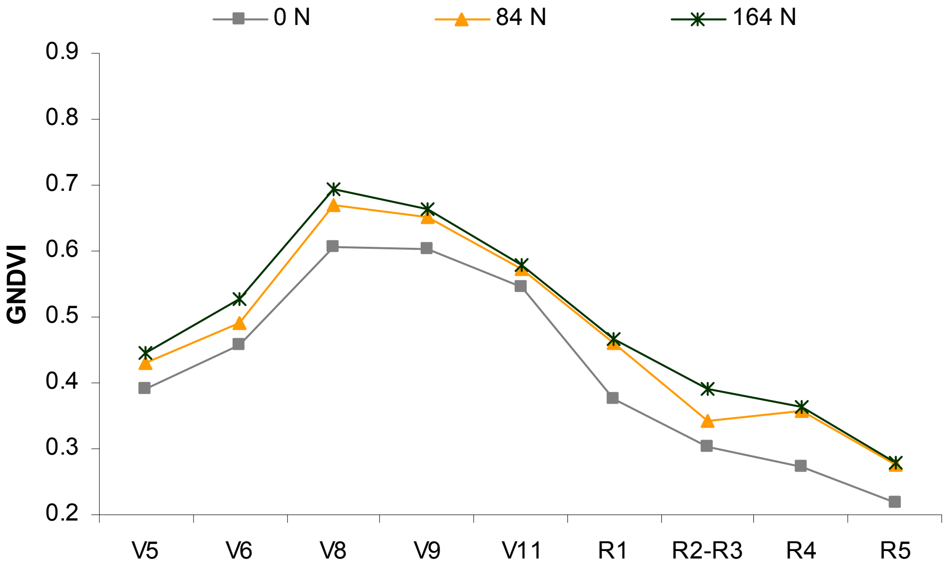


Figure 14. Effect of N rate on RNDVI over time in the 66,690 plants ha $^{-1}$ plant population of the 113bt-day hybrid at Haskell, OK, 2004.

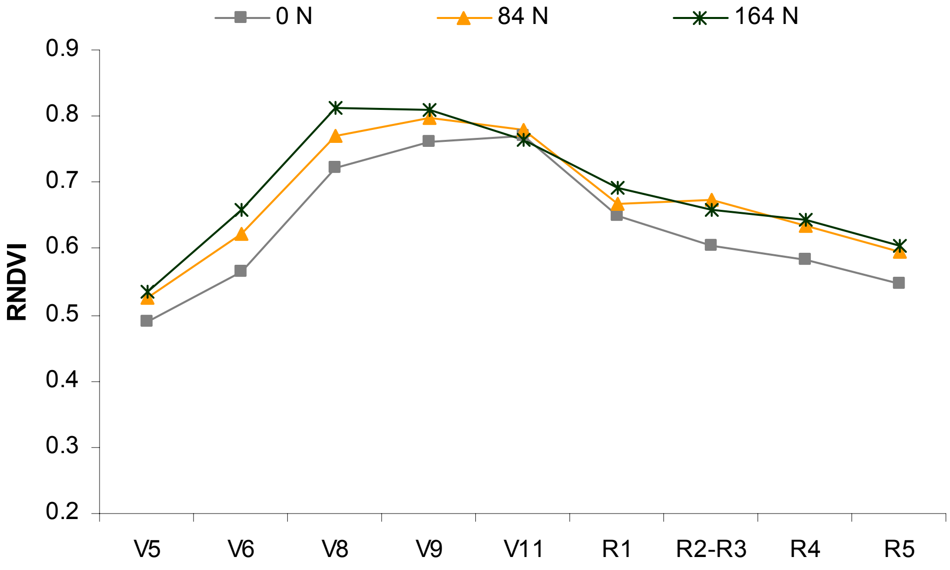


Figure 15. Relationship between RI_{GNDVI} measured at the V8 growth stage and $RI_{HARVEST}$ over three locations, 2004.

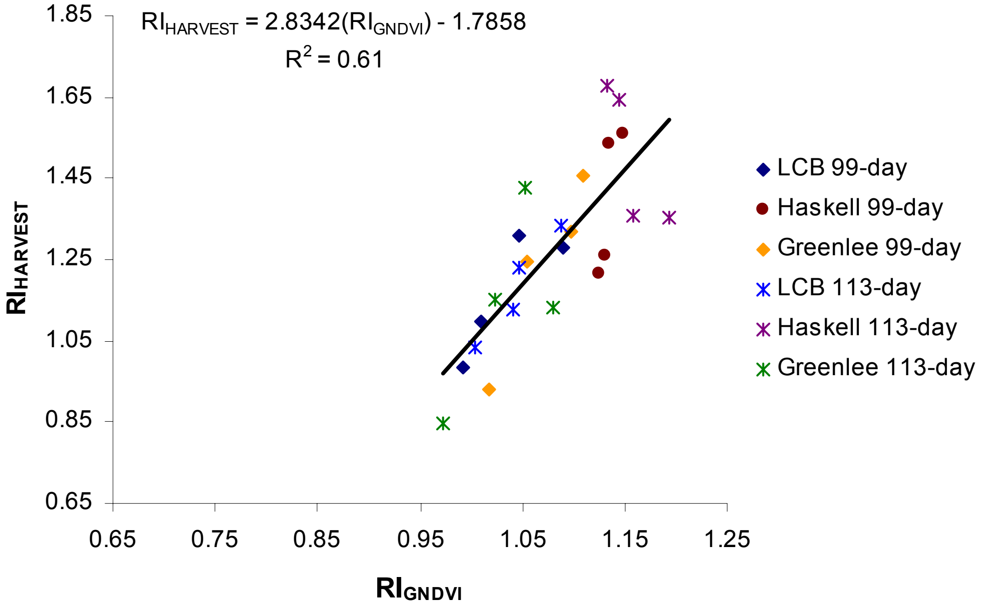


Figure 16. Relationship between RI_{RNDVI} measured at V8 growth stage and $RI_{HARVEST}$ over three locations, 2004.

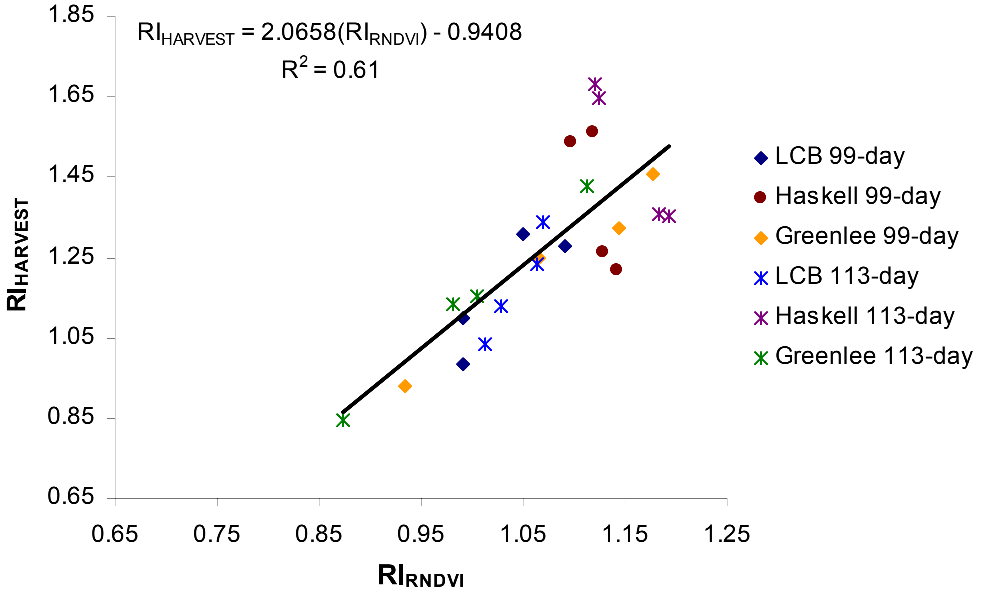
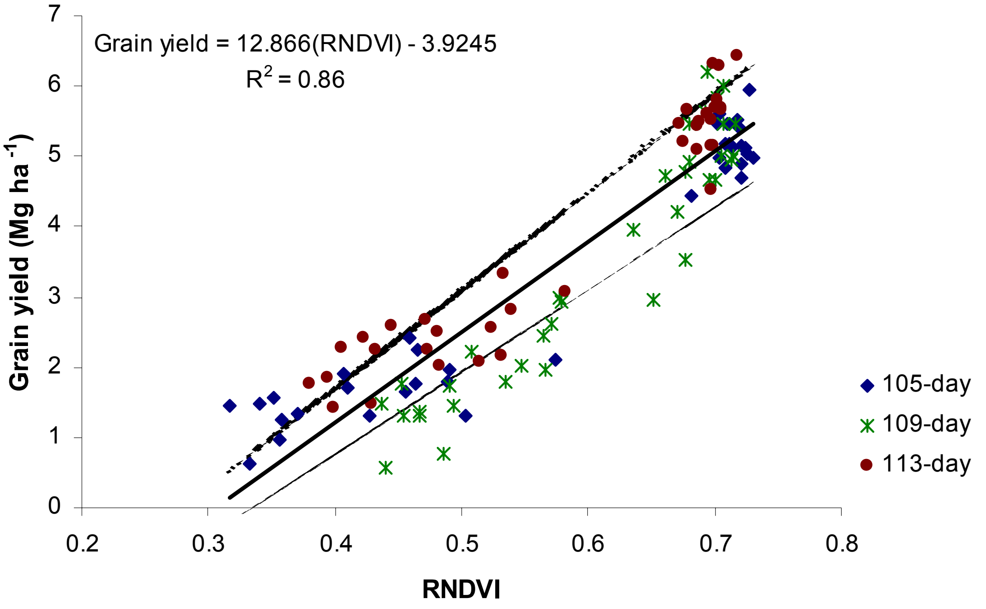
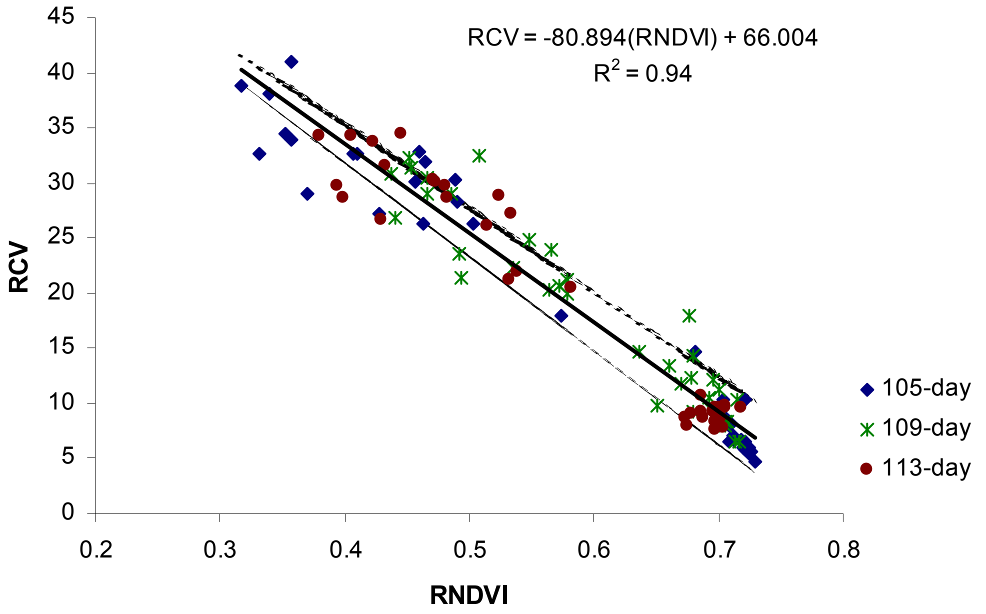


Figure 17. Relationship between grain yield and RNDVI in the R1 growth stage over two locations, 2002.



