REAL-TIME USE OF SOIL MOISTURE DATA FOR REFINED GREENSEEKER SENSOR BASED N RECOMMENDATIONS IN WINTER WHEAT (*Triticum aestivum L.)* AND EFFECT OF FOLIAR P FERTILIZATION ON CORN (*Zea mays L.)* GRAIN YIELD AND PHOSPHORUS USE EFFICIENCY

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PART I. REAL-TIME USE OF SOIL MOISTURE DATA FOR REFINED GREENSEEKER SENSOR BASED N RECOMMENDATIONS IN WINTER WHEAT (*Triticum aestivum L.)*

CHAPTER I

ABSTRACT

The Sensor Based Nitrogen Rate Calculator enables producers to estimate yield potential and obtain nitrogen (N) fertilization rates based on GreenSeeker sensor measurements and the response index, number of days where GDD (growing degree days)>0, agronomic maximum yield, expected grain price, and fertilizer price. Soil moisture levels can vary significantly both site-to-site and year-to-year. Furthermore, soil moisture is known to significantly affect both yield potential and fertilizer use efficiency. The current Sensor Based Nitrogen Rate Calculator does not take in account profile soil moisture at the time of sensing. Limited soil profile moisture leads to overestimation of yield potential and, low fertilizer use efficiency. At-sensing knowledge of the amount of water present in the soil profile can help to more accurately predict yield potential. This will in turn reduce the risk of applying N when it is not required, and to identify years when sufficient moisture is present in the soil profile to produce near maximum yields where more N is needed.

CHAPTER II

INTRODUCTION

Wittwer (1998) identified water resources as the second-limiting factor in increasing crop production after constraints in the arable land area expansion. Soil water availability is one of the major factors limiting crop production worldwide, especially in arid and semi-arid environments (Kramer and Boyer, 1995). In recent years, expansion of irrigated area has slowed considerably, and prospects for increasing irrigated land are restricted by both limited water supplies and increasing environmental concerns (Poster, 1998).

Soil moisture is useful in many disciplines including soil science, agriculture, ecology, civil engineering, meteorology, and water resource management (Wetzel and Woodward, 1987). Previous studies have shown that soil moisture is the basic link between the energy budget of land surfaces and the hydrologic cycle (Houser, 1996). Soil moisture varies spatially and temporally due to soil type, temperature, precipitation, vegetation, and land use practices. In agricultural production, soil moisture controls hydrologic cycle and directly affects the off-site water quality (Wu and Yang, 2006).

Soil water is a critical component in agricultural production systems, for optimization of grain yields, rational water resources management, as well as addressing issues of water quality (Rubin, 2003).

CHAPTER III

LITERATURE REVIEW

SOIL MOISTURE AND PLANT GROWTH

Water stress is known to affect numerous processes within a plant-soil system. Inadequate plant growth and development and decreased leaf expansion often indicate plant water stress (Dale, 1988). Nutrient uptake through diffusion, mass flow and root uptake capacity, are affected by insufficient soil moisture (Dunham and Nye, 1976). Several researchers have documented that plant roots exposed to drying topsoil induce a root hormonal signal to the shoot, causing stomatal closure which helps to maintain leaf water potential and leaf turgor (Zhang and Davies, 1989).

Others showed that osmoregulation was mediated via leaf or shoot responses to leaf water stress, not through root responses to soil water deficit (Morgan, 1995). Further depletion of soil profile moisture tends to form a hydraulic gradient between the plant stem and leaves and drying soil. Insufficient plant available soil moisture during vegetative growth leads to low leaf area index, low intercepted radiation and results in low biomass growth. Decreased biomass production ultimately reduces grain yields due to lower production of assimilates available for translocation during the grain filling phase. Also, soil water deficit later in the growing season can indirectly limit yield by negatively affecting yield-determining factors (including number of grains per ear and unit grain weight) Braga (2000). An experiment was conducted in South Africa to study available soil moisture and water use of wheat. Meyer and Green (1980) observed superior root growth in well-watered wheat plants. They found that well-watered root systems were 10% more efficient in extraction of water from the soil than less-developed roots (80 versus 70%).

SOIL MOISTURE AND NITROGEN USE EFFICIENCY

Nitrogen use efficiency (NUE) for cereal crops (including wheat, *Triticum aestivum* L., corn, *Zea mays* L., rice, *Oryza sativa* L., barley, *Hordeum vulgare* L. sorghum, *Sorghum bicolor*, L., rye, *Secale cereale* L., oats, *Avena sativa* L., and millet, *Pennisetum glaucum* L.) is estimated to be approximately 33% worldwide (Raun and Johnson, 1999). Various methods may be used to estimate fertilizer removal and NUE; however, regardless of the computational method, NUE estimates almost always range from 30 to 35% (www.nue.okstate.edu, 2008-a). Failure to accurately assess a crop's fertilizer requirement, ignoring the impact of spatial and temporal variability, and difficulty identifying the most appropriate timing for fertilizer application result in inefficient fertilizer management. Low NUE values in crop production are generally due to N loss (65-70%) from soil-plant system via various pathways (gaseous plant emission, denitrification, leaching, surface runoff and volatilization) which represents an annual $15.9 billion loss (Raun and Johnson, 1999).

The yield goal approach widely used to predict yield and to make fertilizer recommendations is based on the average yields achieved in the past (Raun et al., 2001), and thus fails to recognize the large year-to-year variation in yield present in all production systems. Attempts have been made by several researchers to improve the yield goal concept by emphasizing the importance of temporal factors including the soil moisture component.

Rehm and Schmitt (1989) suggested increasing yield goal by 10-20% over the recent average when adequate soil moisture is present at planting. The authors also pointed out that yield goal estimates based on the average of yields achieved in the past might not be accurate if soil moisture is limiting. Black and Bauer (1988) proposed that the yield goal estimates should account for the amount of water available to winter wheat in the spring up to a depth of 1.5 m plus the amount of precipitation projected for the growing season.

Yield potential, as defined by Evans and Fischer (1999), is “the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled”. Dahnke et al. (1988) defined potential yield as “the highest grain yield achievable with ideal management, soil, and weather”. Raun et al. (2001) emphasized that potential yield is associated with soil- and weather-specific conditions. They refer to the “highest yield obtainable in ideal conditions” as the maximum yield.

The response index (RI) as proposed by Johnson et al. (2000) projects the actual crop response to applied fertilizer N. Response index values help to identify responsive and non- responsive site-years and assist in determining of N fertilizer needs, and clearly demonstrate temporal dependency of grain yields. Research results suggest that the magnitude of response cannot be predicted from year to year; thus, fertilizer management decisions should be made in-season (Johnson and Raun, 2003).

Recognizing that the actual grain yield cannot be predicted due to a complex relationship and interaction between the yield-determining factors, Raun et al. (2001) established a non-destructive estimation of yield potential using spectral measurements.

Raun et al. (2002) combined mid-season yield potential prediction and N response using In-Season Estimated Yield (INSEY) and RI to develop an algorithm for midseason topdress N fertilization. The INSEY index has been modified by using the number of days from planting to sensing, where temperatures were above (GDD>0). This approach accounted for days during the cropping season when plant growth was not possible due to low temperatures, regardless of the soil moisture conditions. Johnson et al. (2000) noted that timely precipitation could increase crops' response to applied N, resulting in a larger ratio (response index) of harvested grain to nitrogen fertilizer ($RI_{HARVEST}$) than estimated using RI_{NDVI} values (response index determined from mid-season NDVI measurements) to nitrogen fertilizer. Humphreys et al. (2004) suggested that incorporation of soil characteristics such as soil texture and soil moisture capacity can improve the accuracy of yield potential (YP) prediction using the INSEY approach. Derby et al. (2005) stated that it is not wise to continue to make fertilizer N recommendations based on a static yield response curve in anticipation of achieving maximum yields every year. They proposed that soil properties as well as soil moisture availability and climatic conditions present during the growing season should be considered when making fertilizer recommendations.

Girma et al. (2006) proposed that adoption of agronomic practices which account for temporal variability would enable adjusting N and P fertilizer application rates according to temporal conditions present in-season, and would lead to more efficient, profitable, and sustainable crop production.

SOIL MOISTURE AND GRAIN YIELD

Raun et al. (1999) commented that crop grain yield is a function of combined growth factors present within a particular growing environment. Many researchers recognize plant available moisture as one of the key yield-affecting factors (Daniels et al., 1987; Fiez et al., 1994; Wright et al., 1990).

Grain yields for all crops are directly related to the amount of transpired water (Tanner and Sinclair, 1983). Holford and Doyle (1978) reported that wheat grain yields were severely reduced due to inadequate available soil moisture during the growing season.

Gillies et al. (1997) discussed the importance of soil water content for estimating crop yields. Traditional reliance on a close relationship between soil characteristics and crop production means that soil testing must be performed in order to improve management decisions. One major drawback of the soil-based methods is that it is costly; thus, soil testing is rarely practiced by farmers both in the U.S. (Zhang et al., 1998), and Australia (Robertson et al., 2006).

Carlson et al. (1995) noted that lack of homogeneity in soil water content is apparent and indicates the need for evaluation of factors affecting soil moisture spatial and temporal variability, even though many soil properties (such as plant available water capacity) can be relatively accurately estimated using soil type information (Robertson et al., 2006). Plant available water capacity (PAWC) is an important parameter, which helps to manage problem areas within a field, assists in improving site-year specific grain yield estimation, as well as to improve fertilizer recommendations. Relying on the soil classification maps to estimate PAWC, however, clearly ignores spatial and temporal variability that is known to exist within a single soil type within and across agricultural fields. Robertson et al. (2006) stated that the use of remote sensing and development of algorithms which would relate remotely sensed signals to a specific soil characteristic (such as PAWC), which, in turn, could be related to yield potential, is expected to significantly expand in the future. The use of simulation models to relate weather conditions and soil parameters to grain yields could greatly increase agronomic productivity.

Kumar et al. (2006) investigated the relationship between seasonal crop water stress index (based on evapotranspiration deficits and NDVI) and sorghum grain yields. They employed a root zone soil moisture model to assess the seasonal soil moisture flux and actual evapotranspiration. The results demonstrated that improved grain yield estimates could be achieved mid-season when spectral indices (i.e. NDVI) along with soil water parameters were incorporated in the model.

Casssman (1999) noted that the possibility of increasing the total amount of transpiration in crop production using genetically-based approaches is rather small. He commented that, on the other hand, through efficient soil and residue management (such as no-till), the amount of plant-available water can be increased by improved infiltration and decrease runoff.

Moore and Tyndale-Biscoe (1999) investigated wheat crop performance in Australia over a wide range of soil types, nitrogen (N) fertilizer applications, and weather conditions. The results showed that a large proportion of variability in performance of the wheat crop among different soil types were due to different soil moisture holding capacities. They stated that in soils with adequate infiltration rates, soil moisture holding capacity is perhaps the most important physical soil property, since it determines soils' ability to store water and sustain plant growth. Wong et al. (2006) stated that insufficient plant available water is an underlying cause of both spatial and temporal variability, and a major yield-limiting factor in wheat production systems of Western Australia. They noted that significant year-to-year variation in grain yields coupled with the common practice of "blanket" fertilizer N application result in low fertilizer use efficiency. Wong et al. (2006) suggested that total amount of precipitation, the pattern of distribution, and soil characteristics such as water holding capacity (mainly governed by soil texture) all significantly influenced both spatial and temporal variability.

Grain yields are often more correlated with soil water availability than any other factor; therefore, seasonal soil water use by crops is a key parameter to be considered when evaluating the yield potential, especially in semi-arid regions (Moroke et al., 2006). The authors included slow infiltration rates, small soil water holding capacity, limited rooting depth, and low soil fertility status as possible yield-limiting factors. Wong and Asseng (2006) observed a linear relationship between plant available soil water storage capacity (PAWc) of the top 100 cm of the soil profile and wheat grain yields. Results by Wong and Asseng (2006) indicated that the main source of spatial and temporal grain yield variability was due to interactions of total precipitation, PAWc, and N fertilizer applications.

Investigating the effect of fertilizer N application of grain yields and protein content in wheat, Terman et al. (1969) found that applied N resulted in higher wheat grain yields only when adequate moisture was present within the soil profile. They observed increased protein content in wheat but little or no increase in wheat grain yields was achieved under rain-fed conditions where moisture stress was severe. The authors proposed that available soil moisture appeared to be the main factor influencing wheat crop response to applied N fertilizer. On the other hand, it has been shown that application of N fertilizer can increase water use efficiency (WUE) in wheat by an average of 56% (Brown, 1971).

Diaz-Zorita et al. (1999) reported that because of its positive affect on soil water-holding capacity, soil organic matter (SOM) content was a reliable index of crop productivity, especially in semiarid regions, where water was the limiting factor in cropping systems. They found wheat grain yields were positively correlated with both plant available water and SOM.

Storrier (1962), Colwell (1963), and Fischer (1963) observed decreased yield potential due to inadequate soil moisture at various growth stages. Their results suggest that in grain production post-anthesis period is the most critical in terms of moisture supply. Day and Intalap (1970) examined the effects of soil moisture on spring wheat growth and grain yields and identified jointing as the critical growing stage for soil moisture conditions. They found that moisture stress at jointing resulted in stunted wheat plants, increased lodging, earlier maturity, decreased number of seeds per head and per unit area, and lower grain yields. Seif and Pederson (1978) found that rainfall around anthesis (3 weeks before to 2 weeks after) accounted for over 85% of variation in wheat grain yields.

Musick et al. (1994) reported that increasing available soil moisture at planting in wheat production systems appears to be just as important as irrigation during the growing season in order to eliminate or minimize water stress. French and Schultz (1984) found that, in general, a close relationship between wheat grain yields and available water exists. Their results indicated that amount of water present within the soil profile at planting is more vital in promoting grain yield that rainfall-derived moisture due to lesser effect of evapotraspiration of soil-stored water. Ramig and Rhoads (1963) also showed that water use efficiency is higher when soil profile moisture at planting is adequate.

SPATIAL AND TEMPORAL VARIABILITY

The spatial variability of site-specific soil characteristics associated with plant available soil water has been identified as one of the major crop yield determining factors (Paz, 2000; Sadler et al., 1993, 2000; Nijbroek, 1999; Braga, 2000; Irmak et al., 2002). It has been shown that yields can be maximized if levels of plant available soil water are consistently adequate throughout the growing season.

Across years and sites, more than 50% of crop yield variability is due to temporal effects (Huggins and Alderfer, 1995; Clarke et al., 1996). Paz et al. (1998) found that over 69% of variability in soybean yields was due to varying soil moisture level and water stress. Water stress has been identified as the dominant yield-limiting factor in soybean production, and that little can be done to address this issue in rain-fed cropping systems Paz et al. (1998). However, if the soil moisture data were considered when estimating yield potential, more accurate fertilizer recommendations could be obtained and producers' profits could be optimized.

Morton et al. (1999) studied the effect of spatial variability of plant-available soil-water on corn grain yields. By combining evapotranspiration, deep percolation and water stress variables in a multiple linear regression model they accounted for 83% of the variability in observed in grain yield. Hoogenboom et al. (1994) and Moore and Tyndale-

Biscoe (1999) concluded that the profile soil-water holding capacity contributes more to grain spatial variability than spatial variability in soil N status.

Irmak et al. (2002) proposed that deeper understanding of spatial soil water uptake by plant roots is essential for better understanding of spatial and temporal variability in grain yields. They observed variation in soybean yields of approximately 24%. The authors suggested that this was most likely due to variability in soil water during pod filling. Lower soybean yields were achieved at sites that suffered from water stress earlier in the growing season. Soybean yield was positively correlated ($r^2 > 0.48$) with plant available soil water. Overall, the variability in soil water explained more than 48% of yield variability in all of the 30 sites evaluated (Irmak et al., 2002).

Interactions between biotic (plant genotype, soil fauna, diseases and pests) and abiotic (soil chemical, physical properties, and climatic conditions) factors influence both temporal and spatial variability in crop yields (Braum et al., 1998; Machado et al., 2000; Sadler et al., 2000). While the effects of abiotic factors on crop yields are relatively predictable (Moran et al., 1997; Machado et al., 2000), observed yields do not always follow the expected trends. The discrepancy is most likely due to interaction among the factors as well as significant effect of climatic factors throughout the growing season (such as air and soil temperature, precipitation, and soil moisture). Nonetheless, site-specific farming (SSF) is currently based on information about chemical and physical properties of soils (Robert et al., 1996; Robert et al., 1998). Evaluating yield-limiting factors in winter wheat production, Geesing et al. (2002) observed that with low plant available soil moisture (ASM), grain yields depended significantly on water supply.

Whereas in soils with abundant ASM, the rate of N applied was the main cause of variability in grain yields.

Machado et al. (2002 contended that assessing the impact of temporal factors on crops' growth and yield potential in-season would increase the efficiency in resource management, and might lead to substantial gains in productivity and profitability.(Machado et al. (2002) focused on quantification of the effects of water, soil texture, pests, and diseases on corn grain yields by monitoring of plant growth and development throughout the growing season. They reported that growth analysis helped to explain variability in grain yields, noting that the information provided by the growth analysis was more useful in drought years compared to years with abundant precipitation. This illustrates the importance of accounting for a soil moisture parameter when estimating yield potential in-season.

Johnson and Raun (2003) noted that excess N and P application may not be necessarily a result of poor fertilizer management, but rather the result of existing environmental conditions at a particular crop growing region. Weather factors such as temperature and precipitation often play an important role in determining soil mineral nutrients' availability and plant uptake. For example, in cropping years where enough precipitation is observed, there is a greater risk of N loss from the soil-pant system through leaching. High variability in grain yields and in response to applied fertilizer across years, as well as among years where similar grain yield are obtained, suggests that crop production is highly dependent on factors other than N and P fertilizer application (Girma et al., 2007). The authors proposed that models that include variables which consider both spatial and temporal variability must be encouraged in crop production.

Hubbard et al. (2002) noted that water distribution in the top 1 m of the soil often governs success in crop production. They named soil precipitation, topography, soil heterogeneity, crop cover, and evapotranspiration as the leading factors contributing to spatial and temporal variability in soil water content.

SOIL MOISTURE AND NDVI

Nicholson and Farrar (1994) found that NDVI was linearly correlated with rainfall as long as total amount of precipitation does not exceed 50-100 mm per month. The authors suggest that the linear relationship levels off due to "saturation response" leading to a very slow increase in NDVI values with an increase in rainfall. They examined rain-derived water use efficiency over a wide range of soil types and various vegetation cover types. The results indicated that soil type plays a more important role in rain use efficiency compared to vegetation type. Highest rain efficiency occurs on clay soils compared to sandy soils.

Results by Eklundh (1997) indicated that 10% and 36% of variation in NDVI values could be explained by variation in rainfall on 10-day scale and monthly scales. The author noted that the attempt to use rainfall data to predict vegetative growth may be constrained by variability in soil characteristics (i.e. soil type, soil water holding capacity), as well as rainfall pattern (i.e. duration and intensity). Eklundh (1997) pointed out the importance of more detailed research on understanding the soil moisture-NDVI-yield relationship. Daughtry et al. (2000) suggested that changes in surface soil moisture significantly contribute to differences in crop canopy reflectance (even for homogeneous canopies), making plant stress identification and quantification more challenging.

The ability of the crop canopy, at a given time, to absorb some fraction of the incident PAR (photosynthetically active radiation) is defined as f_a (Daughtry et al., 1992). The NDVI values of bare soil contribute to the variation in observed relationship between NDVI and f_a (particularly when crop canopy is not dense) (Hall et al., 1990; Baret and Guyot, 1991). Consequently, the slope and intercept of the f_a-NDVI relationship may be more accurately determined if NDVI could be adjusted for soil moisture (i.e. using soil color). Several soil-adjusted spectral vegetation indices have been developed and evaluated (Huete, 1989; Major et al., 1990; Baret and Guyot, 1991).

Hong et al. (2001) investigated the effect of various agronomic practices (irrigation, fertilizer N application), soil texture and soil water status on spectral reflectance properties of cotton. They found that, among other factors, soil water content significantly affected agronomic responses of cotton. The authors observed a significant increase in crop reflectance (visible, NIR and MIR) with increased soil water content. Hong et al. (2001) concluded that landscape and soil texture characteristics determine the degree to which soil, plant, and water factors contribute to the variation in a reflectance signal.

Daughtry et al. (1992) pointed out plant response to PAR is usually complex due to the effects of temperature and moisture on plant growth and yields. Therefore, the application of strictly spectral data-based models is limited. It has been proposed that incorporation of weather and soil data into models used for crop yield prediction may increase model applicability and accuracy (Daughtry et al., 1992).

Combining remotely sensed multispectral data with weather information enabled prediction of crop growth and estimation of crop yield (Maas, 1987). Model results must be consistently accurate for a model to be useful in agricultural applications such as assessing crop condition and grain yield prediction. Model performance is, therefore, highly dependent on the ability to approximate real biological system parameters. The model used by Maas (1987) was significantly improved by updating the state variables using remotely sensed data and by adjusting crop stress values based on canopy temperature measurements.

SOIL MOISTURE RESEARCH

Baier and Robertson (1968) evaluated use of soil moisture estimates and the direct climatological measurements to predict wheat grain yield and explainvariation in yield. Their results suggested that if climatological data were expressed in terms of environmental factors directly affecting crops' growth and development, a significant crop-weather relationship could be attained.

Many researchers have attempted to apply crop models to account for temporal and spatial variability due to stresses resulting from limitations in water, temperature, and soil nutrients. Models used to simulate the effects of temporal factors on plant growth and crop yield are sensitive to temporal patterns of stress. These models are generally designed assuming field homogeneity, and as a result; spatial characteristics (which are often unknown or difficult to estimate or predict) are assumed uniform (Batchelor et al., 2002).

Recognizing the importance of soil moisture for agriculture and land-atmosphere interactions, several research institutions across the United States are dedicated to collect and manage comprehensive soil moisture and other climatic information. The Climate Prediction Center (CPC) of the National Weather Center offers extended volumes of climatological data on temperature, precipitation, and soil moisture for the United States as well as other regions of the world. The information can be easily accessed on the CPC web site (Climate Prediction Center, 2007).

The High Plains Regional Climate Center upgraded the Automated Weather Data Network (AWDN) to enable soil water monitoring in Nebraska. Presently, over 50 AWDN sites are equipped with the soil moisture sensors. Soil moisture data have been systematically collected since 1998 (High Plains Regional Climate Center, 2007). The soil moisture measurements provided by the AWDN are generally being used in modeling for estimation of historical soil moisture data, which is an essential component of risk management. The soil moisture database is also being relied upon for drought and climate monitoring. Future projects will involve studies on soil moisture temporal variability in various cropping systems.

The Illinois State Water Survey (ISWS), housed within the Illinois Department of Natural Resources, has been collecting extensive atmospheric and water information for over 100 years. The Water and Atmospheric Resources Monitoring Program (WARM) was initiated in 1980s to manage the archives of the ISWS containing valuable data on a wide range of water and atmospheric variables. Most archived data are available to researchers as well as public (Illinois State Water Survey, 2007).

The Oklahoma Mesonet, an automated statewide system of 115 remote meteorological stations, installed sensors to measure soil moisture levels (Brock et al., 1995). Soil moisture observations are available within the Oklahoma Mesonet network through and interactive web site. Soil moisture data compiled by the Oklahoma Mesonet contributes to research (drought studies, investigation of moisture impact on soil conditions) and public knowledge (precipitation patterns, duration and intensity, agricultural modeling) (Brock et al., 1995). The near real time and historical soil moisture data in form of interactive graphs and maps are accessible to public on the Oklahoma Mesonet web site.

Since 2002, the Sensor Based Nitrogen Rate Calculator, a free on-line tool, has been provided by Oklahoma State University. The calculator is provided to make a more informed decision in soil nutrient management and provides crop producers with more accurate mid-season fertilizer N recommendations tailored for many different crops (winter wheat, spring wheat, rainfed and irrigated corn, canola *(Brassica napus L.)*, Bermuda grass *(C. dactylon L.)*, grain sorghum, and rice *(Oryza sativa L.)* and regions (USA, Mexico, Australia, Argentina, Canada, and China). Long-term research and on-farm trials, results suggest that farmer profits can be increased by more than $10/ac in wheat production and $20/ac in corn production systems (www.nue.okstate.edu, 2008-b).

Establishing a deeper understanding of soil moisture-grain yield relationship must be attained for soil moisture parameters to be successfully used in yield potential prediction. When sound methodology for practical use of the soil moisture measurements is developed, crop producers will benefit fully from an impressive volume of historical and current soil moisture data which is readily available from numerous sources.

CHAPTER IV

HYPOTHESIS AND OBJECTIVES

The hypothesis for this study was that soil moisture measurements would enable more precise prediction of yield potential and more efficient N fertilizer use efficiency.

The objectives of this study were:

1. Determine the effect of mid-season soil profile moisture on prediction of yield potential in winter wheat, and to
2. Establish the functional relationship for adjusting fertilizer N recommendations based on profile moisture and to
3. Refine the on-line Sensor Based Nitrogen Rate Calculator.

CHAPTER V

MATERIALS AND METHODS

Two long-term experimental sites were used for this project in 2007 and 2008: experiment 502 at the North Central Research Station in Lahoma, Oklahoma, and experiment 801 - the NP study at the Cimarron Valley Agronomy Research Station in Perkins, Oklahoma. Experiment at Lahoma was initiated in 1971 to assess the effects of long-term N, P and K fertilizer application in continuous winter wheat production under conventional tillage. The soil was a Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll).

Wheat has been planted in 0.25 meter rows with seeding rate of 67.2 kg ha^{-1}. Since 1996, wheat has been continuously grown at the Perkins NP study on Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll). Seeding rate was 67.2 $kgha^{-1}$ and row spacing ranging from 0.15 to 0.30 m. The tillage system was changed from conventional to no-till in 2005. The treatment structures for experiments 502 and 801 are reported in Tables 1 and 2 respectively. Treatments 1 though 7 (experiment 502) were included in the analysis. Yield potential (YP) sub-plots ($4m^2$) were originally established within the plots of experiment 502 and 801 (treatments 1 through 7 at Lahoma, and treatments 3, 6, 9, and 12 – at Perkins). The YP sub-plots were used to obtain a library of YP prediction equations.

Four 229-L water matric potential sensors manufactured by Campbell Scientific were installed prior to planting at each experimental site at depths of 5, 25, 60, and 75 cm to record moisture observations. The 229-L sensors used in these experiments measure the rate of heat dissipation, and consist of a heating element and copper-constantan thermocouple and a resistor (with the range from 32.5 to 33.5 ohms) embedded in epoxy in a hypodermic needle enclosed in a porous ceramic matrix. The sensors are right-cylinder in shape, measure 60 mm in length and weigh 10 g. The 229-L is capable of measuring soil water matric potential in a range from 0.1 to 10 bars, and has a measurement time of 30 seconds. A CE-4 50 mA ($\pm$1 mA, per channel, regulated) excitation module by Campbell Scientific applies constant current to the heating element; the thermocouple measures the temperature rise (ΔTsensor) after the heat pulse is introduced. The CE-4 module weighs 131 g and has the following dimensions: 11.5cm x 5.4cm x 2.7 cm.

The thermocouple consisted of four 229-L wires (three copper and one constantan) encased in burial-grade sheath and connected to the datalogger. CR1000 dataloggers by Campbell Scientific were used for registering and storing soil moisture values. Datalogers were encased in a locked 30.5 by 35.5 cm weather resistant enclosure and secured on a tripod mast mounting to ensure protection from weather and animal damage. Data collected by the datalogger were downloaded using a portable computer employing LoggerNet - Campbell Scientific developed software, which supports programming direct communication and data retrieval between the datalogger and a computer.

A 12V car battery coupled to a 10 Watt – 12 V outdoor solar panel (BSP-1012LSS) by Sundance Solar (Warner, NH) were installed at each research location to ensure constant power supply to the datalogger during the growing season. The solar cells of the solar panel were laminated between sheets of ethylene vinyl acetate with a stainless steel substrate. The solar panel weighs 1.134 kg and its' dimensions are 26.7cm x 44.5 cm. The panels' electrical characteristics are as follows: Maximum Power (P_{max}): 10 W; Maximum Voltage: 17.3 V; Current at P_{max}: 0.58 A; Short-circuit current: 0.66 A; Open-circuit voltage: 21.3 V. The SunGuard 4 Charge Controller (manufactured by Morningstar) was used with the solar panel to provide regulated voltage and current from the solar panel to the battery. The SunGuard 4 Charge Controller employs the Pulse Width Modulation (PWM) principle to achieve constant voltage battery charging by switching the solar system controller's power devices. The PWM regulation, ensures that the current from the solar array tapers according to the battery's condition and recharging needs.

Each 229-L sensor was individually calibrated by collecting ΔT values to obtain the threshold temperature values, two temperatures were measured: ΔTmin (the wettest value obtained by saturating the ceramic matrix of a sensor in water) and ΔTmax (the driest value determined by drying the sensor ceramic matrix with a desiccant).

A linear regression: $TR = m * \Delta T + b$, where TR is referred to as the ΔTref temperature, was used to "normalize" the response of each sensor (ΔTsensor) to the response of a reference sensor. This idealized reference sensor has the following characteristics: ΔTmax = 3.96 C°, ΔTmin = 1.38 C°.

The regression coefficients m and b were determined using the following equation:

$m = (3.96 – 1.38) / (\Delta Tmax – \Delta Tmin)$,

and

$b = 3.96 – m * \Delta Tmax$.

Thus, each sensor has its own unique coefficients for normalizing its response.

Estimates of soil moisture including: MP - matric, or soil water potential (bars), WC -volumetric water content (m^3water/m^3soil), and FWI - fractional water index (unitless) were then derived from TR values.

The following equation was applied to determine MP:

$MP = - (c * \exp (a * TR))/100$, where:

MP = matric potential (bars),

TR = ΔT reference (C°),

$a = 1.788$,

$c = 0.717$.

The MP values were then converted into soil water content as follows:

$WC = WCr + (WCs - WCr) / (1 + (a * -MP) ^ n) ^ (1 – 1 / n)$, where:

WC = soil water content on a volume basis (m^3water/m^3soil),

WCr = residual water content (m^3water/m^3soil),

WCs = saturated water content (m^3water/m^3soil),

a, n = empirical constants,

MP = matric (soil-water) potential (bars).

The coefficients (WCr, WCs, a, and n) for each depth for each site are available from the Oklahoma Mesonet database. These coefficients are influenced by the following soil properties: soil texture, bulk density, porosity, etc.

Fractional water index values were determined using the following equation:

$FWI = \Delta Tdry - TR\Delta Tdry - \Delta Twet$, where:

FWI = fractional water index (unitless),

$TR = \Delta T$ reference (C°),

$\Delta Tdry = 3.96$ C°,

$\Delta Twet = 1.38$ C°.

All equations were obtained from the Oklahoma Mesonet (http://www.mesonet.org/instruments/SoilMoisture.pdf).

Within each of the YP sub-plots, wheat spectral reflectance was measured using a GreenSeeker™ hand-held optical sensor (N-tech Industries) at the Feekes 5 growth stage. The GreenSeeker sensor employs a patented technology to measure crop reflectance and calculate Normalized Difference Vegetative Index (NDVI). The hand-held unit senses a 0.6 x 0.01 m area as it is held at 0.6 to 1.0 m above the canopy. The sensor samples at approximately 700 Hz, averages the data, and transmits it computer every 0.1 s. The sensor was carried by hand. The sensor used active illumination from LED's at 650 $\pm$ 10 nm FWHM and NIR 770 $\pm$ 15 nm FWHM bands (FWHM = full width at half maximum) By Pulse modulating the light at 40, kHz background light could be filtered.

The sensor measured the intensity of luminance from the LED's enabled calculation of reflectance.

NDVI was calculated by equation (xx):

NDVI = $(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$,

where: ρ_{NIR} = fraction of emitted NIR radiation returned from the sensed area (reflectance), and ρ_{Red} = fraction of emitted Red radiation returned from the sensed area (reflectance). In-Season Estimated Yield (INSEY) was calculated as NDVI at Feekes 5 divided by growing degree days (GDD>0).

Yield potential (YP) sub-plots ($4m^2$) were harvested with a Massey Ferguson 8XP self propelled combine to record wheat grain yield. Grain yields were extremely low at Perkins in 2009 ranging from 8 kg ha^{-1} for the unfertilized check plot to 685 kg ha^{-1} for treatments that received 168 kg N ha^{-1}. This low yields were due to several hail storms at Perkins in the spring of 2009. A particularly severe storm occurred in Perkins on the June 12^{th}, 2009; baseball size hail was observed at Perkins site on this date. Data for Perkins for the 2008-2009 growing season was not included in the analysis. Correlation of NDVI (at Feekes 5) and INSEY with winter wheat grain yield were analyzed. 64 variables which incorporating soil moisture (WC and FWI) were evaluated in this study to assess if soil moisture can help to estimate winter wheat grain yield:

1. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, at planting (NDVI*WC5plant),

2. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, at planting (NDVI*WC25plant),

3. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, at planting (NDVI*WC60plant),

4. NDVI at Feekes 5 multiplied by WC at the 75 cm depth, at planting (NDVI*WC75plant),
5. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, at sensing (NDVI*WC5sens),
6. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, at sensing (NDVI*WC25sens),
7. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, at sensing (NDVI*WC60sens),
8. NDVI at Feekes 5 multiplied by WC at the 75 cm depth, at sensing (NDVI*WC75sens),
9. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around planting (NDVI*WC5av30plant),
10. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around planting (NDVI*WC25av30plant),
11. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around planting (NDVI*WC60av30plant),
12. NDVI at Feekes 5 multiplied by WC at the 75 cm depth, average of 30 days around planting (NDVI*WC75av30plant),
13. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around sensing (NDVI*WC5av30sens),

14. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around sensing (NDVI*WC25av30sens),

15. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around sensing (NDVI*WC60av30sens),

16. NDVI at Feekes 5 multiplied by WC at the 75 cm depth, average of 30 days around sensing (NDVI*WC75av30sens),

17. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, at planting (INSEY *WC5plant),

18. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, at planting (INSEY *WC25plant),

19. INSEY at Feekes 5multiplied by WC at the 60 cm depth, at planting (INSEY *WC60plant),

20. INSEY at Feekes 5multiplied by WC at the 75 cm depth, at planting (INSEY *WC75plant),

21. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, at sensing (INSEY *WC5sens),

22. INSEY at Feekes 5multiplied by WC at the 25 cm depth, at sensing (INSEY *WC25sens),

23. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, at sensing (INSEY *WC60sens),

24. INSEY at Feekes 5 multiplied by WC at the 75 cm depth, at sensing (INSEY *WC75sens),

25. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around planting (INSEY *WC5av30plant),

26. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around planting (INSEY *WC25av30plant),

27. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around planting (INSEY *WC60av30plant),

28. INSEY at Feekes 5 multiplied by WC at the 75 cm depth, average of 30 days around planting (INSEY *WC75av30plant),

29. INSEY at Feekes 5multiplied by WC at the 5 cm depth, average of 30 days around sensing (INSEY *WC5av30sens),

30. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around sensing (INSEY *WC25av30sens),

31. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around sensing (INSEY *WC60av30sens),

32. INSEY at Feekes 5 multiplied by WC at the 75 cm depth, average of 30 days around sensing (INSEY *WC60av30sens),

33. NDVI at Feekes 5 multiplied by FWI at the 5 cm depth, at planting (NDVI*FWI5plant),

34. NDVI at Feekes 5 multiplied by FWI at the 25 cm depth, at planting (NDVI*FWI25plant),

35. NDVI at Feekes 5 multiplied by FWI at the 60 cm depth, at planting (NDVI*FWI60plant),

36. NDVI at Feekes 5 multiplied by FWI at the 75 cm depth, at planting (NDVI*FWI75plant),

37. NDVI at Feekes 5 multiplied by FWI at the 5 cm depth, at sensing (NDVI*FWI5sens),

38. NDVI at Feekes 5 multiplied by FWI at the 25 cm depth, at sensing (NDVI*FWI25sens),

39. NDVI at Feekes 5 multiplied by FWI at the 60 cm depth, at sensing (NDVI*FWI60sens),

40. NDVI at Feekes 5 multiplied by FWI at the 75 cm depth, at sensing (NDVI*FWI75sens),

41. NDVI at Feekes 5 multiplied by FWI at the 5 cm depth, average of 30 days around planting (NDVI*FWI5av30plant),

42. NDVI at Feekes 5 multiplied by FWI at the 25 cm depth, average of 30 days around planting (NDVI*FWI25av30plant),

43. NDVI at Feekes 5 multiplied by FWI at the 60 cm depth, average of 30 days around planting (NDVI*FWI60av30plant),

44. NDVI at Feekes 5 multiplied by FWI at the 75 cm depth, average of 30 days around planting (NDVI*FWI75av30plant),

45. NDVI at Feekes 5 multiplied by FWI at the 5 cm depth, average of 30 days around sensing (NDVI*FWI5av30sens),

46. NDVI at Feekes 5 multiplied by FWI at the 25 cm depth, average of 30 days around sensing (NDVI*FWI25av30sens),

47. NDVI at Feekes 5 multiplied by FWI at the 60 cm depth, average of 30 days around sensing (NDVI*FWI60av30sens),

48. NDVI at Feekes 5 multiplied by FWI at the 75 cm depth, average of 30 days around sensing (NDVI*FWI75av30sens),

49. INSEY at Feekes 5 multiplied by FWI at the 5 cm depth, at planting (INSEY *FWI5plant),

50. INSEY at Feekes 5 multiplied by FWI at the 25 cm depth, at planting (INSEY *FWI25plant),

51. INSEY at Feekes 5multiplied by FWI at the 60 cm depth, at planting (INSEY *FWI60plant),

52. INSEY at Feekes 5multiplied by FWI at the 75 cm depth, at planting (INSEY *FWI75plant),

53. INSEY at Feekes 5 multiplied by FWI at the 5 cm depth, at sensing (INSEY *FWI5sens),

54. INSEY at Feekes 5multiplied by FWI at the 25 cm depth, at sensing (INSEY *FWI25sens),

55. INSEY at Feekes 5 multiplied by FWI at the 60 cm depth, at sensing (INSEY *FWI60sens),

56. INSEY at Feekes 5 multiplied by FWI at the 75 cm depth, at sensing (INSEY *FWI75sens),

57. INSEY at Feekes 5 multiplied by FWI at the 5 cm depth, average of 30 days around planting (INSEY *FWI5av30plant),

58. INSEY at Feekes 5 multiplied by FWI at the 25 cm depth, average of 30 days around planting (INSEY *FWI25av30plant),

59. INSEY at Feekes 5 multiplied by FWI at the 60 cm depth, average of 30 days around planting (INSEY *FWI60av30plant),

60. INSEY at Feekes 5 multiplied by FWI at the 75 cm depth, average of 30 days around planting (INSEY *FWI75av30plant),

61. INSEY at Feekes 5multiplied by FWI at the 5 cm depth, average of 30 days around sensing (INSEY *FWI5av30sens),

62. INSEY at Feekes 5 multiplied by FWI at the 25 cm depth, average of 30 days around sensing (INSEY *FWI25av30sens),

63. INSEY at Feekes 5 multiplied by FWI at the 60 cm depth, average of 30 days around sensing (INSEY *FWI60av30sens),

64. INSEY at Feekes 5 multiplied by FWI at the 75 cm depth, average of 30 days around sensing (INSEY *FWI60av30sens).

CHAPTER VI

RESULTS AND DISCUSSION

CLIMATE CONDITIONS

During the 2007-2008 growing season, much more abundant precipitation was observed at Lahoma compared to Perkins. Lahoma received 727 mm of precipitation – over 180 mm more than Perkins. Average air temperatures at Lahoma were more than 10 Cº higher than at Perkins: 20 Cº at Lahoma compared to 9 Cº at Perkins site (Table 5).

A drastic difference in weather conditions was experienced at Lahoma between the 2007-2008 and 2008-2009 growing seasons. Much more cool and dry conditions were experienced during the second year of the study. Less than 181 mm of precipitation was received at Lahoma in 2008-2009 compared to 2007-2008. The average air temperatures were 10 Cº lower in 2008-2009 compared to 2007-2008 (Table 5).

While average temperatures at Lahoma in 2008-2009 were comparable to those at Perkins in 2007-2008, Perkins received 200 mm more precipitation than Lahoma (Table 5).

Soil temperatures varied greatly from year to year and site to site. The warmest soil average temperatures (20 C°) were observed at Lahoma in the 2007-2008 growing season, while in the 2008-2009 growing season soil temperatures at Lahoma averaged 11 C°. In Perkins in 2008-2009, average soil temperatures were 13 C° (Table 5).