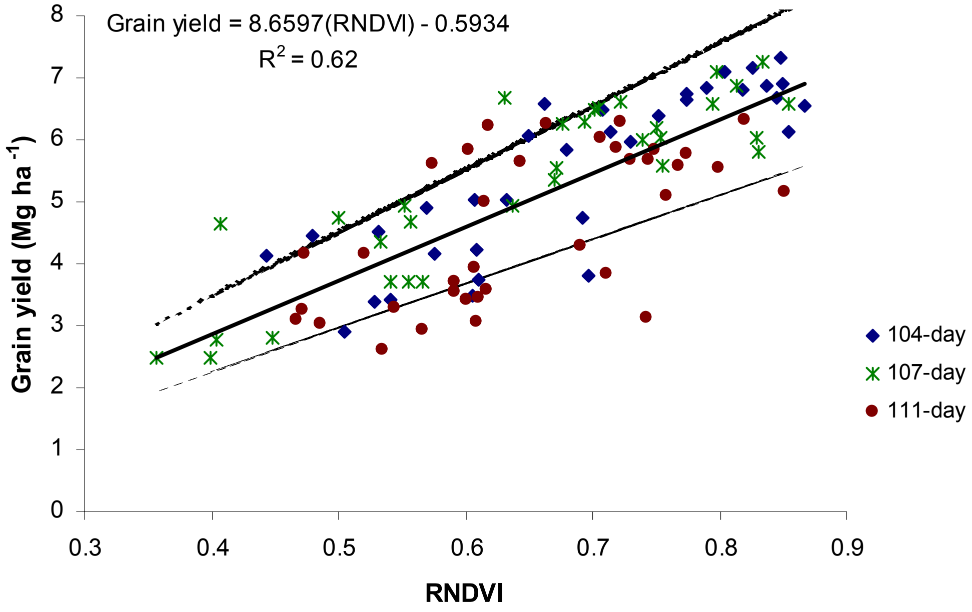
Confidence intervals set at 95%.

Figure 18. Relationship between RNDVI and RCV derived from RNDVI in the R1 growth stage over two locations, 2002.



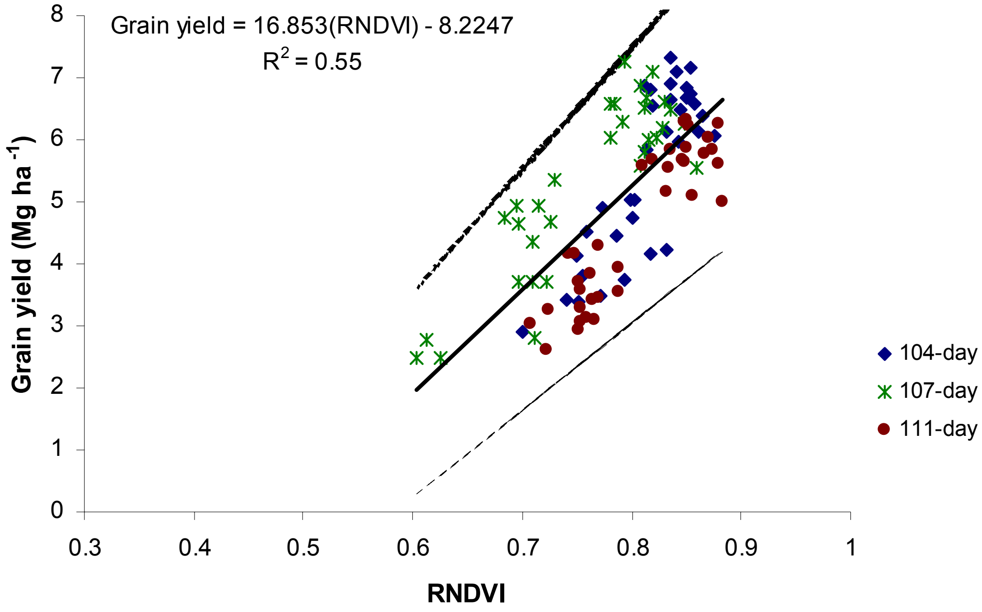
Confidence intervals set at 95%.

Figure 19. Relationship between grain yield and RNDVI of the V8 growth stage over two locations, 2003.



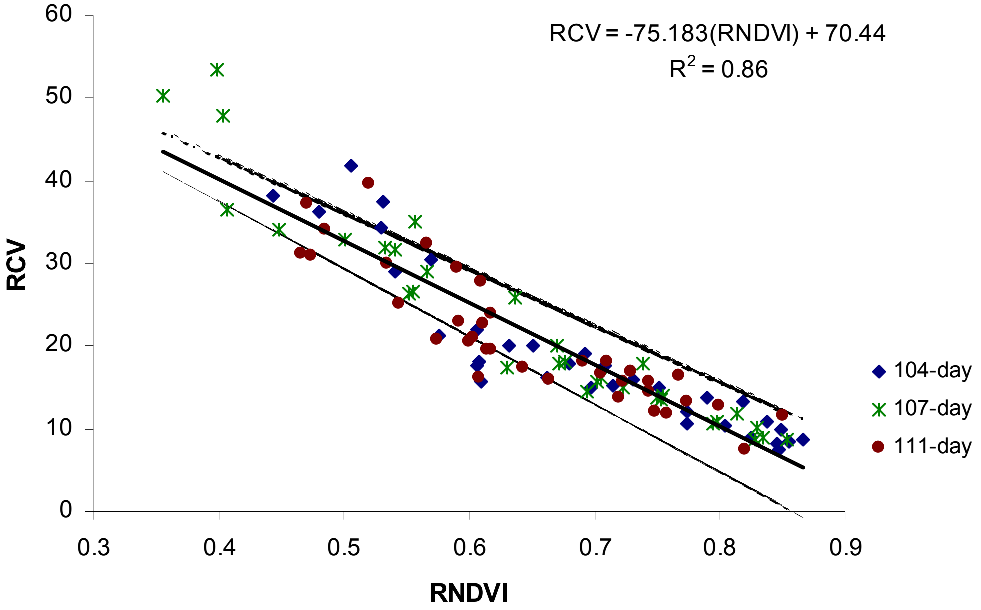
Confidence intervals set at 95%.

Figure 20. Relationship between grain yield and RNDVI of the R2 growth stage over two locations, 2003.



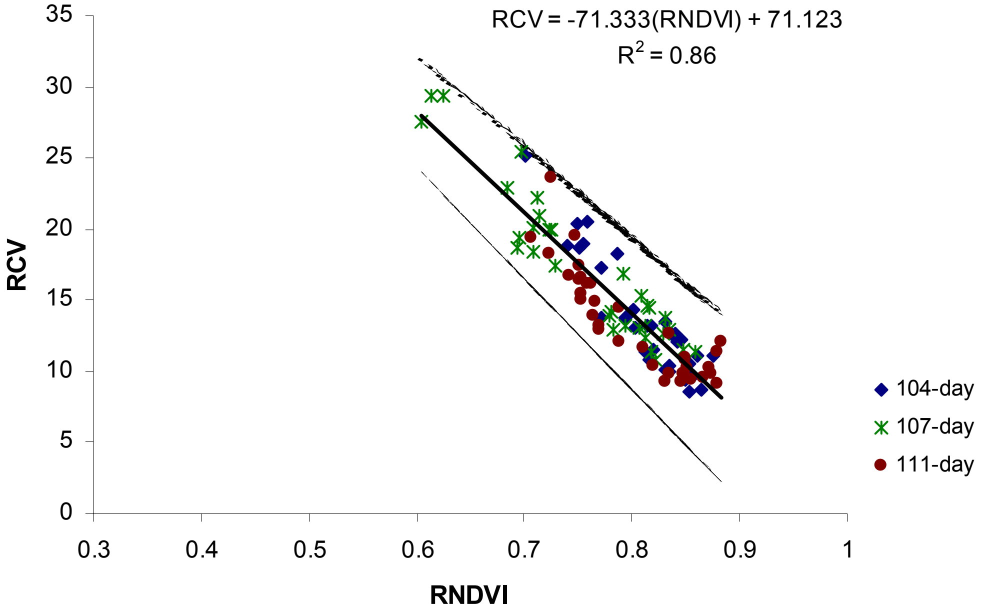
Confidence intervals set at 95%.

Figure 21. Relationship between RNDVI and RCV derived from RNDVI of the V8 growth stage over two locations, 2003.



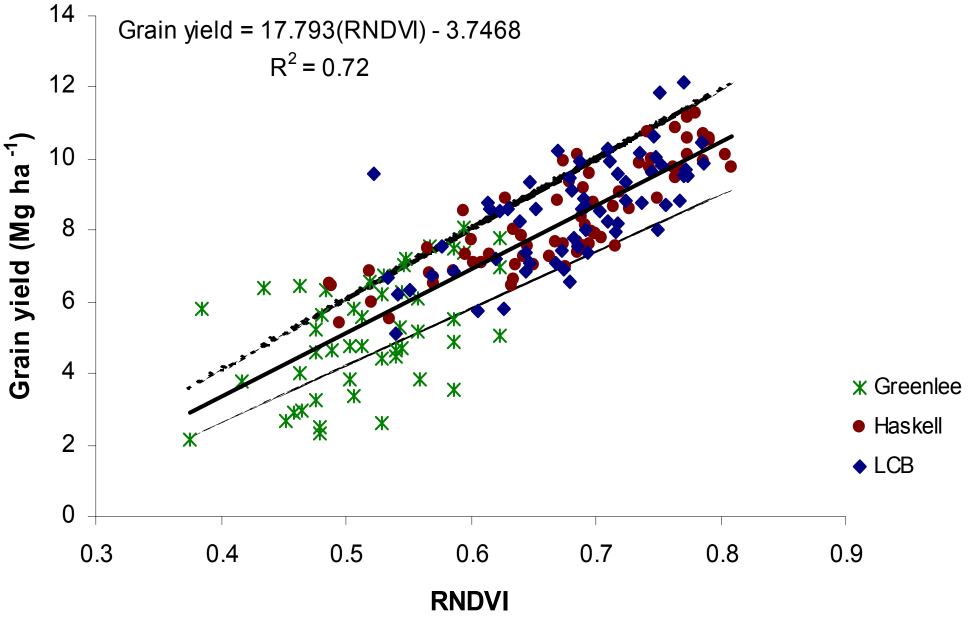
Confidence intervals set at 95%.

Figure 22. Relationship between RNDVI and RCV derived from RNDVI of the R2 growth stage over two locations, 2003.



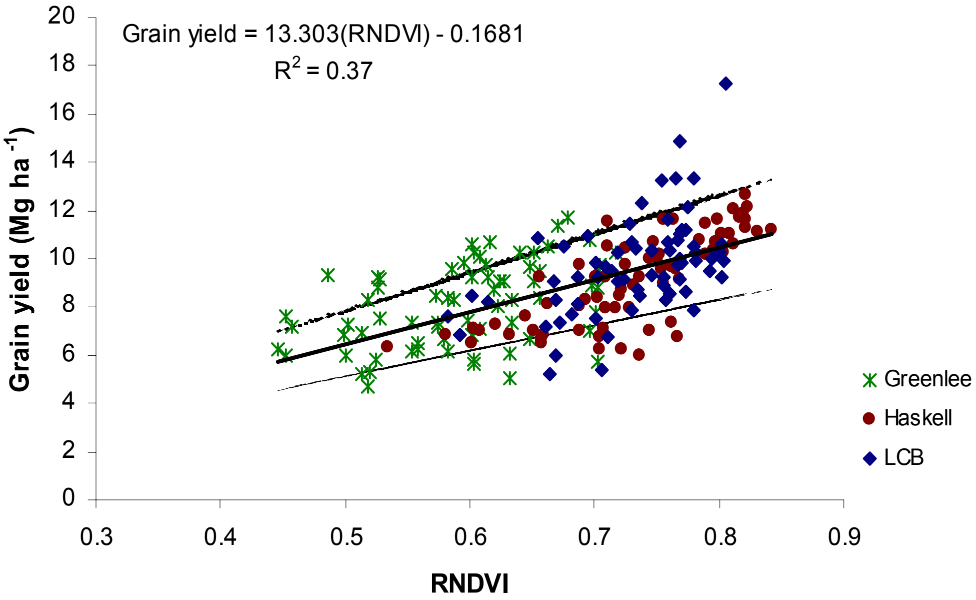
Confidence intervals set at 95%.

Figure 23. Relationship between corn grain yield and RNDVI at V8 growth stage for the 99-day hybrid over three locations, 2004.



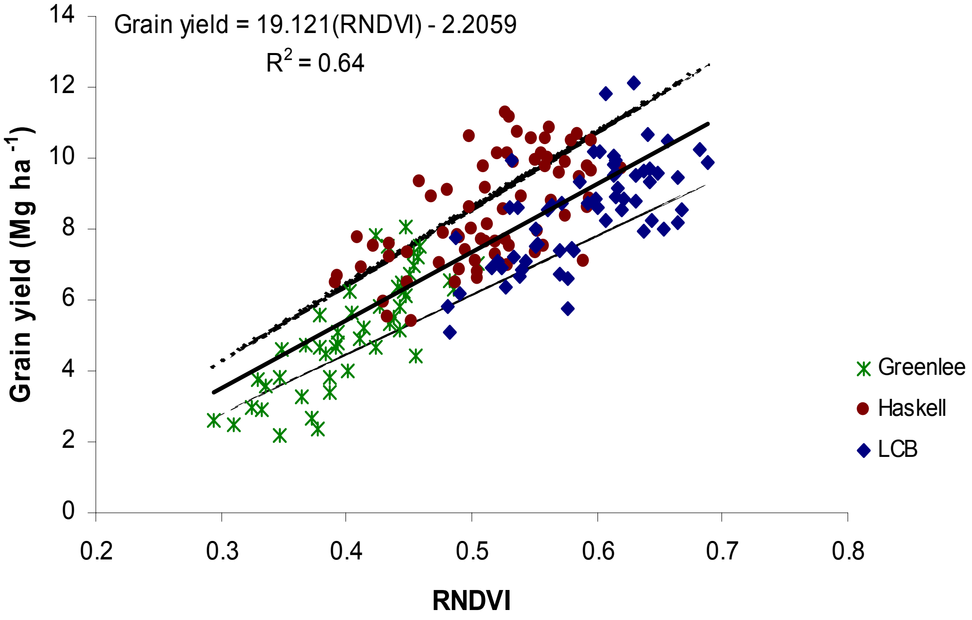
Confidence intervals set at 95%.