In summary, all three site-years were very different weather wise. Lahoma in 2007-2008 was the warmest and the wettest of all site-years. While Perkins in 2007-2008 was the coolest site-year, Lahoma in 2008-2009 was the driest compared to others.

2008 - GRAIN YIELD - LAHOMA

In 2008, at Lahoma winter wheat grain yields ranged from 2591 kg ha^{-1}(treatment 1, the unfertilized check plot) to 6280 kg ha^{-1} (treatment 7)(Table 3). Winter wheat responded to N fertilization, and grain yields increased linearly with increased N rate applied (Figure 1) (Table A1). Statistically significant differences between mean winter wheat grain yields associated with N rate were observed in 2008 at Lahoma (Figure 2).

2008 - GRAIN YIELD - PERKINS

At Perkins, winter wheat responded to fertilizer N in 2008, however, grain yields were generally lower compared to those at Lahoma. Winter wheat grain yields ranged between 1433 kg ha^{-1} and 4583 kg ha^{-1} (Table 4). Statistical analysis indicated that grain yields increased linearly with the increase in N applied (Figure 3) (Table A2).

Statistically significant differences between mean winter wheat grain yields associated with N rate were observed at Perkins in 2008 (Figure 4).

2008 - NDVI, INSEY, AND SOIL MOISTURE - LAHOMA

In 2008, 81% of the variation in mean grain yield was explained by NDVI at the Feekes 5 growth stage. A linear relationship (r^2=0.81) was observed between NDVI and winter wheat grain yield (Figure 5). Also, 81% of the variation in wheat grain yields was explained by the other parameters evaluated (for example, NDVI*WC5sens, NDVI*WC25sens, NDVI*WC60sens, and NDVI*WC75sens) (Figures 6, 7, 8, and 9, respectively) (other data not shown). Thus, even though all 64 soil moisture indices were strongly correlated with grain yield, NDVI alone was just as good in predicting grain yields in 2008 at Lahoma. Plentiful and timely rainfall events throughout the 2007-2008 growing season resulted in adequate soil moisture present within the soil profile. Sufficient soil moisture facilitated proper crop establishment and development, assisted in efficient nutrient uptake, and allowed the crop to realize its maximum yield potential. In-Season Estimated Yield explained 81% of variation in winter wheat grain yields achieved in 2008 (Figure 10).

2008 - NDVI, INSEY, AND SOIL MOISTURE - PERKINS

At Perkins, NDVI at Feekes 5 was also highly correlated with grain yield. Sixty nine per cent of the variation in winter wheat grain yields was explained by NDVI (Figure 15). Similar to Lahoma, all 64 indices that incorporated soil moisture evaluated in this study explained the same amount of variation in mean grain yields as NDVI alone. Figures 16, 17, 18, 19, and 20 show that NDVI*FWI5sens, NDVI*FWI25sens, NDVI*FWI60sens, INSEY, and INSEY*FWI5sens, respectively, explained 69% of the variation in grain yield (other data not shown). Like at Lahoma, NDVI and INSEY alone were good predictors of winter wheat grain yield. At Perkins, the correlation between NDVI and grain yield, and INSEY and grain yield was the weakest of 3 site-years evaluated. Cool temperatures might have had a negative effect on the development of the crop, diminishing its yield potential over time. Also, unlike at Lahoma, winter wheat grain yield at Perkins was linearly correlated with P rate, and there were significant differences in mean grain yields associated with the total amount of P applied (data not shown). Since the crop responded strongly to P fertilization, it might have been deficient in P. This suggests that several factors negatively impacted yield potential during the growing season, probably after the time of sensing.

2009 - GRAIN YIELD - LAHOMA

In 2009, at Lahoma, winter wheat grain yields were much lower compared to those obtained in 2008. The unfertilized check plot in 2009 yielded 1012 kg ha^{-1} less than in 2008. Yields ranged from 1557 kg ha^{-1} to 4914 kg ha^{-1} for treatment 2 (did not receive any fertilizer N) and treatment 7 (112 kg N ha^{-1}), respectively (Table 4). The grain yield of the unfertilized plot (treatment 1) of 1579 kg ha^{-1} was not statistically different from the yield of treatment 2. Winter wheat grain yields increased linearly with an increase in applied N (Figure 17) (Table A1). Statistically significant differences in mean grain yields associated with N rate were observed at Lahoma in 2009 (Figure 18).

2009 - NDVI, INSEY, AND SOIL MOISTURE - LAHOMA

In 2009, at Lahoma, NDVI measurements collected at Feekes growth stage 5 were highly correlated with final winter wheat grain yield (r^2=0.88) (Figure 19). Thus, 88% of the variation in grain yield was explained by NDVI measurements. The relationship between INSEY and final winter wheat grain yield is shown in Figure 20 (r^2=0.88). Interestingly, NDVI better predicted final winter wheat grain yield at Lahoma in the 2008-2009 growing season compared to the 2007-2008. Lahoma was the driest site-year of 3 site-years in 2008-2009 (Table 5). This suggests that NDVI values reflected the lack of soil moisture and, in turn, lower winter wheat yield potential. Like in 2008, all 64 indices that incorporated soil moisture evaluated in this study explained the same amount of variation in mean grain yields as NDVI alone at Lahoma. For example, Figures 21, 22, 23, and 24 show that NDVI*WC5sens, NDVI*WC5plant, INSEY*WC60,30sens, and

NDVI*FWI25,30sens, respectively, explained 69% of the variation in grain yield (other data not shown). Like in 2008 at Lahoma, NDVI and INSEY alone were able to estimate winter wheat grain yield in 2009.

CHAPTER VII

CONCLUSIONS

Generating fertilizer N recommendations based on plant need for N assessed mid-season has a potential to increase NUE. Considering the importance of adequate soil moisture for crop establishment, development and N uptake, it is apparent that knowing how much water is present within the soil profile could assist in assessing crop N requirements. The results of this study showed that NDVI and INSEY were good predictors of grain yield in winter wheat for all site-years. All of the 64 indices incorporating volumetric water content and fractal water index were equally as good in predicting winter wheat grain yield for all site-years.

Post-sensing cool temperatures and, possibly, P deficiency, negatively affected yield potential resulting in lower winter wheat grain yields (Perkins, 2007-2008), decreasing the accuracy of yield potential prediction mid-season. Because NDVI was a better predictor of final winter wheat grain yield in the dry site-year (Lahoma, 2008-2009), it suggests that NDVI values reflected the lack of soil moisture and, in turn, lower winter wheat yield potential.

Previous research and analysis of long-term data strongly suggested that soil moisture measurements could allow for more precise prediction of winter wheat yield potential. However, more research is needed to confirm this hypothesis. The results showed little evidence of using soil profile moisture to better predict yield potential in winter wheat. To establish the functional relationship for adjusting fertilizer N recommendations based on profile moisture, more research is necessary. Soil matric potential sensors used in this study measure the difference in the temperature within the body of the sensor after the voltage is applied. Then, soil water potential and fractal water index were calculated using an array of coefficients and equations provided by the Oklahoma Mesonet. It is suggested for further studies that using different sensors developed specifically for obtaining soil moisture measurements might help to more accurately estimate soil moisture status.

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TABLES

Table 1. Treatment structure for experiment 502, Lahoma, OK, 2008 and 2009.

Treatment	N	P	K
		kg ha^{-1}	
1	0	0	0
2	0	20	56
3	22	20	56
4	45	20	56
5	67	20	56
6	90	20	56
7	112	20	56
8	67	0	56
9	67	10	56
10	67	31	56
11	67	40	56
12	67	31	56
13	112	40	56
14	67	20	56*

N, P, and K applied as ammonium nitrate (34-0-0), triple superphosphate (0-46-0) and potassium chloride (0-0-60), respectively. * K applied as sul-po-mag (0-0-22).

Table 2. Treatment structure for experiment 801, Perkins, OK, 2008 and 2009.

Treatment	N	P
	kg ha^{-1}	
1	0	0
2	0	15
3	0	29
4	56	0
5	56	15
6	56	29
7	112	0
8	112	15
9	112	29
10	168	0
11	168	15
12	168	29

N, and P applied as ammonium nitrate (34-0-0), and triple superphosphate, respectively.

Table 3. Treatment structure and winter wheat grain yield for check plot and yield potential plots, Experiment 502, Lahoma, OK, 2008 and 2009.

Treatment	N	P	K	Winter wheat grain yield, kg ha^{-1}	
		kg ha^{-1}		2008	2009
1	0	0	0	2591	1579
2	0	20	56	2883	1557
3	22	20	56	4195	1995
4	45	20	56	5382	2536
5	67	20	56	4937	2927
6	90	20	56	5360	3854
7	112	20	56	6280	4914
SED*				252	72

*SED – Standard error of the difference between two equally replicated means.
N, and K applied as ammonium nitrate (34-0-0), triple superphosphate (0-46-0) and potassium chloride (0-0-60), respectively.

Table 4. Treatment structure and winter wheat grain yield got check plot and yield potential plots, for Experiment 801, Perkins, OK, 2008.

Treatment	N	P	Winter wheat grain yield kg ha^{-1}
1	0	29	1967
3	0	29	2200
6	56	29	2650
9	112	29	4583
12	168	29	3567
SED*			179

*SED – Standard error of the difference between two equally replicated means.
N, and P applied as ammonium nitrate (34-0-0), and triple superphosphate, respectively.

Table 5. Field activities including planting dates, seeding rates, cultivars, fertilizer application dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Experiment 502, Lahoma, OK, 2007-2008 and 2008-2009, and Experiment 801, Perkins, OK, 2007-2008.

2007-2008		
Field activity	Lahoma	Perkins
Planting date	October 12, 2007	October 20, 2007
Cultivar	Endurance	Duster
Fertilization date	October 12, 2007	October 20, 2007
Sensing date, Feekes 5	March 13, 1008	March 19, 2009
Harvest date	June 26, 2009	June 6, 2009
Rainfall (mm) *	727	546
Average air temperatures (C°)*	20 C°	9 C°
Average soil temperatures (C°)*	20 C°	13 C°
2008-2009		
Field activity	Lahoma	
Planting date	September 30, 2008	
Cultivar	Endurance	
Fertilization date	September 23, 2008	
Sensing date, Feekes 5	March 11, 2009	
Harvest date	June 18, 2009	
Rainfall (mm) *	346	
Average air temperatures (C°)*	10 C°	
Average soil temperatures (C°)*	11 C°	

* Rainfall, average air and average soil temperatures for the period from planting through harvest.

FIGURES

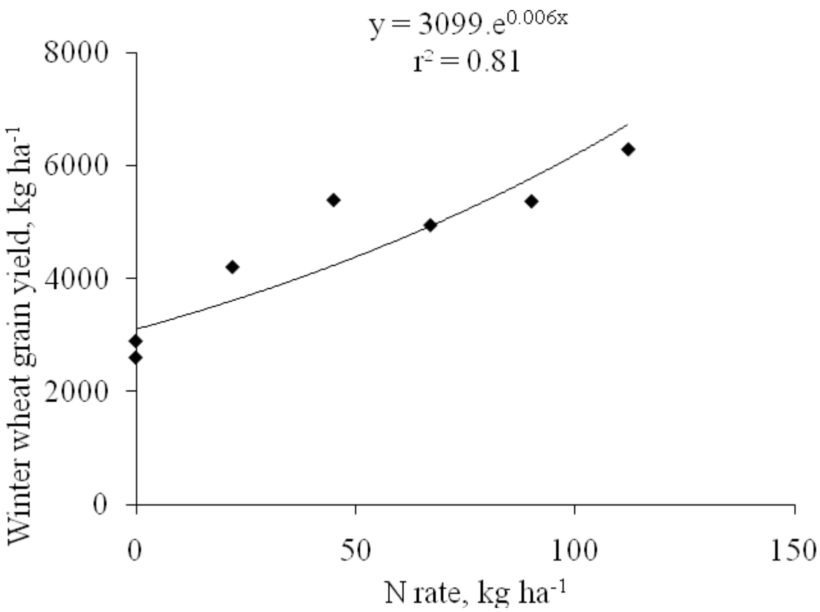

Figure 1. Relationship between N rate and winter wheat grain yield, Lahoma, OK, 2008.

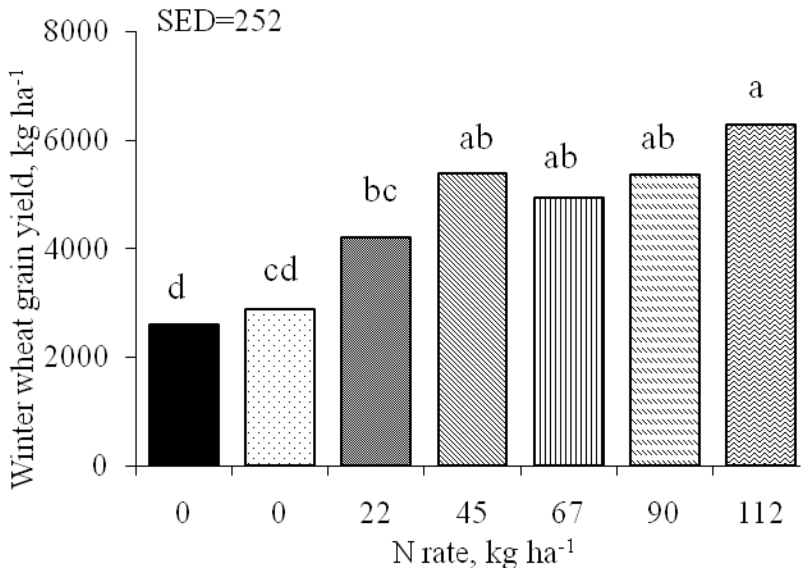

Figure 2. Winter wheat grain yield as affected by N rate, Lahoma, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

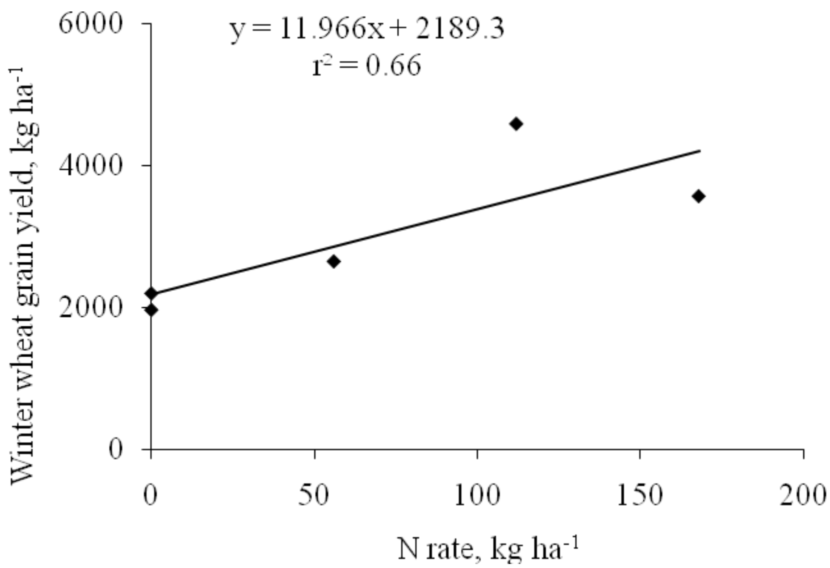

Figure 3. Relationship between N rate and winter wheat grain yield, Perkins, OK, 2008.

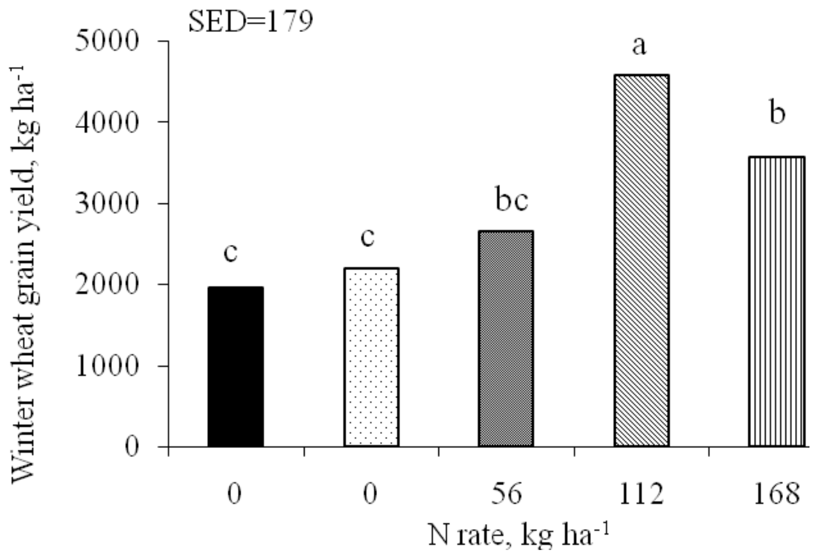

Figure 4.Winter wheat grain yield as affected by N rate, Perkins, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at p<0.05 using Least Significant Difference (LSD) mean separation procedure.

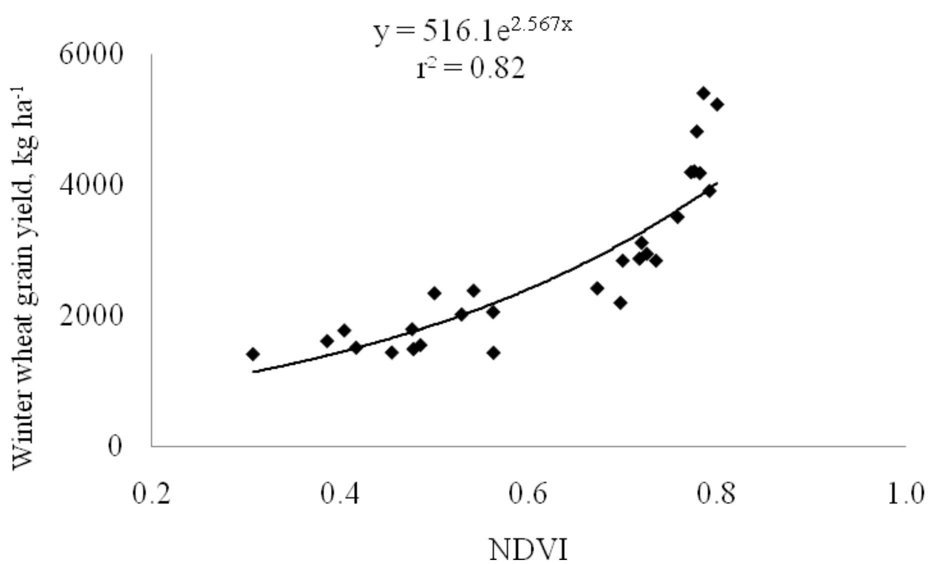

Figure 5. Relationship between NDVI at Feekes 5 growth stage and winter wheat grain yield, Lahoma, OK, 2008.

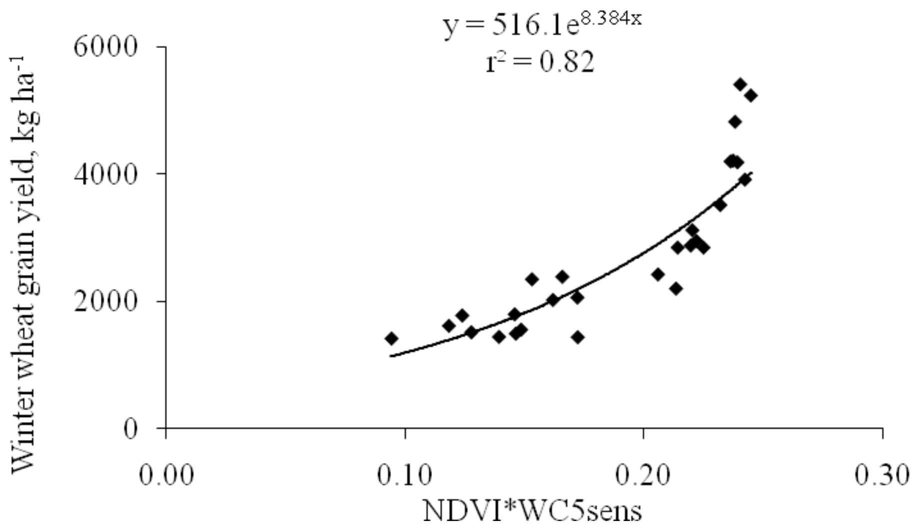

Figure 6. Relationship between NDVI at Feekes 5 multiplied by volumetric soil water content at the 5 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 2008.