Figure 24. Relationship between corn grain yield and RNDVI at V8 growth stage for the 113-day hybrid over three locations, 2004.



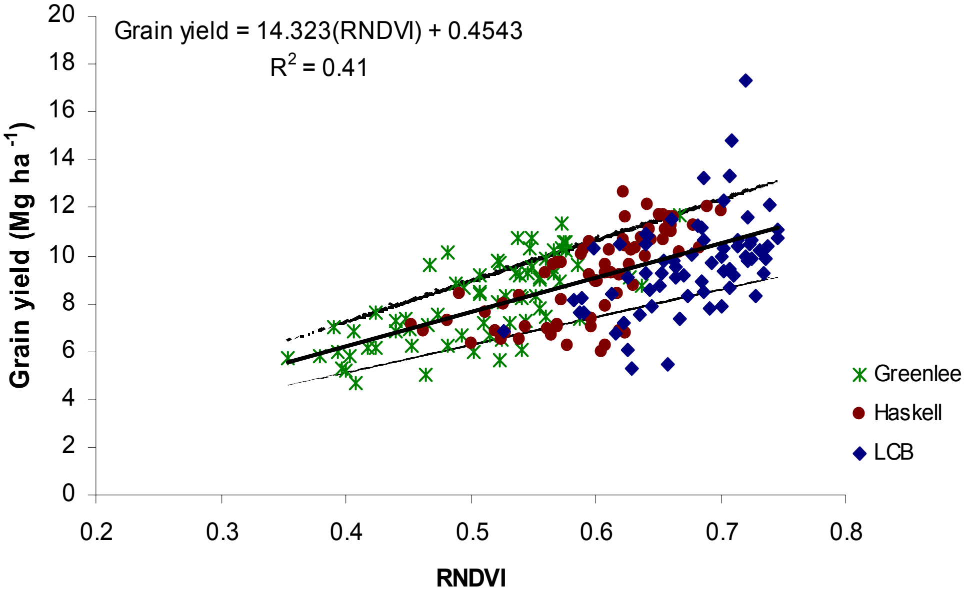
Confidence intervals set at 95%.

Figure 25. Relationship between corn grain yield and RNDVI at R4 growth stage for the 99-day hybrid over three locations, 2004.



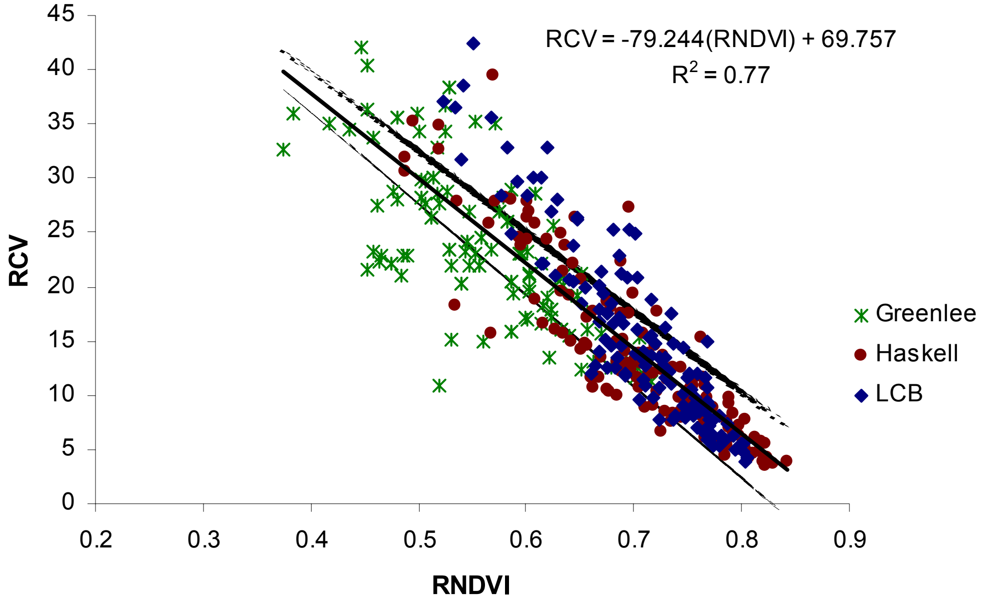
Confidence intervals set at 95%.

Figure 26. Relationship between corn grain yield and RNDVI at R4 growth stage for the 113-day hybrid over three locations, 2004.



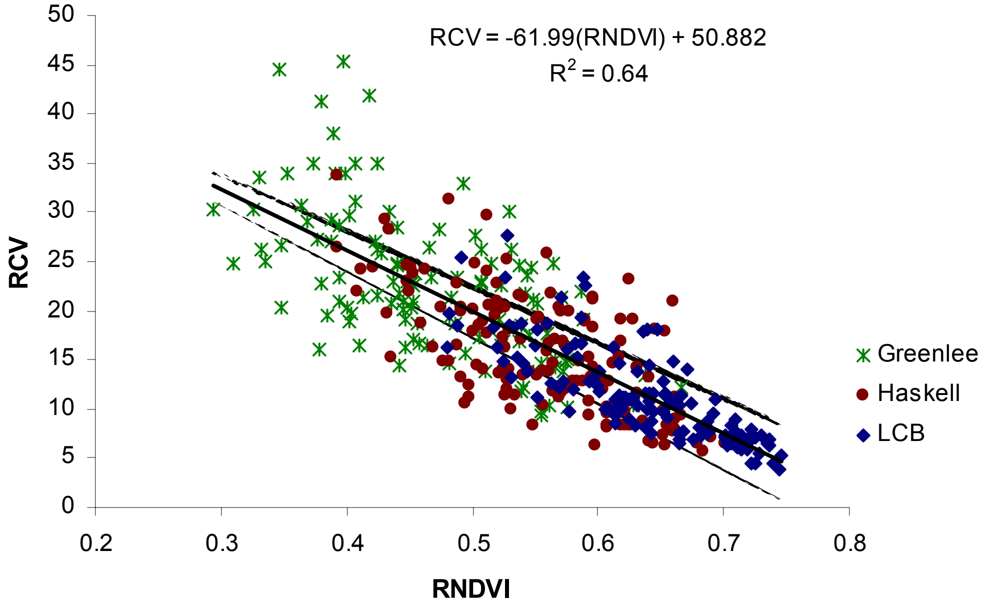
Confidence intervals set at 95%.

Figure 27. Relationship between RNDVI and RCV derived from RNDVI at V8 growth stage for two hybrids over three locations, 2004.



Confidence intervals set at 95%.

Figure 28. Relationship between RNDVI and RCV derived from RNDVI at R4 growth stage for two hybrids over three locations, 2004.



Confidence intervals set at 95%.

EFFECT OF TILLAGE AND ANHYDROUS AMMONIA APPLICATION ON NITROGEN USE EFFEICIENCY OF HARD RED WINTER WHEAT

ABSTRACT

Nitrogen use efficiency (NUE) in cereal grain production is estimated to be 33% throughout the world, and can be lower when N is applied in single, pre-plant applications compared with split N applications. This study was conducted to evaluate tillage system and anhydrous ammonia (AA) application methods on yield, N uptake, and NUE in hard red winter wheat (*Triticum aestivum* L.), using a narrow (10 cm) nozzle spacing on a V-blade (Noble or sweep blade) applicator and wide (46 cm) nozzle spacing on a knife applicator. Over the four-year period evaluated, conventional tillage was significantly higher in grain yield and grain N uptake in five of eight site years over no-till. However, no-till was significantly higher in grain yield and grain N uptake at Lahoma in 2003 where the highest overall grain yield and grain N uptake was observed. Mixed results were evaluated from NUE for tillage; four site years of no significant differences between tillage systems and the other four site years split evenly between conventional till and no-till. The V-blade improved NUE in no-till three site years at Lahoma, but the knife applicator increased NUE the initial year at Efaw in no-till. Previous crop residue disturbance averaged less than 15% for both AA applicators all four, site years. Mid-season plant populations taken during the 2003 and 2004 crop years were insignificant three of the four site years and plant population did not influence grain yield and NUE. No-till crop production reduced

soil compaction at Efaw and the V-blade applicator reduced soil compaction within the no-till at both locations. Although the no-till system showed the potential to produce grain yield and grain N levels comparable to conventional tillage, conventional tillage had a distinct advantage in grain yield and grain N uptake over the four-year duration of this study. A trend indicated that when compared to conventional-till, no-till improved NUE the initial year or so after establishment due to the increased demand of N for immobilization in low soil inorganic N environments. The V-blade application method improved NUE in no-till conditions at one site, potentially due to reduced soil compaction, but neither AA applicator showed an advantage in conventional tillage.

INTRODUCTION

Soil erosion has been a major concern since the beginning of agriculture, but it was not until the Great Dust Bowl of the 1930s that the problem received worldwide attention. With so many deaths caused by black pneumonia and total crop destruction by wind-borne soil in massive volumes, measures were taken to make sure that this would never happen again. Among those new practices was zero tillage. Zero tillage has been used as a means of annual crop production in most parts of the country for well over thirty years, but not in the Southern Great Plains. Anhydrous ammonia (AA) as a nitrogen fertilizer source is very popular in winter wheat (*Triticum aestivum* L.) production in Oklahoma because of lower cost compared to other nitrogen fertilizers. Limited published research has been completed to show the effects of AA in winter wheat production in this area. This study was conducted to determine if tillage and AA application methods affect nitrogen use efficiency (NUE) of winter wheat in Oklahoma.

No-till was originally used as a method to stop soil erosion. Researchers found that planting crops in previous crop stubble greatly reduced the amount of soil removed by water and wind erosion. McGregor et al. (1992) reported that during a 5-year period (1987 through 1991), no-till soybean yielded 44% more than conventional-till yields. Intensive tillage has led to annual sediment discharge of 15.9 Mg ha^{-1} in the southern Great Plains (Smith et al., 1991). McGregor et al. (1992) reports indicated increasing soil losses with time under conventional-till and decreasing soil loses with time for no-till. This study conducted over 14 years; noted no-till soybean yields exceeded those of conventional-till yields by 800 kg ha^{-1} yr^{-1} (McGregor et al., 1999). No-till reduced runoff 1 to 35% over conventional-till and reduced soil loss by 23 to 77% compared to conventional-till (McGregor et al., 1999). King et al. (1995), McIsaac et al. (1990), Pesant et al. (1987) and Lembi et al. (1985), similarly found that long-term no-till practices are effective and practical in reducing rill erodibility and sediment loss. Brenneman and Laflen (1982) and Cogo et al. (1984) concluded that residue cover reduces erosion in one of four ways: 1) dissipation of the energy from raindrop impact: 2) slowing runoff, and increasing flow depth, which in turn reduces the impact of raindrops: 3) absorption of some of the forces from runoff that are usually applied to the soil surface: and 4) creation of small reservoirs of ponded runoff causing deposition.

There have been several other unforeseen advantages of no-till over conventional-till that researchers have discovered over time. Edwards et al. (1990) found that no-till improved soil drainage, while Weersink et al. (1992) stated that no-till reduces labor costs. Aase and Pikul (1995) found that in annual spring wheat production, no-till was the most efficient crop and soil management practice from the standpoint of yield, water use efficiency, soil organic C, and bulk density. However, Mielke et al. (1986), Bruce et al. (1990), Rhoton et al. (1993), and Vyn and Raimbault (1993) have reported that bulk density increases under no-till versus conventional-till. Blevins et al. (1983), Unger (1991), and Ismail et al. (1994) reported that tillage had no effect on bulk density. Alternatively, Lal et al. (1994), Pikul and Aase (1995), and Dao (1993) agreed with Aase and Pikul (1995) reporting that no-till reduced bulk density. After looking at these studies in great detail, it can be concluded that no-till can increase bulk density of soils by increasing soil compaction in saturated clay-textured soils, but in dry clay-textured soils as well as silt and sandy soils of any saturation level, bulk density will decrease with no-till compared to conventional-till. There have been other controversies comparing no-till to conventional-till systems as well as bulk density, one such argument being pH. Blevins et al. (1977) and Dick (1983) found that pH decreased under no-till as compared to conventional-till as nitrogen rates were increased, but Lal et al. (1994) found no effect of tillage on pH.