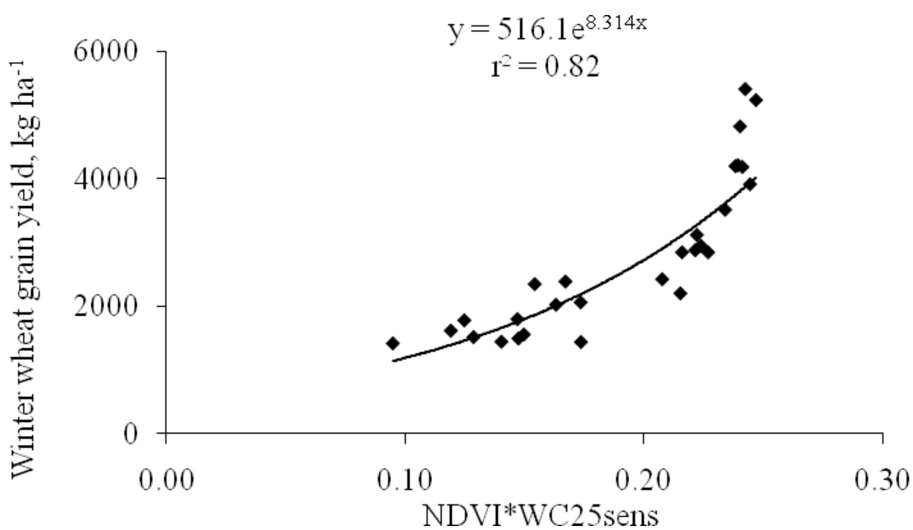

Figure 7. Relationship between NDVI at Feekes 5 multiplied by volumetric soil water content at the 25 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 2008.

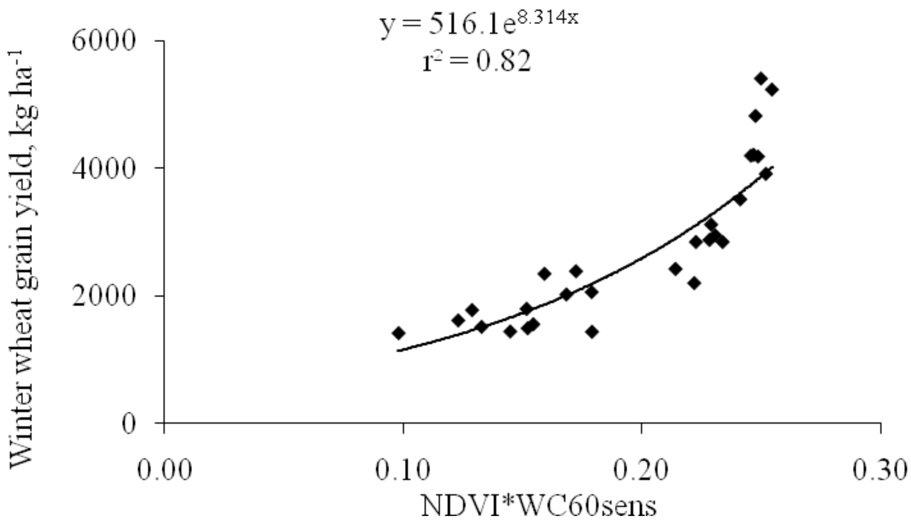

Figure 8. Relationship between NDVI at Feekes 5 multiplied by volumetric soil water content at the 60 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 2008.

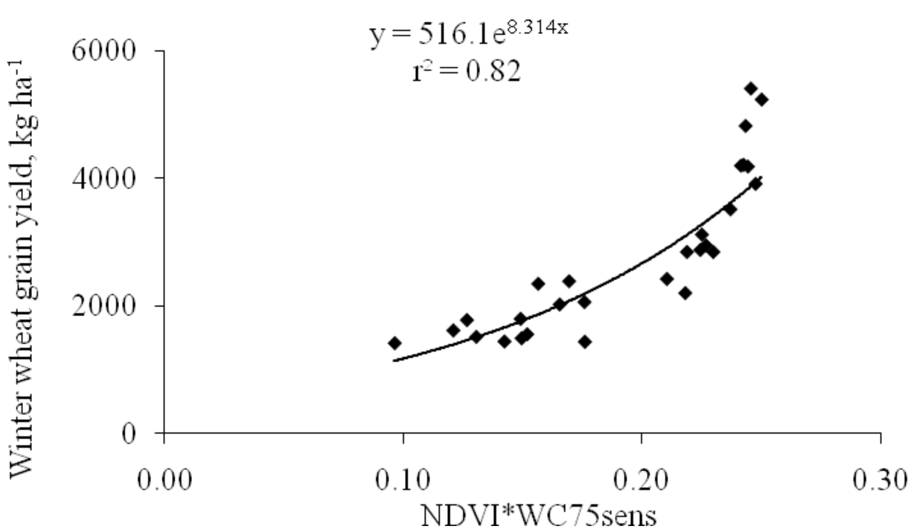

Figure 9. Relationship between NDVI at Feekes 5 multiplied by volumetric soil water content at the 75 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 2008.

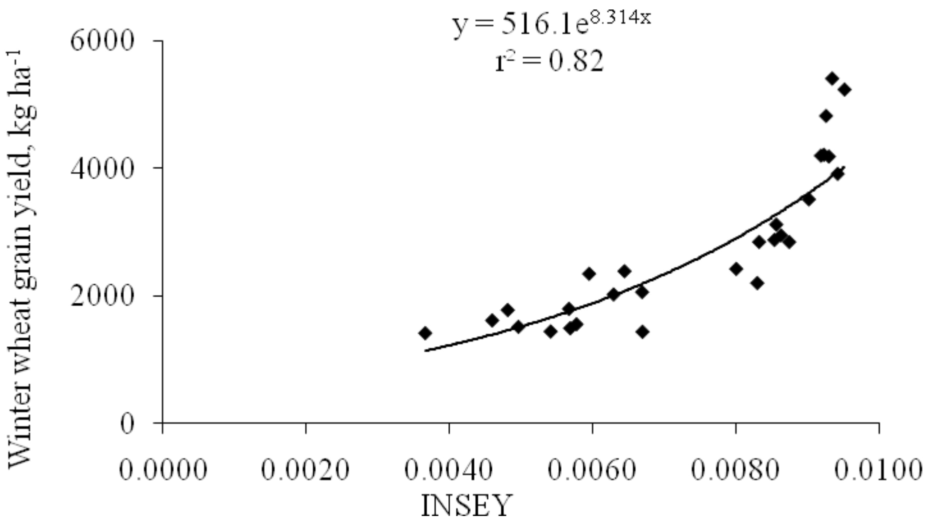

Figure 10. Relationship between INSEY (NDVI at Feekes 5 growth stage/GDD>0) and winter wheat grain yield, Lahoma, OK, 2008.

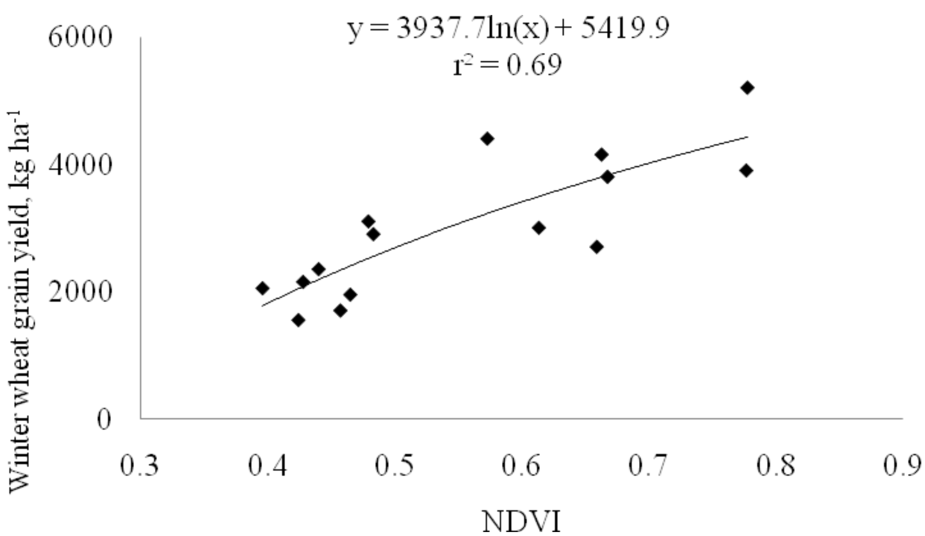

Figure 11. Relationship between NDVI at Feekes 5 growth stage and winter wheat grain yield, Perkins, OK, 2008

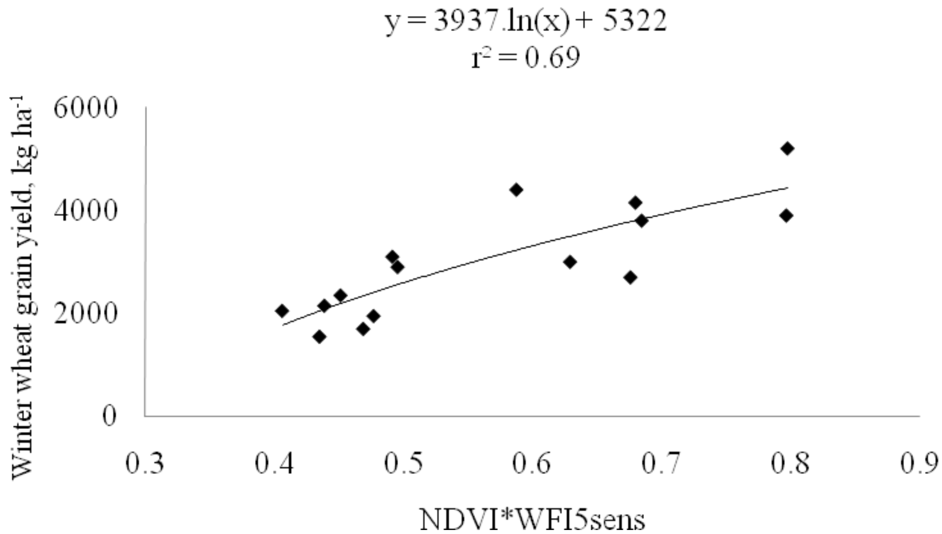

Figure 12. Relationship between NDVI at Feekes 5 multiplied by fractal water index at the 5 cm depth at the time of sensing and winter wheat grain yield, Perkins, OK, 2008.

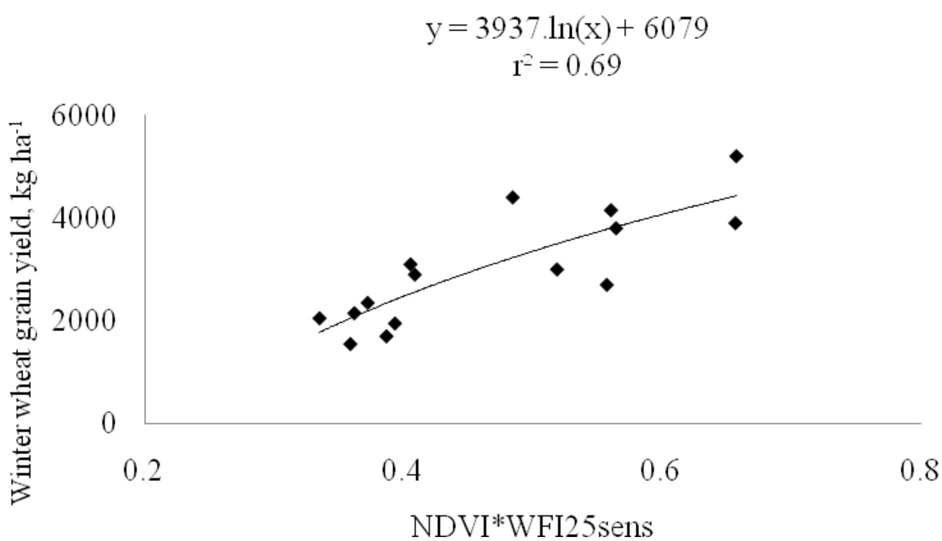

Figure 13. Relationship between NDVI at Feekes 5 multiplied by fractal water index at the 25 cm depth at the time of sensing and winter wheat grain yield, Perkins, OK, 2008.

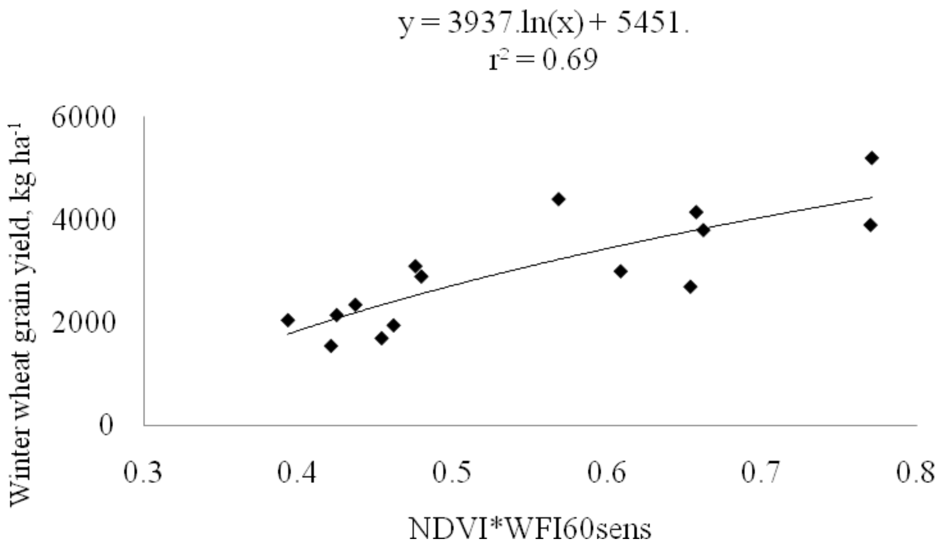

Figure 14. Relationship between NDVI at Feekes 5 multiplied by fractal water index at the 60 cm depth at the time of sensing and winter wheat grain yield, Perkins, OK, 2008.

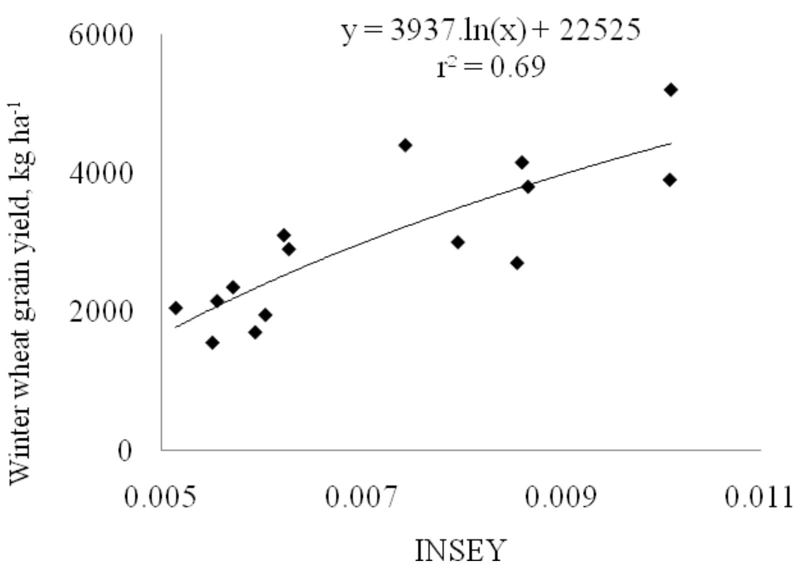

Figure 15. Relationship between INSEY (NDVI at the Feekes 5/GDD>0) and winter wheat grain yield, Perkins, OK, 2008.

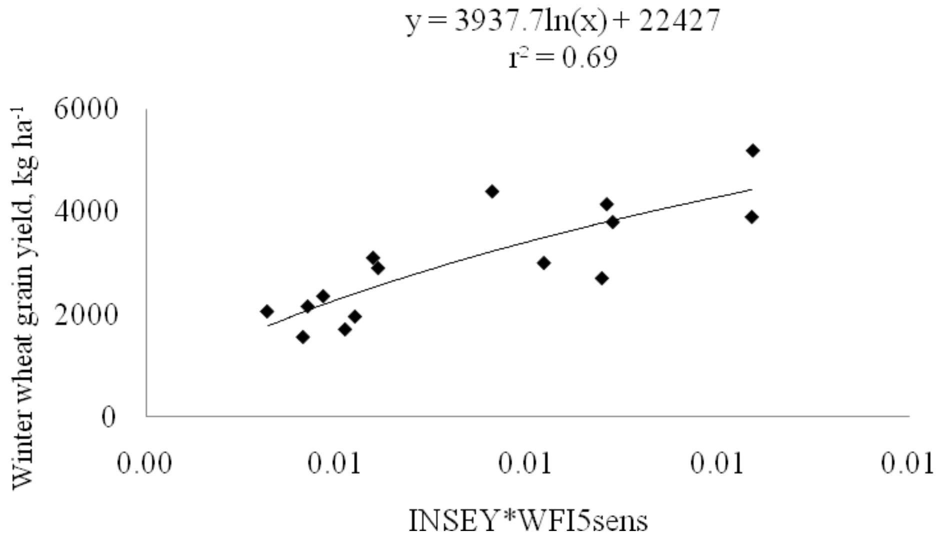

Figure 16. Relationship between INSEY (NDVI at Feekes 5/GDD>0) multiplied by fractal water index at the 5 cm depth at the time of sensing and winter wheat grain yield, Perkins, OK, 2008.

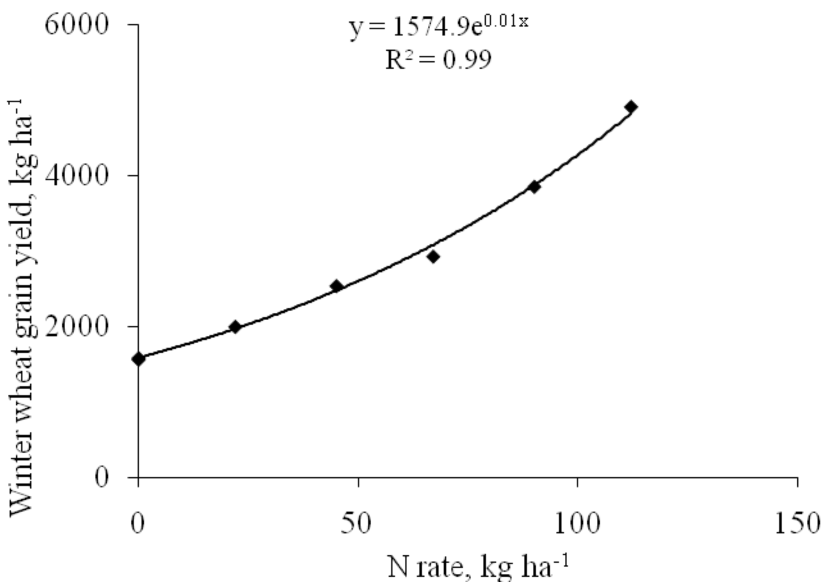

Figure 17. Relationship between N rate and winter wheat grain yield, Lahoma, OK, 2009.

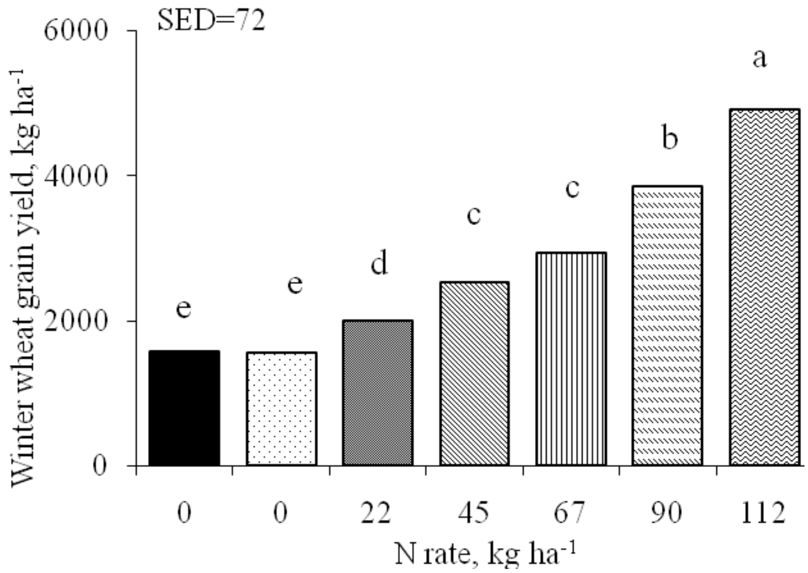

Figure 18. Winter wheat grain yield as affected by N rate, Lahoma, OK, 2009. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at p<0.05 using Least Significant Difference (LSD) mean separation procedure.

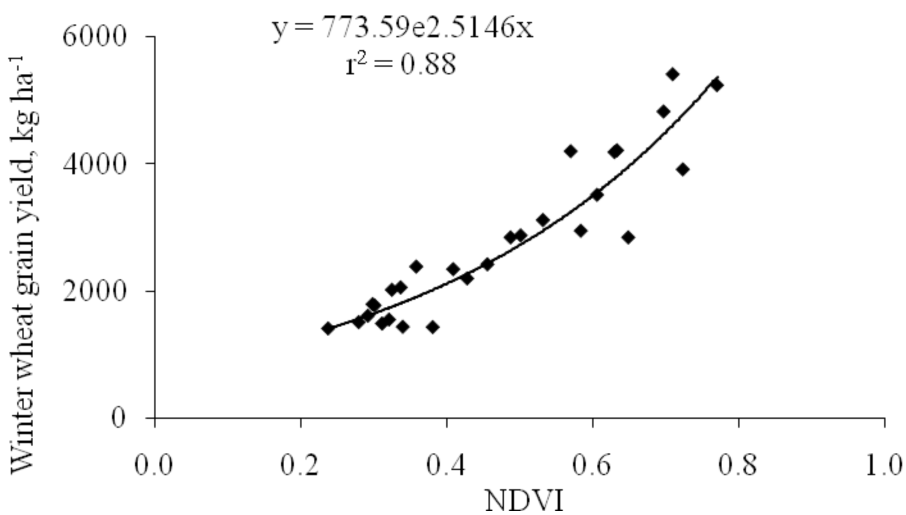

Figure 19. Relationship between NDVI at Feekes 5 growth stage and winter wheat grain yield, Lahoma, OK, 2009.

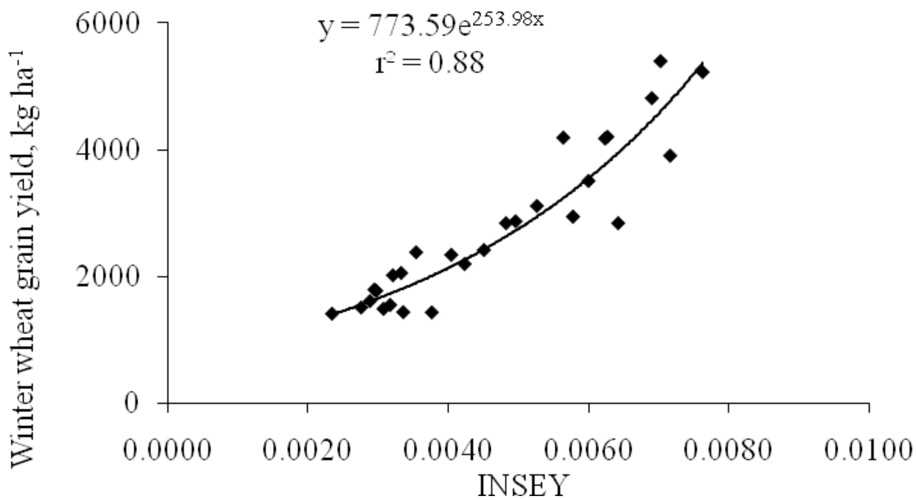

Figure 20. Relationship between INSEY (NDVI at the Feekes 5 growth stage/GDD>0) and winter wheat grain yield, Lahoma, OK, 2009.

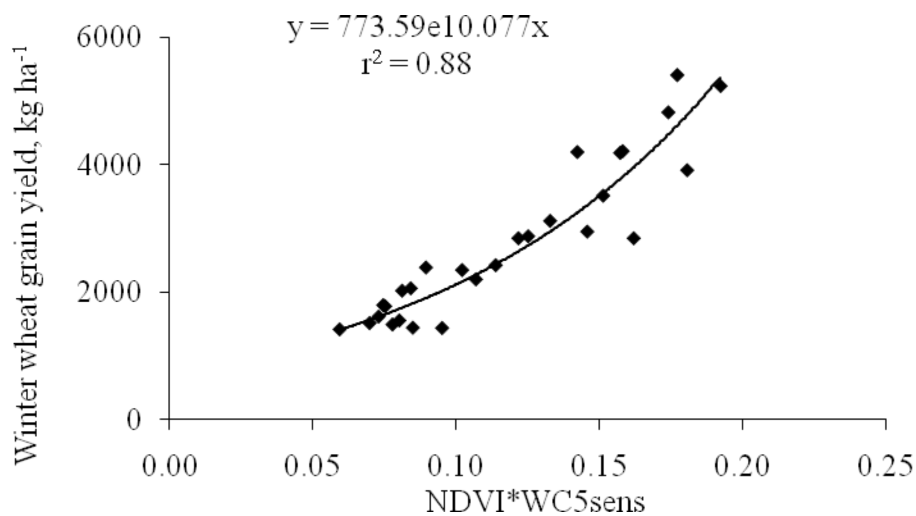

Figure 21. Relationship between NDVI at Feekes 5 multiplied by volumetric soil water content at the 5 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 2009.

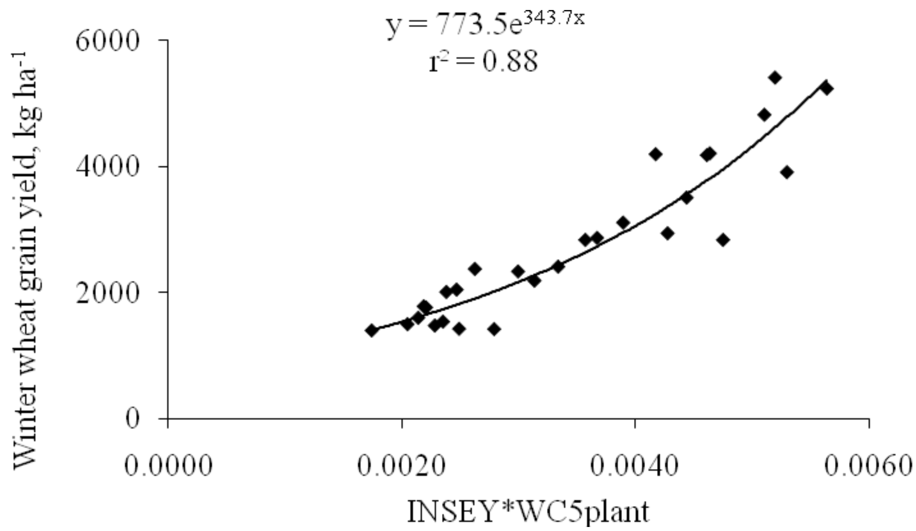

Figure 22. Relationship between INSEY(NDVI at Feekes 5/GDD>0) multiplied by volumetric water content a the 5 cm depth at the time of planting and winter wheat grain yield, Lahoma, OK, 2009.

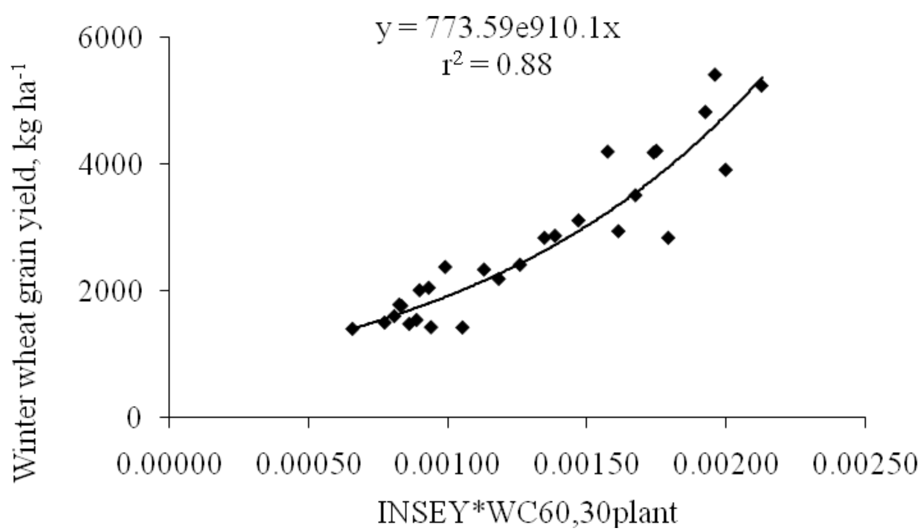

Figure 23. Relationship between INSEY(NDVI at Feekes 5/GDD>0) multiplied by volumetric water content a the 60 cm depth averaged over 30 days around the time of plaiting and winter wheat grain yield, Lahoma, OK, 2009.

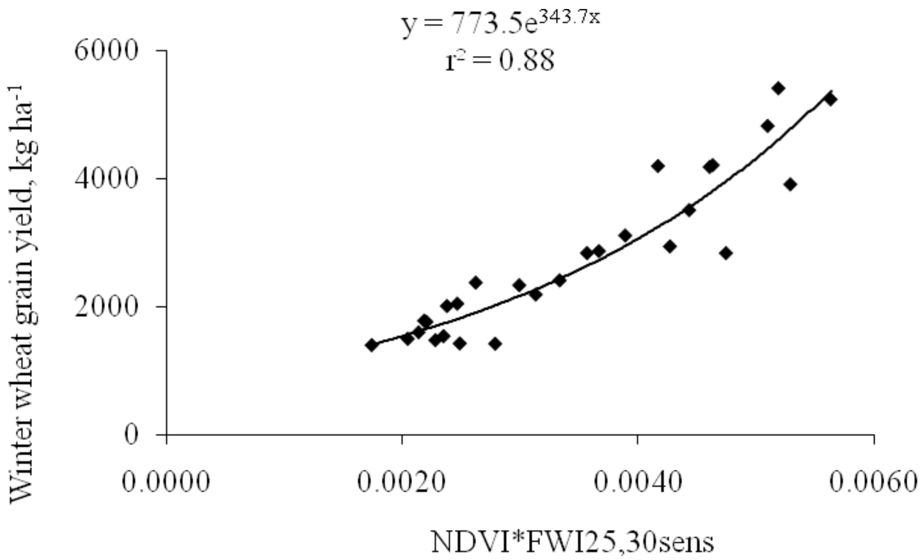

Figure 24. Relationship between NDVI at Feekes 5 growth stage multiplied by fractal water index at the 25 cm depth, averaged over 30 days around the time of sensing, lahoma, OK, 2009.

APPENDICES

Table A-1. Results of linear polynomial orthogonal contrasts for winter wheat grain yield at Lahoma, OK, 2008 and 2009.

Contrast	2008	2009
Linear, N rate	***	***

* - Significant at p< 0.05; ** - Significant at p< 0.01; *** - Significant at p< 0.001; p < 0.1 – Significant at 0.05<p<0.1; ns – Not statistically significant.

Table A2. Results of linear polynomial orthogonal contrasts for winter wheat grain yield at Perkins, OK, 2008.

Contrast	2008
Linear, N rate	**

* - Significant at p< 0.05; ** - Significant at p< 0.01; *** - Significant at p< 0.001; p < 0.1 – Significant at 0.05<p<0.1; ns – Not statistically significant.

PART II. EFFECT OF FOLIAR P FERTILIZATION ON CORN (*Zea mays L.)* GRAIN YIELD AND PHOSPHORUS USE EFFICIENCY

CHAPTER I

ABSTRACT

Application of foliar phosphorus (P) fertilizer to corn could allow for P deficiency correction if it occurs mid-season. This would supply the crop with the P supplement needed to achieve higher grain yield as well as increase phosphorus use efficiency (PUE). The experiment was established in the spring of 2006 at Lake Carl Blackwell (Port-oscar silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustolls) Oklahoma to evaluate the response to various rates and sources of foliar P fertilizer application of in corn. The experiment employed a randomized complete block design with three replications and 15 treatments. All treatments received N fertilizer at a rate of 168 kg ha^{-1} applied preplant as urea (46-0-0) and incorporated into the soil. Topdress fertilizer P was applied foliar one day prior to sprinkler irrigation: at V6 in late May, and at V10 in the beginning of June. The sources of foliar P fertilizer applied were KH_2PO_4 (potassium phosphate monobasic), DAP (diammonium phosphate), APP (ammonium polyphosphate), and TSP (triple super phosphate). Two rates (3 kg P ha^{-1} and 7 kg P ha^{-1}) were evaluated using were KH_2PO_4, DAP, APP, and TSP was applied at 22 kg P ha^{-1} and 168 kg P ha^{-1} (phosphorus-rich treatment). In general, highest corn grain yields

were achieved when 3 kg P ha^{-1} were applied at the V10 growth stage as KH_2PO_4 and DAP. Phosphorus use efficiencies were very low for both growing seasons due to lack of response to P fertilizer applied. The results of the study were inconclusive due to the lack of good quality data caused by adverse weather conditions. Further studies are necessary to determine how foliar P fertilization might benefit corn production.

CHAPTER II

INTRODUCTION

A large responsibility to answer the needs of a continuously growing population lies on the shoulders of scientists as well as crop producers today. The advances in genetics as well as improvement in agronomic practices have a potential to contribute to the growing problem of sustaining food integrity worldwide.

Genetics and plant breeding have continued to increase corn grain yields. Genetic manipulation and traditional plant breeding progress is somewhat constrained by the long time needed to produce reliable results, even though most crop producers are enthusiastic about the new crop varieties offered by plant breeders. The introduction of N P and K fertilizers produced a step increase in grain yields. However, no equivalent increase has occurred since then. One of the most common problems in agronomic fields is that crop producers are often apprehensive of the newly offered agronomic practices concerning tillage, water, or fertilizer use. The common approach to fertilizer use in many cropping systems today is to apply high inputs of fertilizers in an anticipation of higher yields which often results in application of nutrients in excess of crop's needs. While it is not possible to maximize yields relying on the mineral nutrients present in the soil alone, it is important to understand that overgenerous fertilizer application will not necessarily result in higher yields.

The excess fertilizer is being lost from the soil year after year, polluting the water sources, damaging the environment and causing a potential health risk to humans. Inefficient agricultural practices are one of the top causes of accelerated eutrophication, intense algae blooms that restrict the use of surface waters for recreation as well as production of drinking water. As reported by Edwards and Daniel (1993), most of the total annual load of P in surface water can be accounted by the increased soil P levels. The improved fertilizer use practices would allow crop producers to achieve higher grain yields, saving money and time on fertilizer application, while minimizing the negative impact on environment.

CHAPTER III

LITERATURE REVIEW

ROLE OF PHOSPHORUS IN PLANT GROWTH AND DEVELOPMENT

Phosphorus (P) is an essential nutrient that, in a balance with other mineral nutrients such as nitrogen (N) and potassium (K), is required in considerable amounts in plant tissues and is necessary for plant growth and development. The major role of P in plants is storage and transfer of energy in the form of ATP (adenosine triphosphate) and ADP (adenosine diphosphate). Phosphorus is a key structural constituent of nucleic acids, coenzymes, phospholipids, proteins and nucleotides; it also strongly affects plant photosynthetic activity (Guinn, 1984; Taiz and Zeiger, 1991). Russell (1973) reported that P is a constituent of cell nuclei and thus it is essential for cell division and development of meristematic tissue.

P deficiency can lead to decreased number of leaves (Lynch et al., 1991), leaf senescence (Berchtold et al., 1993) and reduced photosynthetic efficiency (Lauer et al., 1989). Phosphorus is a plant mobile nutrient, thus P deficiency is apparent in senescence of older leaves, as the nutrient is remobilized from older to younger leaves, which represent nutrient sinks as they form and develop (Smart, 1994). Several researchers have quantified the effect of P fertilization on pasture (Bernardo and Marino, 1993) and grain crop production on wheat (Bernardo, 1994).

A 50% reduction in lowland rice yield was noted by Saleque et al. (1998) due to P deficiency. Phosphorus deficiency especially at early stages, limits growth of cotton plants (Hearn, 1981). Many studies reported that basal P fertilization is important to obtain N response, while some authors have reported that P addition resulted in improved plant N status and plant growth (Israel, 1987; Araujo and Teixeira 2000).

Large amounts of P are required in the symbiotic system in legumes (Robson, 1983; Graham and Vance, 2000) thus a strong interaction between response to N and P exists in legumes (Sanginga et al., 2000). According to Grant et al. (2001), it is vital to supply P early in the season of crops; moderate amount of P applied at sowing can help sustain early plant growth vigor.

In many crop production systems, P can be the most deficient, and therefore, limiting nutrient after N. Because P has a very low diffusion coefficient in soil, plants can quickly exhaust P within the root zone during the active growing period and may develop P deficiency as available P is depleted (Tyree et al., 1990). The amount of available P depends on many soil characteristics such as: pH, the amount and make-up of organic matter in the soil, soil temperature, and the type of soil minerals present. The degree of interaction between precipitated P and the soil solution, the rate of dissolution and diffusion of solid phase phosphorus are other factors affecting P solubility and, therefore, plant availability.

PHOSPHORUS UPTAKE AND TRANSPORT IN PLANTS

Koontz and Biddulph (1957) showed that the amount of phosphorus translocated form a leaf is proportionate to the leaf’s age, and, thus, leaf’s position on the stem. They observed much larger amounts of phosphorus being translocated from the older leaves compared to younger leaves; the youngest leaves had not exported any phosphorus. The authors also stated that phosphorus translocation is impaired by phosphorus deficiency, as they observed that plants grown in P-deficient media translocated only about 1/5 of P amount compared to those grown in P-rich media. Phosphorus translocation is considered to be an active process since it requires energy input (Barrier and Loomis, 1957; Tuebner et al., 1957). Evaluation of phosphate forms present in stem phloem in squash (Tolbert and Wiebe, 1955) and beans (Witter and Teubner, 1959) both showed that, even though large quantities of organic phosphates are produced, phosphorus occurs in phloem mainly as inorganic phosphates (up to 90% of total P present).

PHOSPHORUS FERTILIZATION AND PUE

Excessive P fertilization is often associated with the concept of sustaining a particular sufficiency level of nutrients in soil. The sufficiency concept is viable in some instances for soil-immobile mineral nutrients such as P. According to Bray’s mobility concept (Bray, 1954), the plant response to immobile mineral nutrients, such as P, depends on the concentration of the nutrient within the Root Surface Sorption Zone, not on the total amount of nutrient in soil. The amount of P taken up by the plant is directly dependent on the root surface and the concentration of plant available P within the roots reach. This is because the larger the root surface, the larger the volume of soil it intercepts, and the higher the concentration, the larger amount of P is potentially available to be taken up by the roots. Thus, the uptake of the soil immobile nutrients is mainly due to diffusion and root interception. To increase the amount of P in the soil, adequate P fertilizer should be applied since more than 80% of the amount applied may be strongly adsorbed or precipitated in the soil (Sample et al., 1980; Sanyal and De Datta, 1991). Mosali et al. (2006) reported the highest PUE of approximately 16% in wheat was achieved when fertilizer is banded with the seed or knifed to the soil.

As corn plants develop, available P supplied by the inorganic fertilizer is being depleted, and plants begin to utilize the slowly available organic forms of P present in soil. Karlen et al. (1988) observed a peak in P uptake in corn during latter vegetative growth stages, a drop in P uptake during pollination, and a continuous linear increase during the grain fill period.

Several studies have shown that maintenance of relatively high moisture and high frequency irrigation resulted in increased P mobility and availability (Bacon and Davey, 1982; Mbagwu and Osuigwe, 1985; Bar-Yosef et al., 1989; Kargbo et al., 1991). Also researchers have demonstrated that P fertilizer only moves 3 to 4 cm from the point of application (Khasawneh et al., 1974; Eghball and Sander, 1989).

Phosphate ion (PO_4^{3-}), a form of P absorbed by plants, is present in both dissolved (soil solution) and particulate forms (Haygarth and Sharpley, 2000), and are readily absorbed by plant via diffusion. Nye and Tinker (1977) reported that the diffusion rate of phosphate ions is influenced by P concentration in the soil solution (intensity factor) and the P sorption capacity of the soil. They further stated that since the radii of water-filled pores decreases when soil water content decreases, P mobility also decreases As a result, lower soil moisture content can reduce P availability and its absorption by the plant.