Research has indicated that soil organic matter content is related to amount of residue returned to the soil (Black, 1973; Campbell and Zentner, 1993;

Eghball et al., 1994; Christensen et al., 1994). In the semiarid regions where dryland wheat is grown, soil organic carbon (C) and nitrogen (N) has declined with years of cultivation (Dodge and Jones, 1948; Haas et al., 1957; Hobbs and Brown, 1957; Young et al., 1960). This loss of soil organic C and N in the Great Plains has been caused by the use of tillage and summer fallow, which have accelerated organic matter decomposition rates and erosion (Ridley and Hedlin, 1968; Haas et al., 1957). Ismail et al. (1994), Lal et al. (1994), Christensen et al. (1994), Unger (1991), and Wood et al. (1991) reported soil organic matter was greater under no-till and increased with time in some instances. Lamb et al. (1985) and Bauer and Black (1981) agreed with long-term studies where virgin soils were put under cultivation, losses of soil organic C and N were much higher for conventional-till than no-till systems. Allison (1973) found that most non-legume crops acquire 30 to 100% of their N nutritional needs from soil organic matter. Bauer and Black (1994) discovered that 1 Mg ha^{-1} of soil organic matter contributed the equivalent of 15.6 kg ha^{-1} of wheat grain yield. Doran (1980), Follett and Schimel (1989), Bakersman and deWit (1970), and Groffman (1984) have reported that microbial activity is generally greater in the first few centimeters of soil under no-till as compared to conventional-till, resulting in reduced organic matter levels in conventional-till as compared to no-till systems. Tillage significantly reduces the diversity of bacteria by reducing both substrate richness and evenness (Lupwayi et al., 1998). Further comparisons showed that no-till enhanced N immobilization and reduced nitrification rates when compared to conventional-till (Doran, 1980; Stinner et al., 1983), often resulting in less nitrate leaching (Elliott et al., 1986; Lamb et al., 1985) and leaving less nitrate in the soil profile (Fenster and Peterson, 1979; Dowdell and Cannell, 1975). Although there are lower nitrate levels in soil profiles in no-till systems, studies have shown that nitrate has been found deeper in the profiles of no-till soils (Eck and Jones, 1992).

The results of a 10-year study have shown that N-mineralization rates were higher in annual cropping systems under no-till, than under conventional-till (Wienhold and Halvorson, 1999). This increased mineralization is caused by increased N stored as labile organic forms. Increased amounts of organic N will supply more nitrogen to crops, which will result in less N required from fertilizers as well as reduced leaching. Wienhold and Halvorson (1999) also believe that higher N rates will increase immobilization because of the increased plant residue resulting from the higher N rates increasing the C/N ratio of the residue. Several other studies have shown that immobilization was higher at lower applied N rates and crop N uptake was less with no-till systems (Kitur et al., 1984; Smith and Sharpley, 1990; Wagger et al., 1985; Black and Reitz, 1972; Cochran et al., 1980; Elliot et al., 1986; Dowdell and Crees, 1980; Knowles et al., 1993; Rice and Smith, 1984). This research has also found evidence that immobilization of surface applied N fertilizers accounts for most of the differences in N response between no-till and conventional-till systems. Their research also shows that no-till systems required more N fertilizer when surface applied at lower rates. However, Fox and Bandel (1986) discovered that no-till increased mineralization compared to conventional-till during the latter part of the growing season. Rice and Smith (1982) and Rodriguez and Giambiagi (1995) found that no-till enhances denitrification, because of the increase in soil water supply commonly occurring in no-till, reducing the amount of aerobic activity in the soil. There are some conflicting views between Wienhold and Halvorson (1999) and the others stated above, but keep in mind that the Wienhold and Halvorson (1999) study was long-term (10 years), while the others were short-term (5 years or less). Wienhold and Halvorson were the only ones to account for the build up of soil organic matter (OM), and it would not be possible for soil OM to be a major factor in a short-term study.

Water use efficiency (WUE) is probably the most important advantage to no-till systems over conventional-till. Bonfil et al. (1999) found that no-till management over a 5-year study increased yields 62 to 67% in wheat-fallow rotations and 18 to 75% in continuous wheat over conventional-till in semiarid regions of Israel. Cantero-Martinez et al. (1999), Peterson et al. (1996), and Kolberg et al. (1996) all found similar results in Australia and the Great Plains of the United States. No-till increases WUE by reducing evaporation, increasing water infiltration, improving soil structure, which in turn enhances root development (Aase and Pikul, 1995; Holland and Felton, 1989; Jones and Popham, 1997; Norwood, 1994; Smika and Unger, 1986; Waddell and Weil, 1996; Kirkegaard et al., 1995; Merrill et al., 1996; Dao, 1993; Lopez-Bellido et al., 1996). Winter wheat is now being produced successfully and out-yielding spring wheat in the Northern Great Plains of the United States and Canada without requiring a fallow period, when no-till is used with adequate N fertilization

(Halvorson et al., 1999; Entz and Fowler, 1991). By increasing stored water in the soil, no-till has reduced the detrimental effects of climate variability on annual winter wheat production (Dao, 1993).

Studies have shown that deep placement of N can minimize volatilization or immobilization losses. Placement of N is a major factor of N utilization and a 20% increase in NUE has been observed with band placement, compared to surface broadcast (Soper et al., 1971; Toews and Soper, 1978; Tomar and Soper, 1981). They found that N immobilization and increased N uptake could be achieved by reducing fertilizer contact with the surface residue. Rao and Dao (1996) found that final grain yield and grain N content were not affected by N placement in plowed plots. No-till improved grain yield by 32% for a below the seed row (BL) application and 15% for between the rows (BT) application. Grain N content was increased by 33% for BL and 25% for BT as compared to a surface broadcast application.

Anhydrous ammonia has the highest amount of fixation of all the forms of ammonium releasing fertilizers (Young and Cattani, 1962). Since surface applications of ammonium-based N can be lost to the atmosphere up to 70% from volatilization (Hamid and Mahler, 1994) and nitrate more readily leaches from the soil than ammonia (Blue and Eno, 1954), anhydrous ammonia (AA) has the greatest potential to increase NUE in single pre-plant applications. Some researchers have agreed that AA moves more in sandy soils with low CEC and low moisture than finer textured soils with high CEC, but under moist conditions and at depths over 10 cm, high rates of AA can be applied with little or no loss from volatilization (Swart et al., 1971; Baker et al., 1959; Blue and Eno, 1954; McDowell and Smith, 1958; Papendick and Parr, 1966). McDowell and Smith (1958) found that ammonia losses were reduced considerably when the applications were changed from 102 cm to 41 cm spacings. Swart et al. (1971) supported this research with his own findings that show differences between 102 cm and 41 cm (greater yields and less ammonia loss at 41 cm), but no differences between 15 cm and 41 cm. Swart et al. (1971) went on to report while vertical movement remains constant (4 to 5 cm) regardless of N rate, higher N rates usually cause greater lateral movement. Other research has suggested that AA decreases pH and depletes the amount exchangeable Ca and Mg leading to decreases in yield due to higher levels of aluminum accumulation (Bouman et al., 1995; Robbins and Voss, 1989).

OBJECTIVE

This experiment was conducted to determine the effects of tillage and AA application rate and placement on grain yield, grain N, and NUE of hard red winter wheat.

MATERIALS AND METHODS

This experiment was conducted initially (2000-02) as a Master of Science research project and continued in 2003 as part of a Doctor of Philosophy research project. Two experimental sites were established in the fall of 2000, one near Stillwater, OK at the Agronomy Research Station (Easpur loam fine-loamy, mixed, superactive, thermic Fluventic Haplustoll), and one in Lahoma, OK at the North-Central Oklahoma Research Station (Grant silt loam fine-silty, mixed, thermic Udic Argiustoll). Initial soil test results are reported in Table 1. The experiment employed an N rate by N method factorial arrangement in a thrice replicated, randomized complete block design within each level of tillage. Individual plots measured 3.0 x 4.6 m.

Anhydrous ammonia (82-0-0) was applied at rates of 0, 61, 123, and 185 kg N ha^{-1} using two different methods of injection. A rolling coulter applicator (DMI) with five knives spaced 46 cm apart at a depth of 15 cm (Figure 1), a method commonly used in nitrogen application of winter wheat, was used as one method of AA application. The Noble or undercutting blade (V-Blade), an experimental applicator, was used as the other method of AA application. The V-blade applicator has a single coulter, centered in front of the point of the undercutting blade, where AA was applied in 10 cm bands at a depth of 10 cm and a total width of 1.5 meters (Figure 2). Wheat residue cover was measured before and after AA applications on the no-till starting in 2002, using a modified, line-intercept method as a means of determining residue disturbance by AA application method (Morrison et al., 1997).

The winter wheat variety 'Jagger' was planted at both sites (planting and fertilizer dates are reported on Table 2). At the Lahoma site, a seeding rate of 95 kg ha^{-1} was planted the initial year and increased to 125 kg ha^{-1} the second year and was sustained through the third and fourth years in 19 cm rows within wheat stubble from the previous year as well as conventionally worked ground. Triple super phosphate (0-46-0) was applied pre-plant at a rate of 90 kg P_2O_5 ha^{-1} the first two years at Lahoma to alleviate possible phosphorous deficiencies, however starting in 2002 at both locations, triple super phosphate was banded with the seed at a rate of 28 kg P_2O_5 ha^{-1}. At the Efaw site, a seeding rate of 125 kg ha^{-1} was planted in 15 cm rows in grain sorghum stubble from the previous summer as well as conventionally worked ground the first two years, but beginning in 2002 the same seeding rate was planted in 18 cm rows within wheat stubble from the previous year as well as conventionally worked ground. In this case, conventional tillage at both sites consisted of disking throughout the summer, and preparing the seedbed with a field cultivator.

Beginning in 2002, plant counts were taken from a 0.54 m^2 area out of the center of each plot for evaluation of plant stands as a potential independent variable or covariate. By-plot soil samples were taken in the summer of 2002 at 0-15 cm depth and in 2004 at 0-15 and 15-30 cm to determine if tillage and/or AA application method had an effect on soil properties. Furthermore, by-plot bulk density measurements using a cylinder (7.5 x 15 cm) and soil compaction measurements using an electronic cone penetrometer (SC 900 Soil Compaction Meter, Spectrum Technologies, Inc.) at 2.5 cm intervals, to a depth of 30 cm were taken post-harvest in 2004.

Wheat grain was harvested with a Massey Ferguson 8XP experimental combine, removing an area of 2.0 x 4.6 m from the center of each plot. A Harvest Master yield-monitoring computer installed on the combine was used to record yield data. Grain yield from each plot was determined and a sub-sample was taken for total N analysis. Response indices (RI) were calculated by dividing the highest N treated grain yield average by the check (0 N rate) average. Grain samples were dried in a forced air oven at 66°C, ground to pass a 140 mesh sieve (100 um), and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer (Schepers et al., 1989). Analyses of variance and single degree of freedom contrasts were performed using SAS (SAS, 1990).

RESULTS AND DISSCUSION

Grain Yield

Delayed planting due to inclement weather at planting time (Table 2) resulted in poor establishment and limited tillering and wheat yield responses to applied N were minimal in 2001 at both locations. However, grain yields were much higher in all three of the preceding years, particularly in 2003 and 2004 when response to applied N was high. While there were no differences between tillage systems at Efaw in 2001 and 2004, conventional tillage did result in significantly higher grain yields at Efaw in 2002 and 2003 (Table 3). Similar advantages in grain yield were observed for conventional tillage in 2001, 2002, and 2004 at Lahoma, but in 2003 the no-till treatments had significantly higher grain yields with three out of eight treatments averaging 5 Mg ha^{-1} (Table 4).

Grain yield was only significantly affected by N application method for the Lahoma no-till in 2002 when the V-blade applicator increased yield over the knife applicator, otherwise there was no significant difference between the applicators on grain yield for either tillage system. At Efaw a positive linear response to N using both applicators was observed in the no-till treatments in all four years (Table 3). A positive linear trend was also observed at Efaw in the conventional till treatments with the knife applicator in 2001 and 2004 and with the V-blade applicator in 2001 (Table 3). A quadratic response to N occurred with the V-blade applicator for conventional till in 2003 and 2004.

At Lahoma a positive linear response to N was observed with the knife applicator for no-till in 2001 and 2004 and for conventional till in 2003 (Table 4). Highly significant quadratic responses to N rate occurred at Lahoma with the knife applicator for no-till in 2002 and 2003, as well as in 2004 for the conventional till (Table 4). Quadratic N rate responses for the V-blade applicator occurred at Lahoma for no-till in 2001, 2002, and 2004, but for conventional till in 2003. Although not specifically measured, increased N immobilization was likely present in no-till plots. Highly significant interactions were found between tillage and N rate in 2001, 2002, and 2004 at Lahoma, also response index (RI) values were greater in five of eight site years for no-till when compared to conventional-till. The lack of an interaction at the Efaw site in all four years would imply that immobilization did not greatly affect N availability for wheat production, but N response was high in 2003 and 2004 as were grain yields. This indicates that N availability was only limited at Efaw during high yielding years possibly due to limited sinks of plant available N in the soil.