FOLIAR NUTRIENT UPTAKE IN PLANTS

During the past few decades, plant physiologists have attempted to identify the possible mechanisms that foliar uptake of nutrients by plants. It has been determined that both leaf stomata (Below et al., 1984) as well as hydrophilic pores of the leaf cuticle (Barel and Black, 1979) facilitate the mineral nutrient uptake. Tyree et al. (1990) noted that even though little is understood about the mechanisms of infiltration of ions through leaf cuticles, the permeation studies identified the size of the cuticle pores to be about 0.9 nm in diameter (Schonherr, 1976) and (Schonherr and Bukovac, 1979). Since the diameter of many ions is less than 0.8 nm in hydrated state, the ion permeation through cuticle pores is very probable.

The efficiency of foliar applied fertilizer compared to soil fertilization has not been established with certainty and has been found to be dependent on the cropping system characteristics such as soil conditions and the type of crops grown (Ro¨mheld and El-Fouly, 1999) and (Below et al., 1984). Many factors should be considered when dealing with foliar fertilization. For example, as Ling and Silberbush (2002) noted that, the plant size as well as the leaf area should be adequate in order for the foliar uptake to be sufficient. However, the plant and leaf size are generally not a concern, since foliar application is usually carried out midseason, when the crop is well established.

FOLIAR PHOSPHORUS APPLICATION

Very little research has been carried out to assess the use of foliar P fertilizer in corn. Hardly any work has been done to assess the relative efficiency of soil-applied versus foliar-applied P fertilizer. Early work by Wittwer and Teubner (1959) stated that all plants are known to obtain water, gases and a wide spectrum of solutes from the environment through the foliage. Considerable amount of research has been done to identify the factors affecting foliar nutrient uptake (Fisher and Walker, 1955; Koontz and Biddulph, 1957; Swanson and Whitney, 1953). It has been noticed that foliar-applied phosphate solution generally is taken up much faster at lower pH levels (pH 2 to 3) (Wittwer and Teubner, 1959). Mono-ammonium phosphates are absorbed at much higher rate at lower pH values (Wittwer al., 1957). According to Wittwer et al. (1957) the total amount of P fertilizer taken up by the leaves is greater, because larger leaf area occurs on plants grown on the P-rich media. Thus, the authors theorize that increased levels of phosphates within the plant tissues, and in their vascular system especially, often inhibit P transport from the leaves to a higher degree than decreased P absorption of P by the leaves.

As proposed by Mosali et al. (2006), use efficiency of the foliar fertilizer should be much higher, since the many possible pathways for P loss associated with the application of nutrient to the soil are eliminated. Instead, the nutrient is directly “fed” to the plant, and the available P is readily taken up, translocated and utilized. Therefore, much smaller amounts of fertilizer would be sufficient to satisfy crop nutritional requirements and to effectively correct P deficiency mid-season. As stated by Mosali et al. (2006), for many decades the potential of foliar P application has been underestimated due to generally lower levels of P in soils. Today, however, much higher P concentrations are present in many cropping systems as a result of application of P fertilizer in excess of crops needs. According to Bundy et al. (2001), the amount of plant-available P in some soils has increased significantly over the past 25 years due to P fertilizer and manure application in excess of crops needs. The fact that solution P fertilizers were not as easily accessible to crop producers in the past, also contributed to the traditional application of P to the soil.

Application of foliar P fertilizer to corn would allow for P deficiency correction if it occurs mid-season. This would supply the crop with the P supplement needed to achieve higher grain yield as well as increase phosphorus use efficiency (PUE). The efficiency of P fertilizer could be higher if P is applied foliar compared to soil applied P fertilizer. Foliar mineral nutrient uptake is much more efficient, because the nutrients taken up mid-season are translocated to the reproductive organs improving grain formation. Application of nutrients like nitrogen (N), P, and potassium (K) as foliar sprays were found to not only increase yield of various crops but also improve their quality (Römheld and El-Fouly, 1999).

In a pot culture corn trial, Barel and Black (1979) observed that 66% of P applied to the mature leaves as a foliar spray in a form of ammonium triple-phosphate was absorbed within 10 days and 87% of the absorbed amount was translocated, showing that corn plants were successful and efficient in uptake and utilization of foliar P applied. Harder et al., (1982) observed a significant reduction in corn grain yields when foliar P was applied 2 weeks after silking. Sawyer and Barker (1999) evaluated the impact of foliar mono-potassium phosphate and urea fertilizer on corn grain yield and grain constituents. They found that foliar fertilization had no significant effect either on corn grain yield, nor grain characteristics. The achieved results can be explained by the following: grain yield levels were quite high at the evaluated sites; soils did not receive any P fertilizer preplant due to very high soil P levels. Therefore, the crop, most likely, did not experience any P deficiencies and thus did not show any response to P fertilizer.

The utilization of foliar-applied phosphorus fertilizer has been found to be dependent on nutrient availability of P in the soil for both peanuts (Halevy et al. (1987))

and cotton (Halevy and Markovitz (1988)). Benbella and Paulsen (1998) reported that foliar P application after flowering resulted in decreased grain yields due to a significant delay in senescence in winter wheat during the grain fill stage. As proposed by Benbella and Paulsen (1998), foliar P should be applied to the crop later in the growing season to effectively delay leaf senescence. According to the findings by Mosali et al. (2005), foliar P fertilization can be delayed until Feekes 10 and may result in increase in PUE by more than 10%. The authors note, however, that for the maximum efficiency, it is preferable to combine N and P fertilization using the same approach earlier in the growing season (Feekes 7). These findings suggest that timing is extremely important in foliar P application, as well as suggest that mid-season foliar application of P fertilizer has the potential to extend the grain fill stage and, thus, increase yield potential.

Many researchers have previously reported that nutrients like N, P, and K are readily taken up via plant leaves with much higher efficiency than nutrient root uptake (Fisher and Walker, 1955). Ling and Silberbush (2002) compared the efficiency of foliar fertilization to that of the soil-applied fertilizer. They evaluated the effect of application of various forms of nitrogen–phosphorus–potassium (NPK) fertilizers and concluded that foliar fertilization may be used as a supplement to compensate for the inadequate uptake of nutrients by the roots from the soil applied fertilizer. The authors also note that it is important to investigate how the nutrients would interact if more than one nutrient is applied as a foliar spray. For instance one nutrient may enhance or inhibit the absorption of another nutrient when applied together (Ling and Silberbush, 2002).

Investigating potential benefits of foliar fertilization application to cereal crops, Gooding and Davies (1992) reported that foliar applications at or 2 weeks following anthesis can be of greater benefit compared to soil applied fertilization. Multiple beneficial effects of foliar P fertilizer application in corn (Leach and Hameleers, 2001), (Pongsakul and Ratanarat, 1999) and (Thavaprakaash et al., 2006), wheat (Sherchand and Paulsen, 1985), (Batten et al., 1986), (Haloi, 1980), and barley (Qaseem et al., 1978) have been documented. Leach and Hameleers (2001), observed a significant increase in both cob index and starch content when P was applied at four-leaf growth stage. Sherchand and Paulsen (1985) and Batten et al. (1986) reported that foliar application of KH_2PO_4 resulted in higher grain yield in winter wheat coupled with the delay in leaf senescence in hot and dry growing conditions. Qaseem et al. (1978) achieved higher yields when P fertilizer was applied to barley as a foliar spray solution.

Mosali et al. (2006) found wheat grain yield to be poorly correlated with P concentration. They noted that delayed maturity is one of the main benefits of foliar P application in wheat production systems. The best results were achieved when preplant P was coupled with mid-season foliar P fertilization. Pongsakul and Ratanarat (1999) reported that foliar application of NPK fertilizers increased grain yield of both field and sweet corn. Thavaprakaash et al. (2006) found that foliar P applied 25 and 45 days after planting boosted growth parameters and resulted in significantly higher corn yields. Boote et al. (1978) stated that foliar application of minerals such as N, P, and K help to maintain proper leaf nutrition, enhances leaf N, P, and K as well as carbon balance, and promotes photosynthesis, which may lead to higher grain yields.

Haloi (1980) however, reported that higher rates of ammonium phosphate applied as a foliar spray to wheat not only resulted in reduced P deficiency but also led to higher grain yields. Mosali et al. (2005) noted that much larger increases in wheat grain yield are expected with foliar P fertilization on low P soils compared to higher P fertility soils. They achieved increases in wheat grain yield when the yield levels were generally lower, possibly - due to water stress, which impaired the P uptake via contact exchange. Therefore, one would expect the maximum response to foliar P fertilization when moisture stress is more severe.

Foliar application of urea in winter as well as NPK foliar sprays in spring are regularly used to intensify flowering and increase yields in citrus production. Albrigo (2002) evaluated the effect of foliar sprays on citrus orange trees. They observed a 9% increase in leaf N concentrations; leaf P and K. However, these increased only when the initial P and K leaf concentrations were low prior to spray application. Grain yields were not significantly different when the foliar sprays had been used for one year, compared to trees that were not sprayed.

CHAPTER IV

MATERIALS AND METHODS

An experimental site was established in the spring of 2006 at Lake Carl Blackwell (Port-oscar silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustolls) Oklahoma to evaluate the response to various rates and sources of foliar P fertilizer application of in corn. The experiment employed a randomized complete block design with three replications and 15 treatments. The size of the plots was 3 m by 6 m with 1.5 m alleys. Soil samples were collected preplant and analyzed for pH, NH_4-N, NO_3-N, and P. Corn was planted at the seeding rate of 12800 plants ha^{-1} (Pioneer 33B51 in 2006, and Delalb DK 66-23 in 2007). All treatments received N fertilizer at a rate of 168 kg ha^{-1} applied preplant as urea (46-0-0) and incorporated into the soil. Topdress fertilizer P was applied foliar one day prior to sprinkler irrigation: at V6 in late May, and at V10 in the beginning of June. The sources of foliar P fertilizer applied were KH_2PO_4 (potassium phosphate monobasic), DAP (diammonium phosphate), APP (ammonium polyphosphate), and TSP (triple super phosphate). Two rates (3 kg P ha^{-1} and 7 kg P ha^{-1}) were evaluated using were KH_2PO_4, DAP, APP, and TSP was applied at 22 kg P ha^{-1} and 168 kg P ha^{-1} (phosphorus-rich treatment). Corn was harvested using a Massey Ferguson 8XP experimental combine removing two center rows from each plot. Corn grain sub-samples were taken for further chemical analysis. Grain samples were dried in a forced-air oven at 660°C, ground to pass a 140 mesh sieve (100 μm), and analyzed for N, C, and total P. Statistical analysis will be carried out using SAS (SAS Insitute, 2001).

CHAPTER IV

OBJECTIVES

The objectives of this study were:

1. To determine whether foliar applications of P can result in increased corn grain yields and P uptake, and improve use efficiency, and

2. To determine the optimum time for foliar P application in corn.

CHAPTER V

RESULTS AND DISCUSSION

Some response to foliar P fertilizer was observed in 2008, reflected by increased corn grain yield for some treatments. For example, sidedress application of DAP at 3 kg P ha^{-1} at V10 growth stage in 2008 resulted in almost 2100 kg ha^{-1} increase in grain yield. Similarly, application of APP at V6 growth stage at a 3 kg P ha^{-1} rate resulted in over 1900 kg ha^{-1} increase in grain yield. On the other hand, grain yield values observed for treatment 1 (unfertilized check plot) were not the lowest for both cropping years. In fact, in 2006, treatments 10 (3 kg P ha^{-1} at V10 growth stage as DAP) and 11 (7 kg P ha^{-1} at V10 growth stage as DAP) yielded almost 1400 kg ha^{-1} and 1300 kg ha^{-1} less respectfully than the check plot. Similarly, treatments 8 (3 kg P ha^{-1} at V10 growth stage as KH_2PO_4), 12 (3 kg P ha^{-1} at V10 growth stage as APP), and 15 (22 kg P ha^{-1} preplant as TSP) yielded much less compared to the check plot in 2008 (Table 5). Several researchers reported on the lack of yield response to foliar P fertilizer. Harder et al. (1982) found that foliar fertilizer applied later in the growing season did not result in increased grain yield.

Multiple plant management and environmental factors are known to affect the benefit of foliar P fertilization. Denelan (1988) reported that foliar application is most successful when the plant is not under water stress. In general, nutrients should be applied when the plant is cool and turgid. Stomata are the major means of foliar applied nutrient absorption in plants (Eichert et al., 1998, Eichert and Burkhardt, 2001). Stomata opening facilitates nutrient absorption (Burkhardt, 1999). Environmental factors that cause stomata to open include warm non-stressing temperatures, high air humidity, and, most importantly, high water potential of the plant. The difference in turgor pressure between guard cells and neighboring epidermal cells regulates stomata opening. High turgor in guard cells causes stomata to open (Martin, personal communication, 2008). Dry conditions during most of 2006 growing season may have diminished the effectiveness of foliar P fertilization to corn. In general, Oklahoma soils tend to be acidic (median pH of 5.9) with up to 40 % of fields having pH values less than 5.5 (Zhang, 2001). The initial soil sample analysis showed soil pH to be 5.5 at the experimental site (Table 2). At pH of 5.5 or less, there is a potential for significant grain yield loss due to soil acidity and lower P availability (Zhang, 2001). Johnson (2002) reported that soil pH between 6.0 to 7.0 is considered to be optimum for nutrient availability and for optimizing grain yields of most crops. However, in most cases, increasing soil pH of a very acidic soil to at least 5.5 is usually adequate to restore grain yields to normal levels. It is typically recommended to apply P fertilizer if the soil test P (STP) index is less than 65. With the STP of 57, soils in Payne County, OK, are considered less than 100% sufficient in P (Zhang, 2001). On the other hand, Goedeken et al. (1998) stated that, because relatively small quantities of P are removed with harvested grain, fairly small amounts of fertilizer P are required to correct crop P deficiency even in areas with low STP.

Girma et al. (2007) observed a response to foliar P applied mid-season at a rate of 8 kg ha^{-1}, which was reflected in improved corn grain yield in some experiments. They found that PUE was relatively high only when a low P rate was applied. They concluded that application of foliar P to corn at V8 growth stage or later could increase corn grain yield and PUE.

Plant management factors such as timing of fertilizer application may affect the effectiveness of foliar P fertilizer. It is usually recommended to apply P fertilizer at the time when the crop is deficient in P, especially when evident P stress occurs during periods of active plant growth (Anonymous, 1995) such as change from a vegetative to a reproductive phase (Cantisano, 2000). No evident P deficiency symptoms such as stunted plants, dark green leaves or marginal purpling of leaves, was observed in 2006 nor 2008. However, P deficiency can restrict plant growth and delay maturation without purpling (Better Crops, 1997); mild to moderate P deficiency may be difficult to identify in the field (Dobermann and Fairhurst, 2000).

GRAIN YIELD

In general, corn grain yields were much lower in 2006 compared to the 2008 growing season (Table 4). This was most probably due to the combined effect of higher air and soil temperatures and much lower rainfall. In 2006, 380 mm of precipitation was received compared to 600 mm in 2008. Also, air temperatures and soil temperatures in 2006 were much higher compared to those in 2008 (Table 3).

2006 - GRAIN YIELD

Corn grain yields in 2006 were very low ranging from 650 kg ha^{-1} for treatment 10 (3 kg P ha^{-1} at V10 growth stage as DAP) to 3535 kg ha^{-1} for treatment 4 (3 kg P ha^{-1} at V6 growth stage as DAP) with unfertilized check plot yielding 2027 kg ha^{-1} (Table 4). Statistical analysis showed that there were no statistically significant differences between any of the treatments in 2006. Thus, time, rate or source of foliar P fertilizer had no statistically significant effect on corn grain yield in the 2006 cropping year.

Interestingly, both the lowest and the highest corn grain yield in 2006 were observed when DAP was used as a P source (Table 4). The lowest grain yields were observed for treatments 10 and 11 that received foliar fertilizer P as DAP at a rate of 3 and 7 kg P ha $^{-1}$, yielding 650 and 768 kg ha $^{-1}$ respectfully. On the other hand, the highest corn grain yield was achieved with the application of DAP at V6 growth stage at 3 kg P ha $^{-1}$ (treatment 4). Another high-yielding (grain yield of 3360 kg ha^{-1}), though not statistically significantly different, in 2006 was treatment 12, which received APP at V10 growth stage at 3 kg P ha $^{-1}$ (Table 4).

When all fertilized P was applied preplant, higher corn grain yields were achieved with a lower 22 kg P ha^{-1} (treatment 15) compared to a very high 168 kg P ha^{-1} (treatment 14) (P rich plot) in 2006.

The only relationship apparent in 2006 was a cubic relationship ($p<0.1$) between timing of fertilization and corn grain yield for treatments that received lower foliar P at 3 kg P ha $^{-1}$ (treatments 2, 4, 6, 8, and 10) (Table A1).

2008 - GRAIN YIELD

Compared to 2006, corn grain yield was much higher in 2008. Grain yield ranged from 5792 kg ha^{-1} (3 kg P ha^{-1} at V10 growth stage as KH_2PO_4) to 10471 kg ha^{-1} (3 kg P ha^{-1} at V10 growth stage as DAP) with the unfertilized check plot yielding 8377 kg ha^{-1}. Interestingly, treatment 10 yielded the highest in 2008, while its grain yield in 2006 was the lowest (Table 4).

Data analysis showed that source of foliar sidedress P applied at V10 growth stage (pooled over P rates) significantly ($p<0.05$) affected corn grain yield (Figure 1). Treatment 10 (3 kg P ha^{-1} at V10 growth stage as DAP) had the highest grain yield of 10,471 kg ha^{-1}, and treatment 8 (3 kg P ha^{-1} at V10 growth stage as KH_2PO_4) had the lowest grain yield of 5792 kg ha^{-1}. Grain yield for treatments 9, 11, 12, and 13 were not statistically different from each other or from the grain yield of the unfertilized check plot (treatment 1) (Figure 1).

Corn grain yield was significantly ($p<0.05$) affected by timing of foliar sidedress P (V6 or V10) applied at 3 kg P ha^{-1} (pooled over P sources) (Figure 2). The highest grain yields were achieved for treatments 6 (3 kg P ha^{-1} at V6 growth stage as APP) and 10 (3 kg P ha^{-1} at V10 growth stage as DAP). The lowest grain yield of 5,792 kg ha^{-1} was observed for treatment 8 (3 kg P ha^{-1} at V10 growth stage as KH_2PO_4). Corn grain yields for other treatments were comparable to each other and to grain yield of unfertilized check plot (treatment 1) (Figure 2).

Timing (V6 or V10) and (3 or 7 kg P ha^{-1}) of foliar sidedress P applied as KH_2PO_4 also significantly ($p<0.05$) affected corn grain yield (Figure 3). The highest grain yield was achieved by application of 7 kg P ha^{-1} at V6 growth stage as KH_2PO_4 (treatment 3), while treatment 8 (3 kg P ha^{-1} at V10 growth stage KH_2PO_4) had the lowest grain yield. Grain yields for other treatments in this category were comparable to each other and to grain yield of the check plot (treatment 1) (Figure 3).

Figure 4. illustrates that corn grain yield was significantly ($p<0.05$) affected by source of foliar sidedress P fertilizer (KH_2PO_4, DAP, APP) applied at 3 kg P ha^{-1} at V10 (Figure 4). At 3 kg P ha^{-1}, significantly higher grain yield was achieved with application

of DAP compared to other P sources, while the lowest grain yield was observed when KH_2PO_4 was applied at 3 kg P ha $^{-1}$. Application of APP resulted in slightly lower (not statistically significant) grain yield compared to grain yield of unfertilized check plot (treatment 1) (Figure 4).

The (3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$) of foliar sidedress P applied as KH_2PO_4 at V10 growth stage also significantly ($p<0.05$) affected corn grain yield in 2008 (Figure 5). Application of a double P (7 kg P ha $^{-1}$) (treatment 9) resulted in almost 2300 kg ha^{-1} increase in grain yield compared to application of 3 kg P ha $^{-1}$ (treatment 8). However, both treatments 8 and 9 yielded less than the unfertilized check plot (treatment 1), even though corn grain yield for Treatments 1 and 9 were statistically not different (Figure 5).

When all fertilizer P was applied prior to planting, greater grain yield of 8779 kg ha^{-1} (treatment 14) was achieved with a very high P (168 kg P ha^{-1}) compared to a grain yield of 7975 kg ha^{-1} (treatment 15) with a lower P rate of 22 kg P ha^{-1} (Table 4).