Grain N Uptake

Grain N uptake was consistent with results for grain yield at both locations; low the initial year and relativity high the following years. Grain N uptake in the conventional tillage system was significantly higher than no-till at Efaw the first three years, but not in 2004 (Table 5). At Lahoma there was 20 and 18 kg ha^{-1}

advantages found for grain N uptake under conventional tillage compared to no-till in 2002 and 2004, but in 2003 no-till was significantly higher in grain N uptake than conventional till (Table 6). No significant differences were found in 2001 between the tillage practices. In 2001, knife application of AA increased grain N uptake over that of the V-blade in no-till at Efaw, but the V-blade increased grain N uptake over knife application of AA in conventional-till the second year. At Lahoma in 2002, knife application of AA had an advantage in conventional-till; conversely the V-blade had an advantage in no-till. No significant differences were found between the AA applicators for either tillage in 2003 and 2004 at either location.

Positive linear responses to N rate were detected in all four years at Efaw for both applicators in the no-till (Table 5). Positive linear N responses were observed at Efaw with the knife applicator for conventional till in 2001, 2002, and 2004. However the V-blade applicator showed a positive linear response for conventional till just in 2001, but the V-blade applicator did show a quadratic response for conventional till in 2004. At Lahoma, positive linear N responses were observed with the knife applicator in 2001 and 2004 for no-till and in 2003 for conventional till (Table 6). Quadratic N responses with the knife applicator occurred for conventional till in 2004 and for no-till in 2003. Positive N response to the V-blade applicator at Lahoma occurred for no-till in 2003 and 2004. However, quadratic N responses to the V-blade applicator were seen for conventional till in 2003 and for no-till in 2001 and 2002. A significant interaction was found between tillage and N rate at Lahoma for grain N uptake three out of four years, maintaining the consistency established in grain yield that immobilization did take place in the no-till plots.

Nitrogen Use Efficiency

Nitrogen use efficiency was generally low the first three years at Efaw and the first two years at Lahoma. At Efaw, NUE was significantly higher for no-till in 2003 when compared to conventional till (Table 7). Nitrogen use efficiency was significantly higher at Lahoma for the no-till in 2001, but in 2003 the conventional till was higher (Table 8). Although at Lahoma both applicators were very responsive to N for conventional tillage in 2003 and the knife applicator in 2004, the V-blade applicator showed no response to N for conventional till in 2004. This indicates that experimental error effected N response for the V-blade applicator and created the false-positive result of no-till significantly improving NUE in 2004. At Efaw, the knife applicator improved NUE over the V-blade in no-till the initial year, but there were no significant differences in NUE between the AA applicators in either tillage practice the following years. The V-blade applicator increased NUE over knife applied AA at Lahoma in the no-till during the 2001, 2002, and 2004 crop years.

A quadratic N response to NUE for the knife applicator was observed in the no-till during the 2003 crop year at Efaw (Table 7). At Lahoma negative linear N responses to NUE occurred for the knife applicator in conventional till during the 2002, 2003, and 2004 crop years (Table 8). Negative linear N responses to NUE were observed for the V-blade applicator at Lahoma in conventional till the first three years and in no-till during the 2001, 2002, and

2004 crop years. Significant interaction between tillage and N method was detected the initial year at Efaw as well as in 2002 and 2004 at Lahoma, further revealing that tillage practices affected applicator efficiency.

Additional Parameters

In light of conflicting results being evaluated for the first two years of data collection, additional parameters were measured starting in 2003. Previous crop residue coverage was measured using a modified, line-intersect method in the no-till at both sites before and after AA application to estimate residue disturbance. Of the four site years of residue coverage data, a significant difference was only found between the AA applicators at Efaw in 2003 where the knife applicator caused less disturbance than the V-blade (data not shown). Furthermore, residue disturbance averaged less than fifteen percent each year. However, while the modified, line-intersect method prevented potential bias and inaccuracy from using a visual estimate of residue coverage and disturbance, the modified method limited accuracy to plus or minus five percent. As a result, small differences in residue disturbance that occurred between the AA applicators may have been overlooked.

In addition to residue coverage and disturbance, plant population was measured mid-season during the 2003 and 2004 crop years. Significant differences were noted for tillage and N method at Efaw in 2003 with the no-till treatments having higher plant populations than the conventional till and V-blade application method having higher plant populations in both tillage practices.

However, a linear relationship failed to exist between plant population and residue coverage at Efaw in 2003 and no significant differences were found at Efaw in 2004 or either year (2003-2004) at Lahoma (data not shown). This data indicates that while plant population was influenced by AA application method at Efaw in 2003, an additional, unidentified soil characteristic other than residue coverage was improved by the V-blade applicator over the knife. Furthermore, no significant differences were found between the AA applicators for grain yield or NUE at Efaw in 2003, signifying that some other effect has caused the V-blade advantage since plant population did not influence either grain yield or NUE.

Post-harvest by-plot soil samples were collected after the 2002 and 2004 crop years. In 2002, surface samples (0-15 cm) were taken, but in 2004 surface and subsoil samples (15-30 cm) were collected. While complete data analysis was conducted on the soil samples, only nitrate (NO_3-N) and ammonium (NH_4-N) levels were found to be significant. The 2002 NO_3-N levels at Lahoma were significantly higher for the knife applicator in both tillage treatments (Table 9). Furthermore, a positive linear NO_3-N response to N rate was observed in the conventional till for the knife applicator and a quadratic NO_3-N response was observed in the no-till for the knife applicator. In 2004, no significant differences were observed in the conventional till at Lahoma, however in no-till higher NO_3-N levels were found in the surface soil over the subsoil. While at Lahoma no NO_3-N level differences occurred between the AA applicators in the no-till, quadratic NO_3-N responses to N rate were found in the surface soil with the V-blade applicator and in the subsoil with the knife applicator (Table 9). At Efaw, the

2002 NO_3-N levels showed a positive linear response to N rate in the conventional till with the V-blade method, however no other significant differences were found (Table 10). In 2004 NO_3-N levels were significantly higher at Efaw in the no-till as well as in the surface soil of both tillage systems (Table 10). While no differences occurred between the AA applicators in 2004 NO_3-N levels, positive linear NO_3-N responses were found for the V-blade applicator in the surface soil of both tillage systems.

Ammonium soil test levels at Lahoma in 2002 were significantly higher in the no-till than the conventional till. In addition, positive linear NH_4-N responses to N rate were evaluated for the knife applicator in both tillage systems and a quadratic NH_4-N response was evaluated for the V-blade applicator in the conventional till. In 2004 the V-blade applicator was significantly higher in surface soil NH_4-N for the conventional tillage and positive linear NH_4-N responses to N rate were found in the surface soil with the knife applicator for both tillage systems. At Efaw NH_4-N levels in 2002 were found to be significantly higher in the no-till, but no other significant differences were seen. In 2004 at Efaw, NH_4-N levels were significantly higher in the surface soil of the no-till otherwise no significant differences were found. Indicating that while some significant NO_3-N and NH_4-N trends were found, these trends did not directly and/or consistently affect N response in the dependent variables (grain yield and NUE) and that some other factors were influencing N uptake in this trial.

Finally, soil compaction was evaluated after the 2004 harvest, measuring bulk density (g cm^3) and resistance (k Pa) in order to determine if tillage and/or

AA application method influenced soil compaction over the four-year period. Bulk density was considerably lower at the Lahoma site compared to Efaw, but no significant differences in bulk density were found in the treatments at either location (data not shown). At Lahoma, the knife applicator had greater soil compaction between the 0-15 and 25-30 cm depths in the no-till and at the 7.5 and 22.5-25 cm depths in the conventional till compared to the V-blade (Figure 5). No significant differences resulted between the tillage systems at Lahoma. However, at Efaw no-till significantly reduced soil compaction at the 0-5 and 15-20 cm depths (Figure 6). Furthermore, the knife applicator had greater soil compaction between the 2.5-12.5 and 27.5-30 cm depths in no-till at Efaw compared to the V-blade, but no differences were found between the AA applicators in conventional till. No-till crop production reduced soil compaction at Efaw and the V-blade applicator reduced soil compaction within the no-till at both locations, but NUE was only improved with the V-blade in no-till at Lahoma and no-till only improved NUE at Efaw one of four years. However, the Efaw soil penetrometer data confirms the presence of a plough pan or root-limiting layer characteristic of intensively tilled soil between the 12.5-17.5 cm depths across both tillage systems (Figure 6). Potentially this explaining the limited effectiveness of the V-blade at Efaw and a possible component of the generally lower grain yields observed at Efaw compared to Lahoma.

CONCLUSIONS

Although the no-till system showed the potential to improve grain yield and grain N levels compared to conventional tillage, conventional tillage had a distinct advantage in grain yield and grain N uptake over the four-year duration of this study. Nitrogen use efficiency was low at both locations the first two years of the experiment and a trend demonstrated no-till to have an advantage the initial year or so after establishment due to the increased demand of N for immobilization in low soil inorganic N environments. A trend indicates that over time N response in conventional till increased tremendously along with grain yield and eventually exceeded no-till. Furthermore, the 61 kg ha^{-1} N rate appeared optimum in conventional till while the 123 kg ha-1 N rate appeared optimum in no-till, suggesting that no-till required higher additional N to maximize grain yield. The V-blade applicator improved grain yield in no-till at one site. The V-blade application method improved NUE in no-till conditions at one site, potentially due to reduced soil compaction, but neither AA applicator showed an advantage in conventional tillage. Previous crop residue disturbance averaged less than fifteen percent for both AA applicators all four site years and residue disturbance did not influence the AA application effects. Mid-season plant populations taken during the 2003 and 2004 crop years were insignificant three of the four site years and plant population did not influence grain yield and NUE.

REFERENCES

Aase, J.K., and J.L. Pikul. 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87:652-656.

Allison, F.E. 1973. *Soil Organic Matter and its Role in Crop Production*. Elsevier Science Publishing Co., Amsterdam.

Baker, J.H., M. Peech, and R.B. Musgrave. 1959. Deterimination of application losses of anhydrous ammonia. Agron. J. 51:361-362.

Bakersman, W.A.P., and C.T. deWit. 1970. Crop husbandry on naturally compacted soils. Neth. J. Agric. Sci. 18:225-246.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166-1170.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185-193.

Black, A.L., and L.L. Reitz. 1972. Phosphorus and nitrate-nitrogen immobilization by wheat straw. Agron. J. 64:782-785.

Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. Soil Sci. Soc. Proc. 37:943-946.

Blevins, R. L., G.W. Thomas, and P.L. Cornelius. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69:383-386.

Blevins, R.L., G.W. Thomas, M.S. Smith, W.W. Frye, and P.L. Cornelius. 1983. Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. Agron. J. 3:135-146.

Blue, W.G., and C.F. Eno. 1954. Distribution and retention of anhydrous ammonia in sandy soils. Soil Sci. Soc. Amer. Proc. 18:420-424.

Bonfil, D.J., I. Mufradi, S. Klitman, and S. Asido. 1999. Wheat grain yield and soil profile water distribution in a no-till arid environment. Agron. J. 91:368-373.

Bouman, O.T., D. Curtin, C.A. Campbell, V.O. Biederbeck, and H. Ukrainetz. 1995. Soil acidification from long-term use of anhydrous ammonia and urea. Soil Sci. Soc. Am. J. 59:1488-1494.

Brenneman, L.G., and J.M. Laflen. 1982. Modeling sediment deposition behind corn residue. Trans. ASAE. 25:1245-1250.

Bruce, R.R., G.W. Langdale, and A.L. Dillard. 1990. Tillage and crop rotation effect on characteristics of a sandy surface soil. Soil Sci. Soc. Am. J. 54:1744-1747.

Campbell, C.A., and R.P. Zenter. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J. 57:1034-1040.

Cantero-Martinez, C., G.J. O'Leary, and D.J. Connor. 1999. Soil water and nitrogen interaction in wheat in a dry season under a fallow-wheat cropping system. Australian Journal of Experimental Agriculture. 39:29-37.

Christensen, N.B., W.C. Lindemann, E. Salazar-Sosa, and L.R. Gill. 1994. Nitrogen and carbon dynamics in no-till and stubble mulch tillage systems. Agron. J. 86:298-303.

Cochran, V.L., L.F. Elliot, and R.I. Papendick. 1980. Carbon and nitrogen movement under surface applied wheat (*Triticum aestivum*) straw. Soil Sci. Soc. Am. J. 44:978-982.