PHOSPHORUS USE EFFICIENCY

In many crop production systems, PUE rarely exceed 16% regardless of the cereal crop (Sander et al., 1990; Sander et al., 1991). When P was broadcast and incorporated, PUE values averaged 8%; when P was applied with the seed or knifed with anhydrous ammonia average PUE of 16% were achieved in winter wheat (Sander et al., 1991). However, much lower average PUE values were reported by other authors. At three locations in Oklahoma, Girma et al. (2007) found that PUE values ranged between 0.2% and 2% when various P rates (2, 4, and 8 kg P ha^{-1}) were applied to corn. Similarly, very low PUEs were observed for both 2006 and 2008 growing seasons (Table 5). This could have been explained by the fact that unfertilized check plots yielded higher than several treatments that received foliar P fertilizer (Table 4), and due to the lack of an obvious response to fertilizer P. On the other hand, Girma et al (2007) observed that as P rate increased, PUE declined noticeably at all three experimental locations. This was not the case for this experiment, since there was no evident response to P in 2006 and 2008.

2006 – PHOSPHORUS USE EFFICIENCY

In the 2006 growing season, source (KH_2PO_4, DAP, or APP) and (3 kg P ha $^{-1}$ or 7 kg P ha $^{-1}$) of sidedress P fertilizer foliar applied at V10 significantly ($p<0.05$) affected PUE (Figure 6). The highest PUE values (1%) were observed with KH_2PO_4 and APP both applied at a lower 3 kg P ha $^{-1}$ (treatments 8 and 12 respectfully). The lowest PUE was observed for treatment 13, which received 7 kg P ha $^{-1}$ as APP. Treatments 9, 10, and 11 had comparable (not statistically significantly different) PUEs ranging from 0.2% to 0.7% (Figure 6).

Phosphorus use efficiency was significantly ($p<0.05$) affected by the rate of sidedress foliar P fertilizer applied as APP at V10 growth stage in 2006. When APP was applied at a lower 3 kg P ha $^{-1}$ (treatment 12), a greater PUE value of 1 % was achieved compared to a PUE of only 0.1 for treatment 13, which received APP at a double rate of 7 kg P ha $^{-1}$ (Figure 7).

A cubic relationship between the sources of sidedress P fertilizer applied at V10 (pooled over P rate) and PUE was observed in 2006 cropping season. Also, a cubic relationship was observed between corn PUE and application time (V6 or V10) of sidedress foliar KH_2PO_4 (pooled over P rate). A linear relationship between the rate of sidedress foliar APP fertilizer applied at V10 growth stage and PUE was observed in 2006 (Table A-2).

2008 – PHOSPHORUS USE EFFICIENCY

Phosphorus use efficiency was significantly ($p<0.05$) affected by the source of sidedress foliar P fertilizer (KH_2PO_4, DAP, or APP) applied at V10 growth stage (pooled over P rate) (Figure 8). While the highest PUE of 3% was obtained with application of DAP at a lower 3 kg P ha $^{-1}$ (treatment 10), the lowest PUEs were observed with treatments 8 and 9 (KH_2PO_4 at 3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$ respectfully) and treatment 13 (APP at 7 kg P ha $^{-1}$) (Figure 8).

Source of sidedress foliar P fertilizer (KH_2PO_4, DAP, or APP) applied at a lower 3 kg P ha $^{-1}$ (pooled over application time) significantly ($p<0.05$) affected PUE in 2008 (Figure 9). Application of APP at V6 (treatment 6) and DAP at V10 (treatment 10) had the highest PUE of 3%, while treatment 8 (KH_2PO_4 applied at V10) had the lowest PUE of 0.1% (Figure 9).

Also, PUE was significantly ($p<0.05$) affected by the time of sidedress foliar APP application (pooled over P rate) (Figure 10). When APP was applied at a lower 3 kg P ha $^{-1}$, greater PUEs of 3% were achieved when fertilization was carried out at V6 growth stage, compared to treatment 12, which received APP at V10 growth stage. On the other hand, when the rate of APP was doubled to 7 kg P ha $^{-1}$, similarly low PUE values of 0.5% and 0.4% were obtained for treatments 7 (fertilization at V6) and 13 (fertilization at V10) (Figure 10).

A quadratic relationship between the source of sidedress foliar P fertilizer (KH_2PO_4, DAP, or APP) (pooled over P rate) and PUE was observed in 2008 (Table A-2). A linear relationship between time of sidedress foliar APP application (pooled over P rate) and PUE was observed in 2008 (Table A-2).

CHAPTER VI

CONCLUSIONS

In general, corn grain yields were much lower in 2006 compared to 2008 growing season probably due to hotter and dryer climate conditions. In 2006 there were no statistically significant differences between any of the treatments. A cubic relationship ($p<0.1$) between the time of foliar P application and corn grain yields was observed in 2006. Many factors significantly affected corn grain yields in 2008. At 3 kg P ha^{-1}, highest grain yields were observed with APP applied at V6 and with DAP applied at the V10 growth stage. When KH_2PO_4.was applied at V10, significantly higher corn grain yields were achieved with the higher P rate of 7 kg P ha^{-1}. When fertilizer was applied at 3 kg P ha^{-1} at V10 growth stage, the highest corn grain yields were obtained using DAP as a P source. When all P was applied preplant, significantly higher corn grain yields were observed with a higher P rate. Phosphorus use efficiencies were very low for both growing seasons. This was due to lack of response to P fertilizer application. Hot conditions during fertilizer application might have diminished the effectiveness of P fertilization and decreased P uptake though the leaves. Overall, the results of the study were inconclusive due to the lack of good quality data caused by adverse weather conditions. Further studies are necessary to determine how foliar P fertilization might benefit corn production.

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TABLES AND FIGURES

Table 1. Treatment structure evaluating P rate, source and timing for Lake Carl Blackwell, OK, 2006 and 2008.

Treatment	Fertilizer application time	Phosphorus fertilizer applied	
		P (kg P ha $^{-1}$)	P source
1	-	0	-
2	V6	3	KH_2PO_4
3	V6	7	KH_2PO_4
4	V6	3	DAP
5	V6	7	DAP
6	V6	3	APP
7	V6	7	APP
8	V10	3	KH_2PO_4
9	V10	7	KH_2PO_4
10	V10	3	DAP
11	V10	7	DAP
12	V10	3	APP
13	V10	7	APP
14	Preplant	168	TSP
15	Preplant	22	TSP

Table 2. Initial surface (0-15cm) soil chemical characteristics and classification at Lake Carl Blackwell, OK, 2005.

pH	NH_4-N	NO_3-N	P	K
5.5	mg kg $^{-1}$			
	22.6	3.8	33.6	129.0

* pH - 1:1 soil:water; P and K - Mehlich III; NH_4-N and NO_3-N - 2 M KCl.

Table 3. Field activities including planting dates, seeding rates, cultivars, preplant soil sampling dates, preplant fertilizer application dates, sidedress fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures Lake Carl Blackwell, OK, 2006 and 2008.

Field activity	2006	2008
Planting date	April 12	April 18
Cultivar	Pioneer 33B51	Pioneer 33B51
Seeding (plants ha^{-1})	76,000	76,000
Preplant soil sampling date	Fall 2005	-
Preplant fertilization date	April 12	April 18
Herbicide application date†	April 12	April 18
Sidedress N fertilization at V6§	May 24	-
Sidedress N fertilization at V10	June 19	June 20
Harvest date	August 18	August 18
Rainfall (mm) *	380	600
Average air temperatures (C°)*	25	22
Average soil temperatures (C°)*	28	26

† Herbicide – Bicep II Magnum was applied at 930 ml ha^{-1}. § In 2008, sidedress was not applied at V6 due to flooding of the experimental site. * Rainfall, average air and average soil temperatures for the period from planting through harvest.

Table 4. Treatment structure and grain yield for Lake Carl Blackwell, OK, 2006 and 2008.

Treatment	Fertilizer application time	Phosphorus fertilizer applied		Corn grain yield (kg ha^{-1})	
		P (kg P ha^{-1})	P source	2006	2008
1	-	0	-	2027	8377
2	V6	3	KH_2PO_4	2175	8366
3	V6	7	KH_2PO_4	1217	9955
4	V6	3	DAP	3535	8291
5	V6	7	DAP	3128	9363
6	V6	3	APP	1425	10280
7	V6	7	APP	2512	9092
8	V10	3	KH_2PO_4	2911	5792
9	V10	7	KH_2PO_4	2685	8072
10	V10	3	DAP	650	10471
11	V10	7	DAP	768	8687
12	V10	3	APP	3360	7925
13	V10	7	APP	2537	8515
14	Preplant	168	TSP	2196	8779
15	Preplant	22	TSP	2268	7975
SED				266	669

* SED – Standard error of the difference between two equally replicated means.

Table 5. Treatment structure and PUE for Lake Carl Blackwell, OK, 2006 and 2008.

Treatment	Fertilizer application time	Phosphorus fertilizer applied		PUE (%)	
		P (kg P ha^{-1})	P source	2006	2008
1	-	0	-	-	-
2	V6	3	KH_2PO_4	1.2	1.7
3	V6	7	KH_2PO_4	0.4	0.9
4	V6	3	DAP	1.0	0.6
5	V6	7	DAP	0.4	1.1
6	V6	3	APP	0.6	2.7
7	V6	7	APP	0.4	0.4
8	V10	3	KH_2PO_4	1.0	0.1
9	V10	7	KH_2PO_4	0.3	0.6
10	V10	3	DAP	1.0	2.9
11	V10	7	DAP	0.7	1.0
12	V10	3	APP	0.4	1.4
13	V10	7	APP	0.1	0.6
14	Preplant	168	TSP	0.1	0.1
15	Preplant	22	TSP	0.1	0.1
*SED				0.2	0.5

* SED – Standard error of the difference between two equally replicated means.

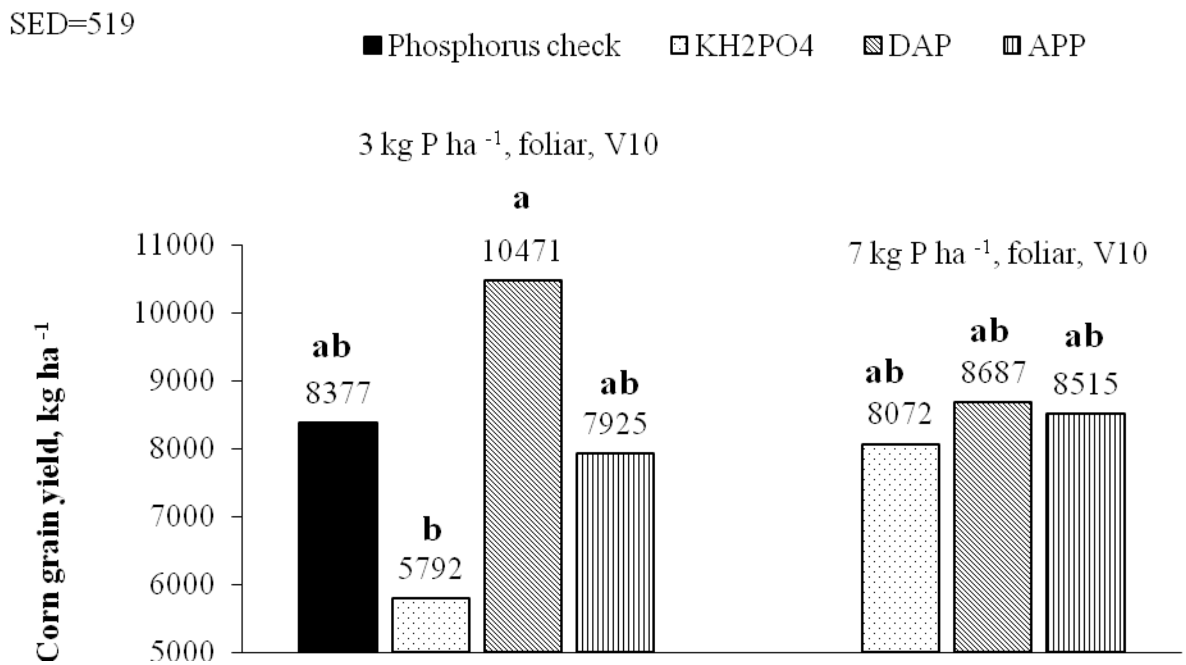

Figure 1. Corn grain yield as affected by source of foliar sidedress P fertilizer (KH_2PO_4, DAP, APP) applied at two different rates (3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$) at V10 growth stage, Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

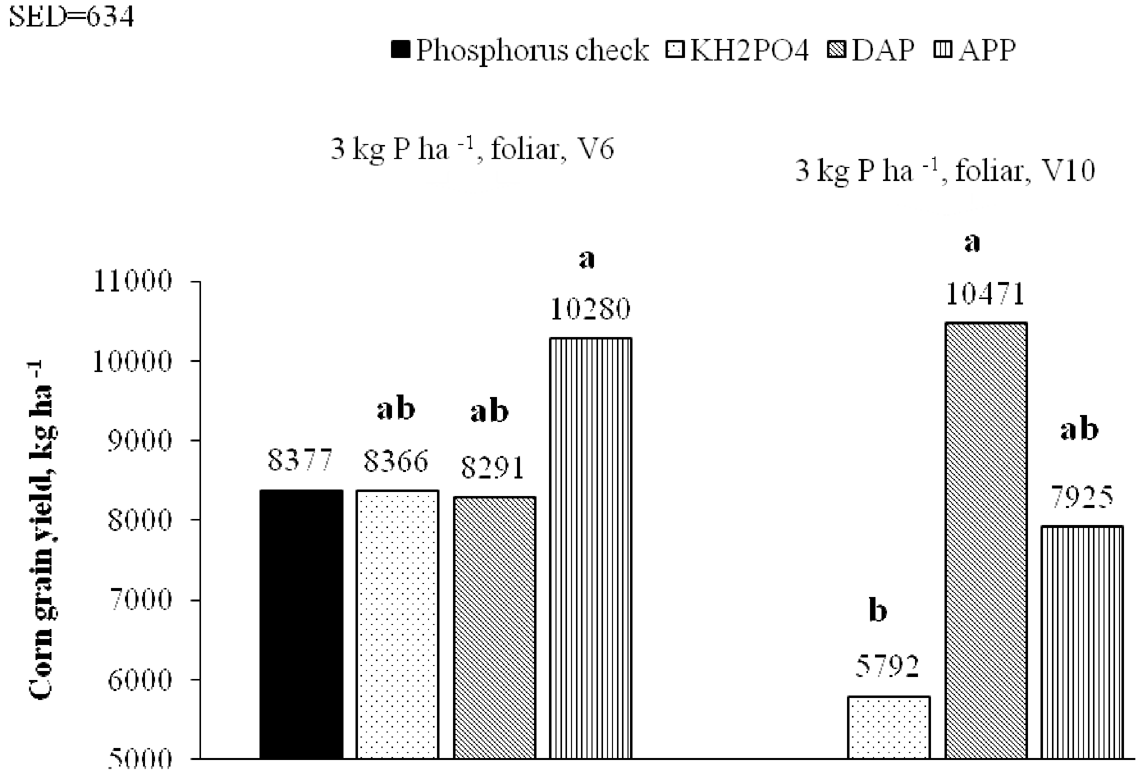

Figure 2. Corn grain yield as affected by source of foliar sidedress P fertilizer (KH_2PO_4, DAP, APP) applied at 3 kg P ha $^{-1}$ at two different growth stages (V6 and V10), Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

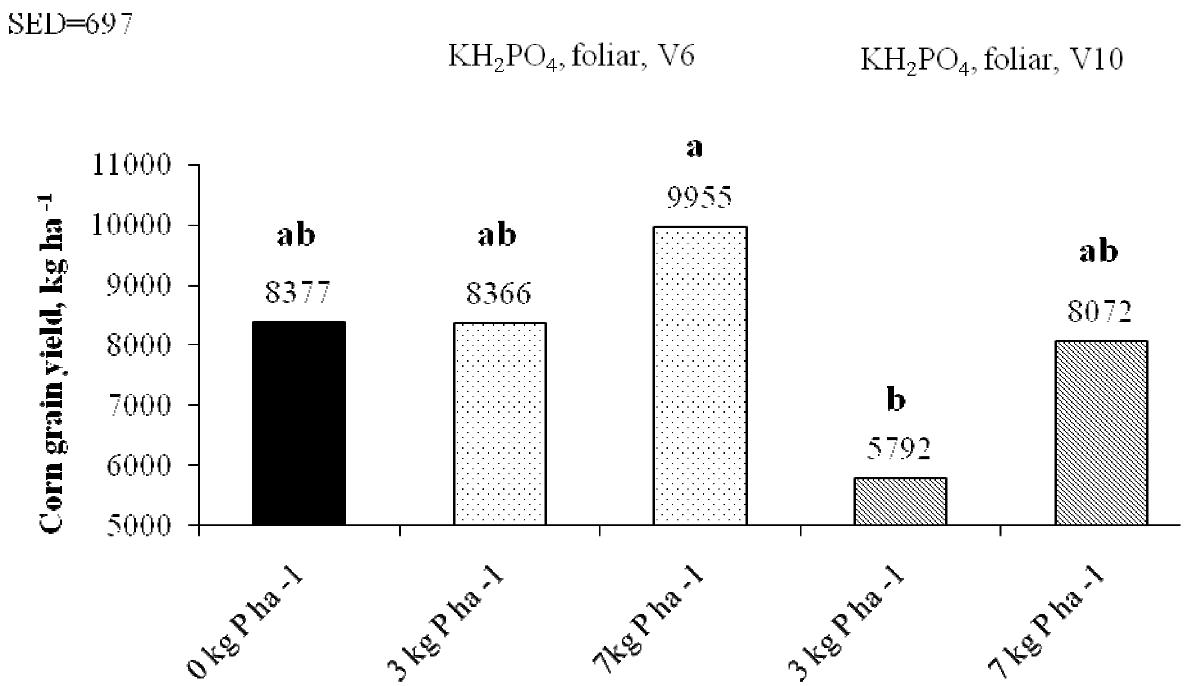

Figure 3. Corn grain yield as affected by rate (3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$) and application time (V6 and V10 growth stage) of foliar sidedress KH_2PO_4, Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

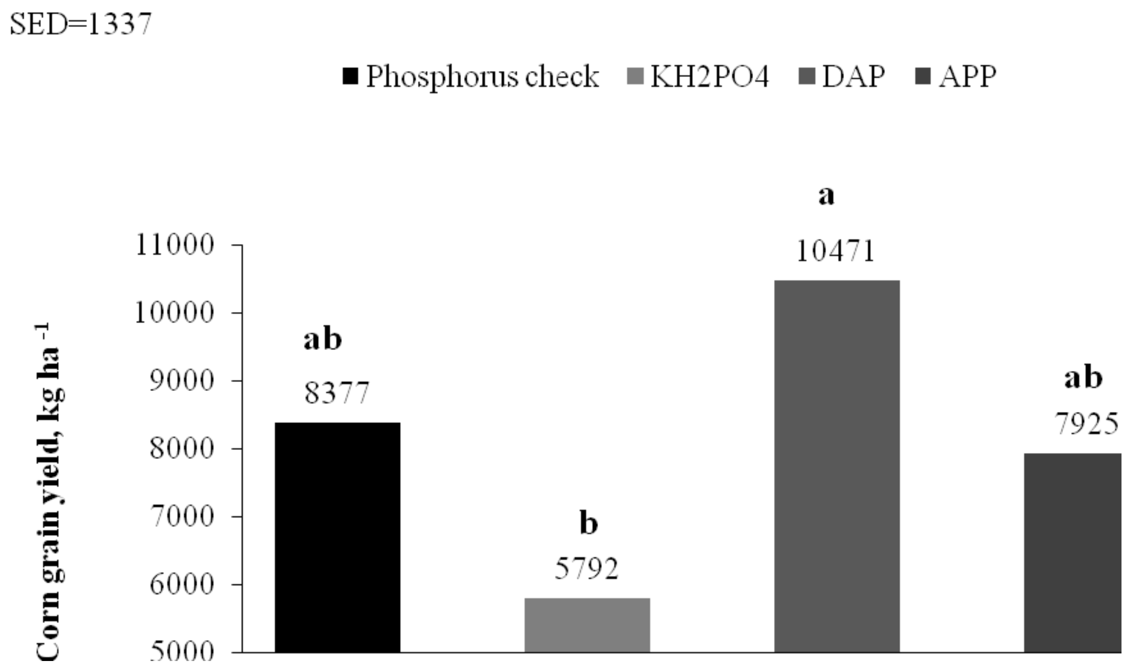

Figure 4. Corn grain yield as affected by source of foliar sidedress P fertilizer (KH_2PO_4, DAP, APP) applied at 3 kg P ha $^{-1}$ at V10, Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