Cogo, N.P., W.C. Moldenhauer, and G.R. Foster. 1984. Soil loss reductions from conservation tillage practices. Soil Sci. Soc. Am. J. 48:368-373.

Dao, T.H. 1993. Tillage and winter wheat residue management effects on water infiltration and storage. Soil Sci. Am. J. 57:1586-1595.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47:102-107.

Dodge, D.A., and H.E. Jones. 1948. The effect of long-time fertility treatments on the nitrogen and carbon content of a prairie soil. J. Am. Soc. Agron. 40:478-485.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Dowdell, R.J., and R.Q. Cannell. 1975. Effect of ploughing and direct drilling on soil nitrate content. J. Soil. Sci. 26:53-61.

Dowdell, R.J., and R. Crees. 1980. The uptake of N-labeled fertilizer by winter wheat and its immobilization in a clay soil after direct drilling or plowing. J. Sci. Food Agric. 31:992-996.

Eck, H. V., and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Edwards, W.M., M.J. Shipitalo, L.B. Owens, and L.D. Norton. 1990. Effect of *Lumbricus terrestris* L. burrows on hydrology of continuous no-till corn fields. Geoderma 46:73-84.

Eghball, B., L.N. Mielke, D.L. McCallister, and J.W. Doran. 1994. Distribution of organic carbon and inorganic nitrogen in soil under various tillage and crop sequences. J. Soil Water ConServ. 49:201-205.

Elliott, E.T., P.W. Tracy, G.A. Peterson, and C.V. Cole. 1986. Leaching of mineralized N is less under no-till cultivation. P. 53-54. *In* Trans. Int. Congr. Soil Sci. 13th, Hamburg, Germany. Vol. 6. Congr. Centurum, Hamburg.

Entz, M.H., and D.B. Fowler. 1991. Agronomic performance of winter versus spring wheat. Agron. J. 83:527-532.

Fenster, C.R., and G.A. Peterson. 1979. Effects of no-tillage fallow compared to conventional tillage in a wheat-fallow system. Nebraska Agic. Exp. Bull. 289.

Follett, R.F., and D.S. Schimel. 1989. Effect of tillage practices on microbial biomass dynamics. Soil Sci. Soc. Am. J. 53:1091-1096.

Fox, R.H., and V.A. Bandel. 1986. Nitrogen utilization with no-tillage. *In* M.A. Sprague and Triplett (eds) No-tillage and surface tillage agriculture, the tillage revolution. P. 117-148. John Wiley and Sons, New York.

Groffman, P.M. 1984. Nitrification and denitrification in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 49:329-334.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Carbon and nitrogen changes in Great Plains soils as influenced by cropping and soil treatments. USDA Tech. Bull. 1164. U.S. Gov. Print. Office, Washington, DC.

Halvorson, A.D., A. L. Black, J.M. Krupinsky, and Stephen D. Merrill. 1999. Dryland winter wheat response to tillage and nitrogen within an annual cropping system. Agron. J. 91:702-707.

Hamid, A., and R.L. Mahler. 1994. The potential for volatilization losses of applied nitrogen fertilizers from northern Idaho soils. Commun. Soil. Sci. Plant Anal. 25(3&4), 361-373.

Hobbs, L.A., and P.L. Brown. 1957. Nitrogen and organic carbon changes in cultivated western Kansas soils. Kansas Agric. Exp. Stn. Tech. Bull. 89.

Holland, J.F., and W.L. Felton. 1989. Effect of tillage practice on grain sorghum production in northern New South Wales. Aust. J. Exp. Agric. 29:843-848.

Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58:193-198.

Jones, O.R., and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the southern high plains. Agron. J. 89:222-232.

King, K.W., D.C. Flanagan, L.D. Norton, and J.M. Laflen. 1995. Rill erodibility parameters influenced by long-term management practices. Trans. ASAE. 38:159-164.

Kirkegaard, J.A., R. Munns, R.A. James, P.A. Gardner, and J.F. Angus. 1995. Reduced growth and yield of wheat with conservation cropping: II. Soil biological factors limit growth under direct drilling. Aust. J. Agric. Res. 46:75-88.

Kitur, B.K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of N-depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76:240-242.

Knowles, T.C., B.W. Hipp, P.S. Graff, and D.S. Marshall. 1993. Nitrogen nutrition of rainfed winter wheat in tilled and no-till sorghum and wheat residues. Agron. J. 85:886-893.

Kolberg, R.L., N.R. Kitchen, D.G. Westfall, and G.A. Peterson. 1996. Cropping intensity and nitrogen management impact of dryland no-till rotations in the semi-arid Western Great Plains. J. Prod. Agric. 9:517-522.

Lal, R., A.A. Mahboubi, and N.R. Fausey. 1994. Long-term tillage effect and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58:517-522.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Wheat-fallow tillage systems ‘effect on newly cultivated grassland soils’ nitrogen budget. Soil Sci. Soc. Am. J. 49:352-356.

Lembi, C.A., M.D. Bri Hon, and M.A. Ross. 1985. Evaluation of nitrogen application technique and tillage system on nitrogen runoff from an erodible soil. Technical Report 174. Purdue Univ., West Lafayette, Ind.

Lopez-Bellido, L., M. Fuentes, J.E. Castillo, F.J. Lopez-Garrido, and E.J.

Fernandez. 1996. Long-term tillage, crop rotation and nitrogen fertilizer effects on wheat yield under rainfed Mediterranean conditions. Agron. J. 88:783-791.

Lupwayi, N.Z., W.A. Rice, and G.W. Clayton. 1998. Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. Soil Biol. Biochem. 30:1733-1742.

McDowell, L. L., and G.E. Smith. 1958. The retention and reactions of anhydrous ammonia on different soil types. Soil Sci. Soc. Amer. Proc. 22:38-42.

McGregor, K.C., C.K. Mutchler, and R.K. Cullum.1992. Soil erosion effects on soybean yields. Trans. ASAE. 35:1521-1525.

McGregor, K.C., R.F. Cullum, and C.K. Mutchler. 1999. Long-term management effects on runoff, erosion, and crop production. Trans. ASAE. 42:99-105.

McIsaac, G.F., J.K. Mitchell, and M.C. Hirshi. 1990. Contour and conservation tillage for corn and soybeans in Tama silt loam soil. Hydraulics and sediment concentrations. Trans. ASAE. 33:1541-1550.

Merrill, S.D., A.L. Black, and A. Bauer. 1996. Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci. Am. J. 60:575-583.

Mielke, L.N., J.W. Doran, and K.A. Richards. 1986. Physical environment near the surface of plowed and no-tilled soils. Soil Tillage Res. 7:355-366.

Norwood, C. 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86:558-563.

Papendick, R.I. and J.F. Parr. 1966. Retention of anhydrous ammonia by soil: III. Dispensing apparatus and resulting ammonia distribution. Soil Sci. 102:193-201.

Pesant, A.R., J.L. Dionne, and J. Genest. 1987. Soil and nutrient losses in surface runoff from conventional and no-till corn systems. Can. J. Soil Sci. 67:835-843.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180-186.

Pikul, J.L., Jr., and J.K. Aase. 1995. Infiltration and soil properties as affected by annual cropping in the northern Great Plains. Agron. J. 87:656-662.

Rao, S.C., and T. H. Dao. 1996. Nitrogen placement and tillage effects on dry matter and nitrogen accumulation and redistribution in winter wheat. Agron. J. 88:365-371.

Rhoton, F.E., R.R. Bruce, N.W. Buehring, G.B. Elkins, C.W. Langdale, and D.D. Tyler. 1993. Chemical and physical characteristics of four soil types under conventional and no-tillage systems. Soil Tillage Res. 28:51-61.

Rice, C.W., and M.S. Smith. 1982. Denitrification in no-till and plowed soils. Soil Sci. Soc. Am. J. 46:1168-1173.

Rice, C.W., and M.S. Smith. 1984. Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. Soil Sci. Soc. Am. J. 48:295-297.

Ridley, A.O., and R.A. Hedlin. 1968. Soil organic matter and crop yields as influenced by frequency of summerfallowing. Can. J. Soil Sci. 48:315-322.

Robbins, S.G., and R.D. Voss. 1989. Division S-8-fertilizer technology and use acidic zones from ammonia application in conservation tillage systems. Soil Sci. Soc. Am. J. 53:1256-1263.

Rodriguez, M.B., and N. Giambiagi. 1995. Denitrification in tillage and no-tillage Pampean soils: relationships among soil water, available carbon, and nitrate and nitrous oxide production. Commun. Soil. Sci. Plant Anal. 26:3205-3220.

SAS Institute. 1990. SAS/STAT user's guide. Release 6.03 ed. SAS Inst., Cary, NC.

Schepers, J.L., and R.A. Cattani. 1962. Mineral fixation of anhydrous ammonia by air-dry soils. Soil Sci. Soc. Am. Proc. 26:147-152.

Smika, D.E., and P.W. Unger. 1986. Effect of surface residues on soil water storage. Adv. Soil. Sci. 5:111-138.

Smith, S.J., and A.N. Sharpley. 1990. Soil nitrogen mineralization in the presense of surface and incorporated crop residues. Agron. J. 82:112-116.

Smith, S.J., A.N. Sharpley, J.W. Naney, W.A. Berg, and O.R. Jones. 1991. Water Quality impacts associated with wheat culture in the southern Plains. J. Environ. Qual. 20:244-249.

Soper, R.J., G.J. Racz, and P.I. Fehr. 1971. Nitrate nitrogen in the soil as a means of predicting the fertilizer nitrogen requirements of barley. Can. J. Soil Sci. 51:45-49.

Stinner, B.R., G.D. Hoyt, and R.L. Todd. 1983. Changes in soil chemical properties following a 12-year fallow: A 2-year comparison of conventional tillage and no-tillage agroecosystems. Soil Tillage Res. 3:277-290.

Swart, C.L., L.S. Murphy, and C.W. Swallow. 1971. Retention patterns and effectiveness of anhydrous ammonia applied with an undercutting blade. Agron. J. 63:881-884.

Toews, W.H., and R.J. Soper. 1978. Effects of nitrogen sources, method of placement and soil type on seedling emergence and barley crop yields. Can. J. Soil Sci. 58:311-320.

Tomar, J.S., and R.J. Soper. 1981. Fate of tagged urea N in field with different methods of N and organic matter placement. Agron. J. 73:991-995.

Unger, P.W. 1991. Organic matter, nutrient, and pH distribution in no- and conventional-tillage semiarid soils. Agron. J. 83:186-189.

Vyn, T.J., and B.A. Raimbault. 1993. Long-term effect of five tillage systems on corn response and soil structure. Agron. J. 85:1074-1079.

Waddell, J.T., and R.R. Weil. 1996. Water distribution in soil under ridge-till and no-till corn. Soil Sci. Soc. Am. J. 60:230-237.

Wagger, M.G., D.E. Kissel, and S.J. Smith. 1985. Mineralization of nitrogen from nitrogen-15 labeled crop residues under field conditions. Soil Sci. Soc. Am. J. 49:1220-1226.

Weersink, A., M. Walker, C. Swanton, and J.E. Shaw. 1992. Costs of conventional and conservation tillage systems. J. Soil and Water Cons. 47:328-334.

Wienhold, B.J., and A.D. Halvorson. 1999. Nitrogen mineralization responses to cropping, tillage, and nitrogen rate in the northern great plains. Soil Sci. Soc. Am. J. 63:192-196.

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen on initiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470-476.

Young, R.A., J.C. Zubriski, and E.B. Norum. 1960. Influence of long-term fertility management practices on chemical and physical properties of a Fargo clay. Soil Sci. Soc. Am. J. 24:124-128.

Table 1. Initial surface (0-15 cm) and sub-soil (15-30 cm) test results prior to experiment initiation at Efaw and Lahoma OK.

	NH_4-N	NO_3-N	P	K	
Sample	---------------------------- mg kg^{-1}			---------------------------	pH
Lahoma (0-15 cm)	14.35	8.86	9.34	282	5.67
Lahoma (15-30 cm)	15.78	3.89	6.49	222	6.23
Efaw (0-15 cm)	15.87	11.16	28.23	225	5.70
Efaw (15-30 cm)	13.70	7.41	7.44	190	6.35

NH_4-N and NO_3-N – 2 M KCL extract; P and K – Mehlich-3 extraction; pH – 1:1 soil:deionized water

Table 2. Planting, fertilizer, and harvest dates at Efaw and Lahoma, OK, 2000-04.

Location	Crop Year	Planting	Fertilizer Application	Grain Harvest
	2000-2001	11-30-00	11-22-00	6-11-01
	2001-2002	10-01-01	9-11-01	6-21-02
	2002-2003	10-17-02	9-03-02	6-23-03
Efaw	2003-2004	9-27-03	9-18-03	6-15-04
	2000-2001	11-27-00	11-27-00	6-14-01
	2001-2002	10-03-01	9-04-01	6-25-02
	2002-2003	10-08-02	9-06-02	6-17-03
Lahoma	2003-2004	10-16-03	9-19-03	6-12-04

Table 3. Grain yield treatment means and analysis of variance at Efaw, 2001-2004.

Treatment			2001	2002	2003	2004	Avg.
Tillage	App/ Source	N rate kg N ha^{-1}	Grain Yield (Mg ha^{-1})				
CT	Knife	0	2.26	3.57	3.40	3.03	3.12
		61	2.27	3.59	3.82	4.18	3.46
		123	2.50	3.80	3.78	4.48	3.64
		185	2.53	3.64	3.68	4.98	3.71
	Avg.		2.39	3.65	3.67	4.17	3.49
	V-blade	0	2.13	3.83	2.67	2.34	2.58
		61	2.48	3.73	3.89	4.29	3.60
		123	2.63	3.99	3.84	4.96	3.85
		185	2.61	3.76	3.87	4.91	3.79
	Avg.		2.51	3.85	3.57	4.13	3.51
CT Response Indices (RI)			1.23	1.08	1.46	2.12	1.49
NT	Knife	0	1.90	2.98	2.67	2.48	2.57
		61	2.29	3.42	3.50	3.56	3.19
		123	2.55	3.66	3.04	4.54	3.50
		185	2.66	3.81	3.50	4.81	3.67
	Avg.		2.35	3.43	3.18	3.85	3.23
	V-blade	0	2.10	2.94	2.70	2.49	2.53
		61	2.11	3.11	3.23	3.13	2.87
		123	2.48	3.25	3.40	4.40	3.38
		185	2.44	3.67	3.56	4.78	3.61
	Avg.		2.28	3.24	3.22	3.70	3.12
NT Response Indices (RI)			1.40	1.25	1.32	1.94	1.42
SED			0.13	0.27	0.12	0.36	---

Source of Variation	Level of Significance				
Tillage	NS	*	**	NS	---
N rate	***	*	***	***	---
N method	NS	NS	NS	NS	---
N rate * N method	NS	NS	*	NS	---
Tillage * N rate	NS	*	NS	NS	---
Tillage * N method	NS	*	NS	NS	---
Tillage * N rate * N method	NS	NS	NS	NS	---
CT, Knife vs. V-blade	NS	NS	NS	NS	---
NT, Knife vs. V-blade	*	NS	NS	NS	---
CT, Knife linear	*	NS	NS	***	---
NT, Knife linear	***	**	***	***	---
CT, Knife quadratic	NS	NS	NS	NS	---
NT, Knife quadratic	NS	NS	NS	*	---
CT, V-blade linear	**	NS	***	***	---
NT, V-blade linear	**	**	***	***	---
CT, V-blade quadratic	NS	NS	***	***	---
NT, V-blade quadratic	NS	NS	NS	NS	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant. SED is the standard error of the difference between two equally replicated means.

CT= conventional tillage; NT= no-till

RI = highest N treated average grain yield divided by the average check (0 N rate).

Table 4. Grain yield treatment means and analysis of variance at Lahoma, 2001-2004.

Treatment			2001	2002	2003	2004	Avg.
Tillage	App/ Source	N rate kg N ha^{-1}			Grain Yield -------------------------------- (Mg ha^{-1}) --------------------------------		
CT	Knife	0	1.77	3.98	3.63	2.25	2.97
		61	2.13	4.29	4.07	4.51	3.75
		123	1.29	3.92	4.71	4.31	3.56
		185	2.07	3.86	4.48	3.98	3.60
	Avg.		1.82	4.01	4.22	3.66	3.48
	V-blade	0	1.90	3.74	2.28	4.24	3.15
		61	2.45	4.07	4.31	4.27	3.73
		123	1.70	3.80	4.50	4.04	3.51
		185	1.97	3.94	4.65	4.15	3.68
	Avg.		2.01	3.91	3.93	4.18	3.53
CT Response Indices (RI)			1.29	1.12	2.04	2.00	1.26
NT	Knife	0	1.12	2.50	3.87	2.46	2.56
		61	1.43	2.92	5.03	3.48	3.16
		123	1.54	2.97	5.09	3.71	3.33
		185	1.87	2.60	4.53	3.94	3.24
	Avg.		1.49	2.79	4.63	2.86	3.10
	V-blade	0	0.78	2.62	4.64	1.39	1.85
		61	1.68	3.33	4.80	3.10	3.10
		123	1.89	3.62	4.96	3.78	3.56
		185	1.66	3.59	5.13	3.63	3.50
	Avg.		1.50	3.32	4.97	2.89	3.11
NT Response Indices (RI)			1.67	1.68	1.32	2.71	1.92
SED			0.31	0.20	0.42	0.46	---
Source of Variation					Level of Significance		
Tillage			*	**	***	***	---
N rate			***	***	***	***	---
N method			NS	**	NS	NS	---
N rate * N method			NS	*	NS	NS	---
Tillage * N rate			***	**	NS	**	---
Tillage * N method			NS	***	NS	**	---
Tillage * N rate * N method			NS	NS	NS	*	---
CT, Knife vs. V-blade			NS	NS	NS	NS	---
NT, Knife vs. V-blade			NS	***	NS	NS	---
CT, Knife linear			NS	NS	*	***	---
NT, Knife linear			**	NS	**	***	---
CT, Knife quadratic			NS	NS	NS	***	---
NT, Knife quadratic			NS	**	***	NS	---
CT, V-blade linear			NS	NS	***	NS	---
NT, V-blade linear			***	***	NS	***	---
CT, V-blade quadratic			NS	NS	**	NS	---
NT, V-blade quadratic			***	**	NS	*	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant. SED is the standard error of the difference between two equally replicated means.

CT= conventional tillage; NT= no-till

RI = highest N treated grain yield average divided by the check (0 N rate) average.

Table 5. Grain N uptake treatment means and analysis of variance at Efaw, 2001-2004.

Treatment			2001	2002	2003	2004	Avg.
Tillage	App/ Source	N rate kg N ha^{-1}	Grain N uptake ---------------------------------- (kg ha^{-1})----------------------------------				
CT	Knife	0	55.9	88.7	79.8	52.1	71.2
		61	58.1	91.3	88.8	93.8	85.2
		123	66.8	98.7	95.4	89.5	87.3
		185	65.5	99.7	87.1	127.0	94.1
	Avg.		61.6	94.6	87.8	94.0	84.5
	V-blade	0	49.4	93.2	80.5	43.5	65.6
		61	61.9	102.7	89.5	88.4	87.0
		123	67.6	109.4	93.8	118.6	97.9
		185	69.6	104.5	98.9	125.7	99.5
	Avg.		62.1	104.9	90.6	94.1	88.2
NT	Knife	0	41.6	69.3	56.8	42.8	53.5
		61	53.5	81.9	80.3	71.5	71.8
		123	69.3	91.5	62.3	90.8	81.2
		185	69.9	90.0	88.4	111.8	89.8
	Avg.		58.6	82.3	72.0	79.2	74.0
	V-blade	0	46.1	66.3	53.3	38.8	52.2
		61	48.7	69.4	72.7	59.1	63.1
		123	57.8	82.3	83.8	85.7	77.4
		185	59.5	103.8	90.6	117.8	93.2
	Avg.		53.0	80.4	73.7	81.0	71.6
SED			4.9	8.7	14.8	10.3	---
Source of Variation			Level of Significance				
Tillage			*	**	***	NS	---
N rate			***	***	**	***	---
N method			NS	NS	NS	NS	---
N rate * N method			NS	NS	NS	NS	---
Tillage * N rate			NS	NS	NS	NS	---
Tillage * N method			*	NS	NS	NS	---
Tillage * N rate * N method			NS	NS	NS	NS	---
CT, Knife vs. V-blade			NS	**	NS	NS	---
NT, Knife vs. V-blade			**	NS	NS	NS	---
CT, Knife linear			**	*	NS	***	---
NT, Knife linear			***	*	***	***	---
CT, Knife quadratic			NS	NS	NS	NS	---
NT, Knife quadratic			NS	NS	NS	NS	---
CT, V-blade linear			***	NS	NS	***	---
NT, V-blade linear			**	***	***	***	---
CT, V-blade quadratic			NS	NS	NS	**	---
NT, V-blade quadratic			NS	NS	NS	NS	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till

Table 6. Grain N uptake treatment means and analysis of variance at Lahoma, 2001-2004.

Treatment			2001	2002	2003	2004	Avg.
Tillage	App/ Source	N rate kg N ha^{-1}	Grain N uptake ---------------------------------- (kg ha^{-1})----------------------------------				
CT	Knife	0	41.8	101.6	70.0	55.3	67.4
		61	50.4	114.6	98.1	110.0	93.3
		123	33.8	116.3	119.6	116.8	96.6
		185	52.7	111.1	122.3	121.6	101.9
	Avg.		44.7	110.9	102.5	104.3	90.3
	V-blade	0	43.0	95.9	50.4	101.3	74.9
		61	60.3	111.1	99.7	111.8	94.7
		123	46.2	96.9	99.7	98.2	85.2
		185	51.7	102.7	107.2	106.5	92.0
	Avg.		50.3	102.4	89.3	104.3	87.1
NT	Knife	0	23.9	63.2	79.3	48.5	59.0
		61	34.0	71.2	101.1	83.3	70.3
		123	38.6	77.6	126.6	104.1	86.7
		185	47.8	68.8	119.5	116.4	88.1
	Avg.		36.1	71.3	106.6	89.1	77.5
	V-blade	0	16.6	57.3	83.5	27.4	37.0
		61	43.4	84.3	107.5	75.1	74.9
		123	45.8	96.1	116.9	115.6	93.6
		185	46.1	101.0	129.3	110.7	96.8
	Avg.		38.0	86.5	115.2	87.2	79.2
SED			7.9	8.1	9.5	16.5	---
Source of Variation			Level of Significance				
Tillage			NS	***	***	*	---
N rate			***	***	***	***	---
N method			NS	NS	NS	NS	---
N rate * N method			NS	NS	NS	NS	---
Tillage * N rate			**	*	NS	*	---
Tillage * N method			NS	***	*	NS	---
Tillage * N rate * N method			NS	*	NS	*	---
CT, Knife vs. V-blade			NS	**	NS	NS	---
NT, Knife vs. V-blade			NS	***	NS	NS	---
CT, Knife linear			NS	NS	***	***	---
NT, Knife linear			**	NS	***	***	---
CT, Knife quadratic			NS	NS	NS	**	---
NT, Knife quadratic			NS	NS	**	NS	---
CT, V-blade linear			NS	NS	***	NS	---
NT, V-blade linear			***	***	***	***	---
CT, V-blade quadratic			NS	NS	**	NS	---
NT, V-blade quadratic			**	*	NS	NS	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till

Table 7. Nitrogen Use Efficiency treatment means and analysis of variance at Efaw, 2001-2004.

Treatment			2001	2002	2003	2004	Avg.
Tillage	App/ Source	N rate kg N ha^{-1}			NUE (%)		
CT	Knife	61	5	4	15	68	23
		123	10	8	13	30	15
		185	6	6	4	41	14
	Avg.		7	6	10	46	17
	V-blade	61	22	16	15	74	31
		123	15	13	11	61	25
		185	11	6	10	45	18
	Avg.		16	12	12	60	25
NT	Knife	61	21	21	39	47	32
		123	23	18	10	39	24
		185	16	12	17	37	21
	Avg.		20	17	23	41	26
	V-blade	61	4	5	32	36	18
		123	10	13	25	38	21
		185	7	20	20	43	23
	Avg.		7	13	26	39	21
SED			5	11	12	17	---
Source of Variation					Level of Significance		
Tillage			NS	NS	**	NS	---
N rate			NS	NS	NS	NS	---
N method			NS	NS	NS	NS	---
N rate * N method			NS	NS	NS	NS	---
Tillage * N rate			NS	NS	NS	NS	---
Tillage * N method			***	NS	NS	NS	---
Tillage * N rate * N method			NS	NS	NS	NS	---
CT, Knife vs. V-blade			NS	NS	NS	NS	---
NT, Knife vs. V-blade			***	NS	NS	NS	---
CT, Knife linear			NS	NS	NS	NS	---
NT, Knife linear			NS	NS	***	NS	---
CT, Knife quadratic			NS	NS	NS	NS	---
NT, Knife quadratic			NS	NS	**	NS	---
CT, V-blade linear			*	NS	NS	NS	---
NT, V-blade linear			NS	NS	NS	NS	---
CT, V-blade quadratic			NS	NS	NS	NS	---
NT, V-blade quadratic			NS	NS	NS	NS	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
NUE= (Grain N uptake of N treatment – Grain N uptake of check) / N rate
SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till

Table 8. Nitrogen Use Efficiency treatment means and analysis of variance at Lahoma, 2001-2004.

Tillage	App/ Source	N rate kg N ha^{-1}	2001	2002	2003	2004	Avg.
			NUE (%)				
CT	Knife	61	14	23	46	90	43
		123	0	13	40	50	24
		185	6	6	28	36	19
	Avg.		5	14	38	59	29
	V-blade	61	29	23	64	20	36
		123	3	1	32	0	8
		185	5	4	25	3	9
	Avg.		12	11	40	6	17
NT	Knife	61	19	14	36	58	27
		123	13	13	39	45	27
		185	14	4	22	37	19
	Avg.		15	10	32	43	24
	V-blade	61	44	48	39	78	53
		123	24	35	27	72	39
		185	16	28	24	45	27
	Avg.		28	37	29	65	40
SED			7	9	10	14	---
Source of Variation			Level of Significance				
Tillage			*	NS	*	**	---
N rate			***	***	***	***	---
N method			***	***	NS	**	---
N rate * N method			*	NS	NS	NS	---
Tillage * N rate			NS	NS	NS	NS	---
Tillage * N method			NS	***	NS	***	---
Tillage * N rate * N method			NS	NS	NS	NS	---
CT, Knife vs. V-blade			NS	NS	NS	***	---
NT, Knife vs. V-blade			**	***	NS	*	---
CT, Knife linear			NS	*	*	***	---
NT, Knife linear			NS	NS	NS	NS	---
CT, Knife quadratic			**	NS	NS	NS	---
NT, Knife quadratic			NS	NS	NS	NS	---
CT, V-blade linear			**	**	***	NS	---
NT, V-blade linear			***	*	NS	**	---
CT, V-blade quadratic			*	*	NS	NS	---
NT, V-blade quadratic			NS	NS	NS	NS	---

*, **, *** Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
NUE= (Grain N uptake of N treatment – Grain N uptake of check) / N rate
SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till

Table 9. Soil nitrate N treatment means from post-harvest sampling in 2002 and 2004 at Efaw and Lahoma, OK.

			2002		2004			
			Efaw	Lahoma	Efaw		Lahoma	
			0-15 cm	0-15 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Tillage	App/ Source	N rate kg N ha^{-1}	NO$_3^-$ N ----------------------------------- mg kg^{-1} -----------------------------------					
CT	Knife	0	10.7	10.3	7.1	5.7	12.6	14.2
		61	10.2	17.9	6.7	5.8	14.1	14.4
		123	9.1	17.8	7.1	7.0	13.7	11.6
		185	15.0	30.5	7.3	5.6	14.4	12.5
	Avg.		11.2	19.1	7.0	6.0	13.7	13.2
	V-blade	0	6.8	12.6	6.6	5.3	11.3	12.7
		61	12.9	13.9	7.0	5.6	14.5	19.1
		123	12.6	12.1	7.8	5.1	11.9	11.8
		185	15.7	15.7	8.8	6.3	13.8	16.6
	Avg.		12.0	13.6	7.5	5.6	12.9	15.0
NT	Knife	0	10.7	23.2	9.7	6.4	21.4	17.4
		61	16.2	16.4	10.2	6.3	12.4	11.9
		123	17.2	30.6	9.5	6.1	16.6	11.9
		185	17.0	49.5	8.9	6.8	15.7	12.5
	Avg.		15.3	29.9	9.6	6.4	16.6	13.4
	V-blade	0	13.7	14.6	7.8	7.1	13.6	12.6
		61	21.7	20.9	9.2	6.1	13.2	13.1
		123	11.9	20.8	9.6	6.3	13.8	12.6
		185	17.4	18.6	10.8	6.0	22.4	13.7
	Avg.		16.2	18.7	9.4	6.4	15.7	13.0
	SED		3.0	4.4	1.1	0.8	2.6	2.1

SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till
NO$_3$-N – 2 M KCL extract
In 2002 no subsoil samples (15-30 cm) were collected.

Table 10. Soil ammonium N treatment means from post-harvest sampling in 2002 and 2004 at Efaw and Lahoma, OK.

			2002		2004			
			Efaw	Lahoma	Efaw		Lahoma	
			0-15 cm	0-15 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Tillage	App/ Source	N rate kg N ha^{-1}	NH_4 - N ----- mg kg^{-1} -----					
CT	Knife	0	13.2	8.5	5.6	4.0	5.6	8.0
		61	15.1	10.1	5.8	3.2	9.6	6.1
		123	15.0	10.3	4.0	3.9	8.1	6.0
		185	15.0	14.8	4.5	4.3	12.2	11.4
	Avg.		14.6	10.9	5.0	3.8	8.9	7.9
	V-blade	0	12.8	12.3	3.9	4.7	5.8	6.7
		61	18.1	8.8	5.4	4.4	4.8	9.6
		123	16.1	10.4	4.2	3.5	5.3	6.4
		185	20.3	12.2	6.3	9.7	5.0	10.5
	Avg.		16.8	10.9	4.9	5.6	5.2	8.3
NT	Knife	0	20.3	15.2	4.6	3.3	5.6	6.6
		61	21.9	13.2	4.4	4.1	6.4	3.0
		123	22.4	16.8	3.7	4.0	9.7	6.7
		185	24.3	20.4	5.6	4.2	13.0	10.9
	Avg.		22.2	16.4	4.6	3.9	8.7	6.8
	V-blade	0	25.4	12.5	5.4	4.6	9.7	5.7
		61	19.8	13.7	4.0	2.6	6.3	6.9
		123	19.1	14.9	3.8	3.2	5.3	9.8
		185	19.2	15.4	5.7	3.6	8.9	8.8
	Avg.		20.9	14.1	4.7	3.5	7.5	7.8
	SED		3.7	1.9	1.2	2.1	2.9	2.8

SED is the standard error of the difference between two equally replicated means.
CT= conventional tillage; NT= no-till
NH_4-N – 2 M KCL extract
In 2002 no subsoil samples (15-30 cm) were collected.

Figure 1. Knife applicator

Figure 2. V-blade applicator

Figure 3. Effect of tillage and N method on soil compaction over four years for depths 0-30 cm at Lahoma, OK.

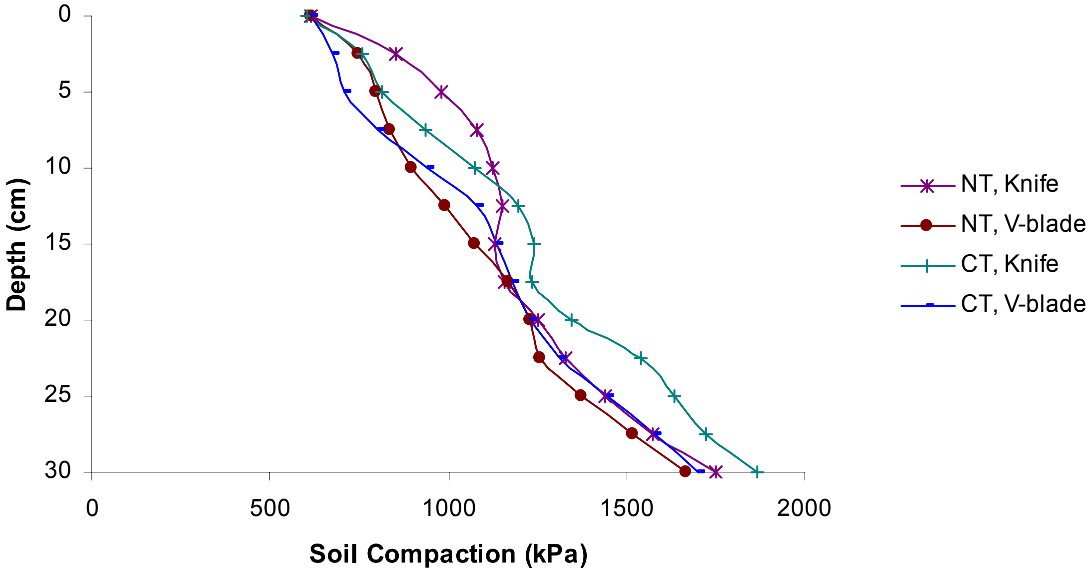
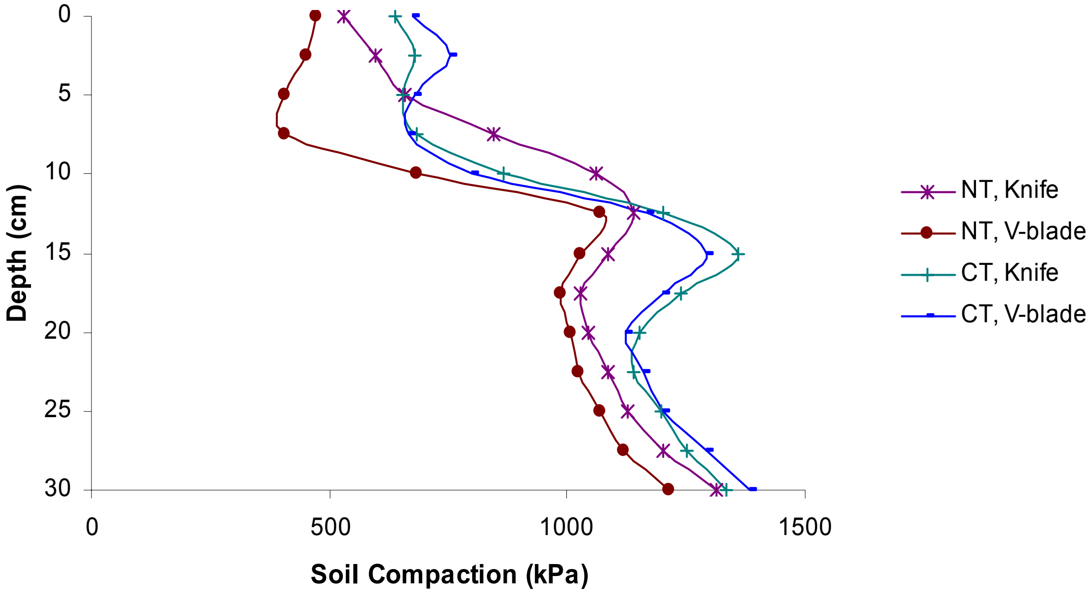


Figure 4. Effect of tillage and N method on soil compaction over four years for depths 0-30 cm at Efaw, OK.



VITA

Roger Keith Teal

Candidate for the Degree of

Doctor of Philosophy

Dissertation: EVALUATING METHODS FOR IMPROVING NITROGEN USE EFFICIENCY IN CORN AND HARD RED WINTER WHEAT

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Title of Study: EVALUATING METHODS FOR IMPROVING NITROGEN USE EFFICIENCY IN CORN AND HARD RED WINTER WHEAT

Pages in Study: 98 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and Method of Study: For chapter one, Corn (*Zea mays* L.) experiments were conducted to evaluate spectral reflectance, measuring the normalized difference vegetation index (NDVI) with a GreenSeeker™ Hand Held optical reflectance sensor as a function of hybrid, plant population, and fertilizer N rate. In the spring of 2004 with the addition of a third site and the availability of a green NDVI sensor, the trials were reconfigured removing one hybrid and imposing two more plant populations and the utilization of both green and red NDVI. Differences in NDVI, grain yield, grain N, and grain N uptake were investigated based on hybrid, plant population, and N rate. For chapter two, Hard red winter wheat (*Triticum aestivum* L.) experiments were conducted to evaluate tillage system and anhydrous ammonia application methods on yield, N uptake, and NUE, using a narrow (10 cm) nozzle spacing on a V-blade (Noble or sweep blade) applicator and wide (46 cm) nozzle spacing on a knife applicator.

Findings and Conclusions: For chapter one, the critical population at which NDVI was no longer affected occurred between 55,000 and 60,000 plants ha $^{-1}$ for the later maturing hybrids and closer to 70,000 plants ha $^{-1}$ for the earliest maturing hybrids. Vegetative response index (RI_{NDVI}) at V8 was highly correlated with RI at harvest ($RI_{HARVEST}$) in 2004. The V8 growth stage was most effective growth stage to predict grain yield. Hybrid maturity did not effect grain yield prediction at V8 and no significant differences occurred between the GNDVI and RNDVI relationships with grain yield in 2004. For chapter two, conventional tillage was significantly higher in grain yield and grain N uptake in five of eight site years over no-till. Mixed results were evaluated from NUE for tillage; four site years split evenly between conventional till and no-till. The V-blade improved NUE in no-till three site years at Lahoma, but the knife applicator increased NUE the initial year at Efaw in no-till. Previous crop residue disturbance averaged less than 15% for both AA applicators all four site years. No-till crop production reduced soil compaction at Efaw and the V-blade applicator reduced soil compaction within the no-till at both locations.

ADVISER'S APPROVAL: Dr. William Raun