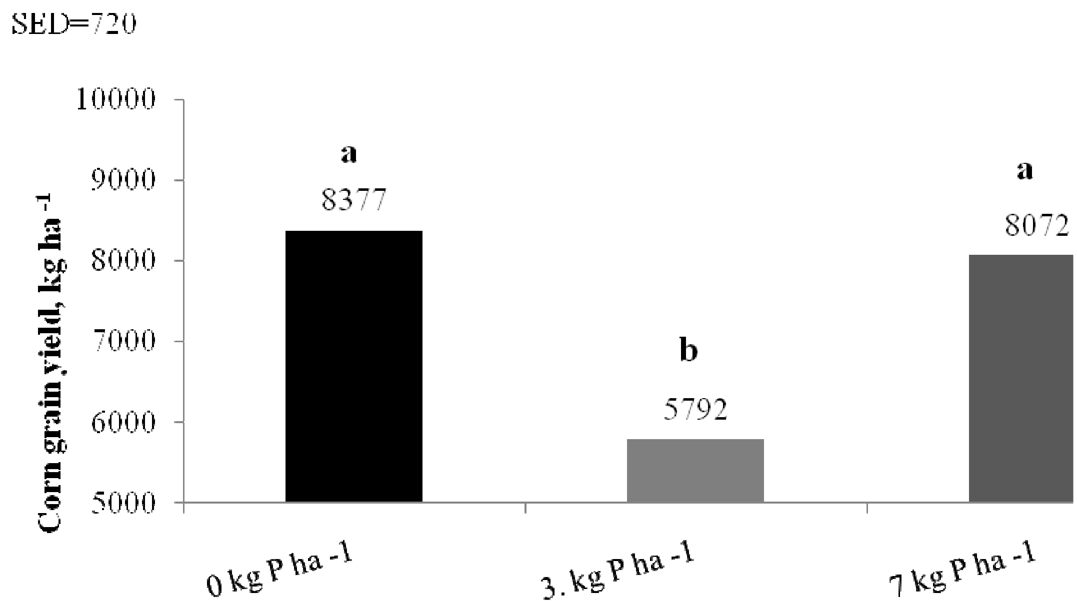

Figure 5. Corn grain yield as affected by rate (3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$) of foliar sidedress P applied as KH_2PO_4 at V10 growth stage, Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

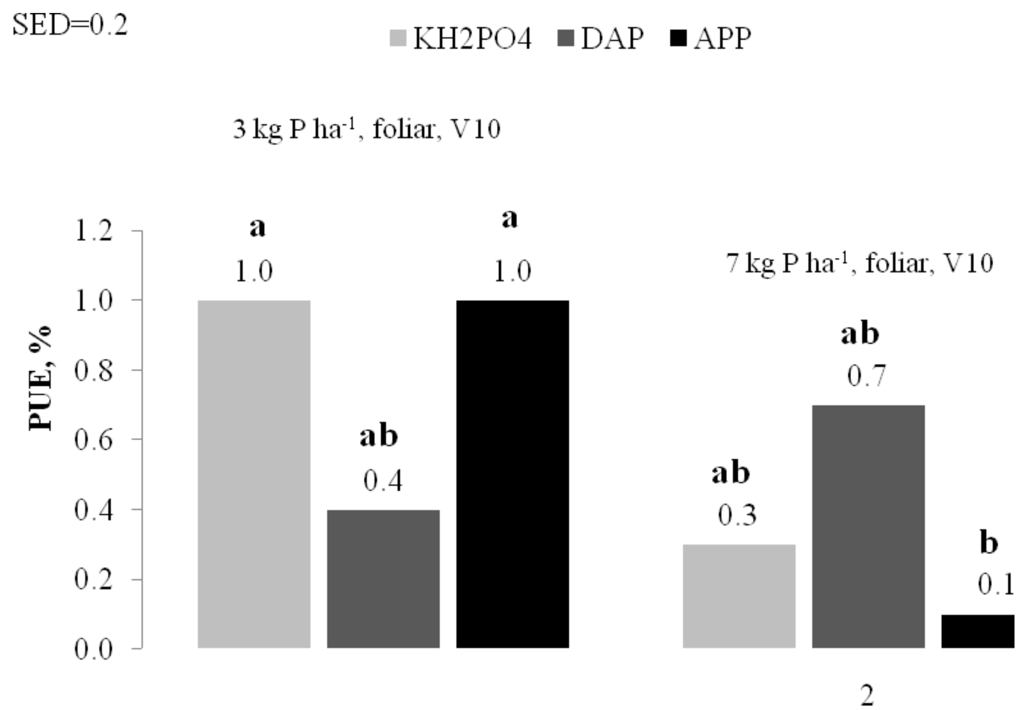

Figure 6. Phosphorus use efficiency as affected by source (KH_2PO_4, DAP, or APP) of sidedress P fertilizer foliar applied at V10 (pooled over P rates), Lake Carl Blackwell, OK, 2006. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

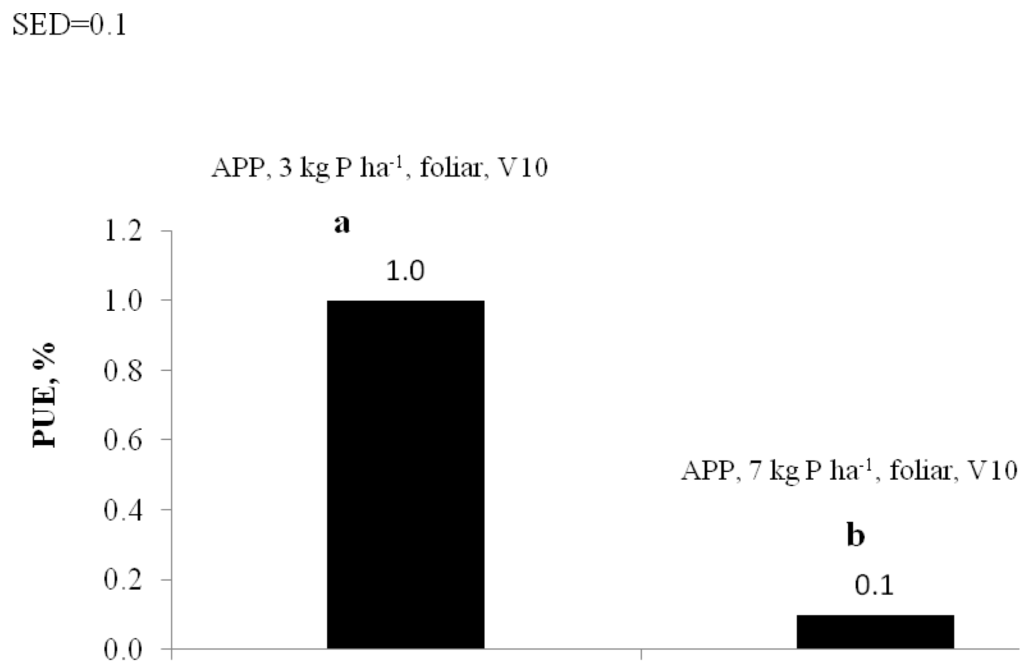

Figure 7. Phosphorus use efficiency as affected by rate (3 kg P ha $^{-1}$ and 7 kg P ha $^{-1}$) of sidedress foliar P fertilizer applied as APP at V10 growth stage, Lake Carl Blackwell, OK, 2006. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at p<0.05 using Least Significant Difference (LSD) mean separation procedure.

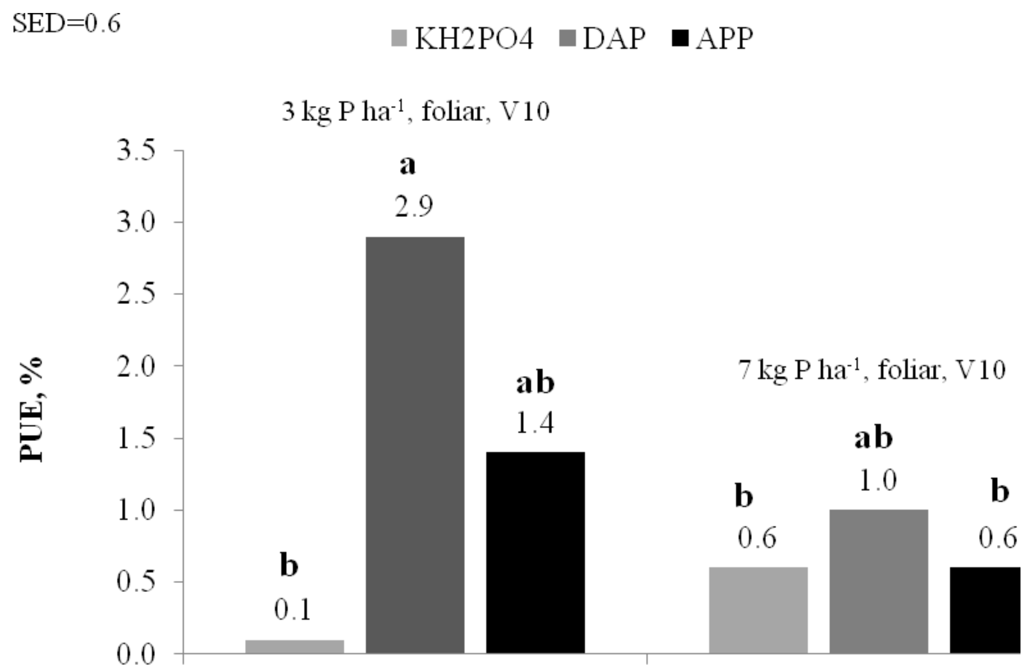

Figure 8. Phosphorus use efficiency as affected by source of sidedress foliar P fertilizer (KH_2PO_4, DAP, or APP) applied at V10 growth stage (pooled over all P rates), Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

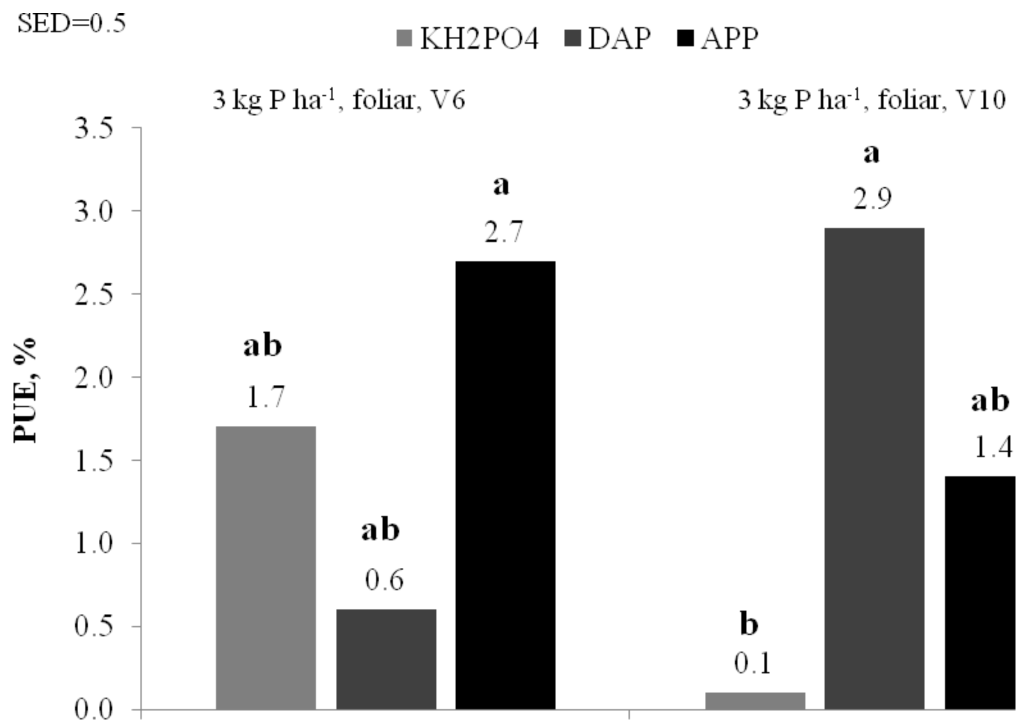

Figure 9. Phosphorus use efficiency as affected by source of sidedress foliar P fertilizer (KH_2PO_4, DAP, or APP) applied at 3 kg P ha $^{-1}$ (pooled over application time), Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

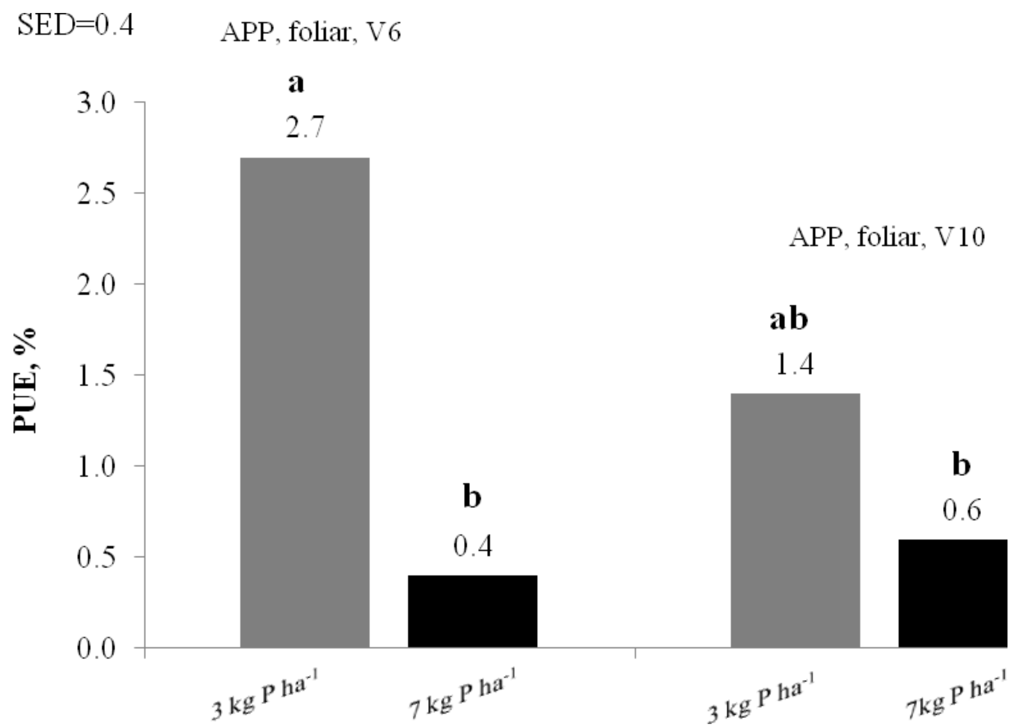

Figure 10. Phosphorus use efficiency as affected by time of sidedress foliar APP application (pooled over P rate), Lake Carl Blackwell, OK, 2008. SED – Standard error of the difference between two equally replicated means. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

APPENDICES

Table A-1. Results of linear, quadratic, and cubic polynomial orthogonal contrasts for corn grain yield at Lake Carl Blackwell, 2006 and 2008.

Treatment	2006	2008
Cubic: 3 kg P ha^{-1}, all P sources, all growth stages	$p < 0.1$	ns
Cubic: Source of P, at V6, at 3 kg P ha^{-1}	ns	*
Quadratic: Rate or P, as KH_2PO_4, at V10	ns	*

*, **, *** - Significant at the 0.05, 0.01, and 0.001 probability levels, respectfully, ns – not significant.

Table A-2. Results of linear, quadratic, and cubic polynomial orthogonal contrasts for PUE at Lake Carl Blackwell, 2006 and 2008.

Treatment	2006	2008
Cubic: Source of P, at V10, all P rates	*	ns
Cubic: Time of P, as KH_2PO_4, all P rates	$p < 0.1$	ns
Linear: Rare of P, as APP, at V10	**	ns
Quadratic: Source of P, at V10, all P rates	ns	*
Linear: Time of P, as APP, all P rates	ns	$p < 0.1$

*, **, *** - Significant at the 0.05, 0.01, and 0.001 probability levels, respectfully, ns – not significant.

APPENDIX A

IDENTIFYING SOIL MOISTURE INDICES FOR REFINED YIELD POTENTIAL PREDICTION IN WINTER WHEAT (*Triticum aestivum L.*).

ABSTRACT

Soil moisture is one of the major yield-limiting factors in most crop production systems. Soil water status is a variable factor under field conditions. The objective was to identify new indices associated with soil moisture status that could be used to refine YP prediction in winter wheat. Analysis of winter wheat grain yield data, NDVI at the Feekes 5 growth stage, and soil moisture data - volumetric water content (WC) and fractal water index (FWI) at the time of sensing was carried out for eight consecutive cropping seasons (1999 through 2006) at a long-term experiment 502 at the North Central Research Station in Lahoma, Oklahoma. Six of 24 soil moisture indices helped to improve NDVI and INSEY correlation with winter wheat grain yield. The results suggested that three indices - NDVI multiplied by WC at 5 cm depth at planting, NDVI multiplied by WC at 5 cm depth at sensing, and INSEY multiplied by WC at 5 cm depth at sensing - have the potential to increase the accuracy of YP_0 estimation in winter wheat. Results showed that soil moisture information could help to assess whether there is enough moisture in the soil to allow the crop to reach its YP_0. Combining the NDVI-based approach with the knowledge of soil water status at the time of sensing and planting, especially at 5 cm

depth, could allow to increase the accuracy of winter wheat YP prediction, which, in turn, could result in improved NUE in wheat production systems.

INTRODUCTION

Traditional N management practices have resulted in low nitrogen use efficiency (NUE) of approximately 33% in many crop production systems worldwide (Raun and Johnson, 1999). One of the main reasons for low NUE is poor synchronization between soil N supply and crop needs for N (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005). Another factor contributing to low NUE is that fertilizer N recommendations are frequently made using the yield goal approach. This method implies setting a yield goal before the crop is even planted based on the previously obtained yields (Shanahan et al, 2005).

The methodology developed by Raun et al. (2002) for winter wheat is based on the ability to estimate crop demand for N from mid-season plant growth. GreenSeeker™ handheld active light optical sensor technology allows measurement of crop canopy reflectance and to calculate Normalized Difference Vegetative Index (NDVI). Normalized Difference Vegetative Index is known to be highly correlated with plant vigor, leaf chlorophyll content and crop N status. In-Season Estimated Yield (INSEY) is calculated as NDVI (Feekes 5) divided by growing degree days (GDD)>0 (Lukina et al., 2001; Raun et al., 2001) which represents the early season growth rate or amount of biomass production per day and serves as an indicator of the rate of plant N uptake (Raun et al., 2002).

This approach provides an accurate estimate of yield potential (YP_0) by assessing crop N status and plant vigor after the crop is well established in the field. Nitrogen fertilizer recommendations are then based on estimated YP of the crop mid-season. Nitrogen use efficiency can be increased by accounting for spatial and temporal variability and by supplying the exact amount of N required by the crop at a particular growing season within a specific field.

Soil moisture is one of the major yield-limiting factors in most crop production systems. Soil water status is a variable factor under field conditions. Soil moisture information could help to assess whether there is enough moisture in the soil to allow the crop to reach its YP_0. It is probable that combining the NDVI-based approach with soil moisture variables would help to more accurately predict winter wheat YP_0 mid-season and, ultimately, increase NUE.

OBJECTIVE

The objective was to identify new indices associated with soil moisture status that could be used to refine YP prediction in winter wheat.

HYPOTHESIS

Knowledge of soil water status at the time of sensing would improve mid-season yield potential estimates in winter wheat.

MATERIALS AND METHODS

Analysis of winter wheat grain yield data, NDVI at the Feekes 5 growth stage, and soil moisture data (volumetric water content) at the time of sensing was conducted for eight consecutive cropping seasons (1999 through 2006) to identify new indices that could help to more accurately predict winter wheat YP mid-season. Winter wheat grain yield data were collected from long-term experiment 502 at the North Central Research Station in Lahoma, Oklahoma. Experiment 502 was established in 1971 to evaluate the effects of long-term N, P and K fertilization in continuous winter wheat production under conventional tillage on a Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll). Winter wheat has been continuously planted at the experimental site in 0.25 meter rows at a seeding rate of 67.2 kg ha^{-1}. Normalized Difference Vegetative Index data was obtained by sensing the crop at Feekes 5 growth stage using a GreenSeeker™ handheld optical sensor (N-tech Industries).

Automated 229-L heat dissipation sensors by Campbell Scientific are currently installed at over 100 Mesonet sites at depths of 5, 25, and 60 cm. WC (volumetric water content) are calculated from the outputs of the sensors (Gleason and Basara, 2007). This data is publically available from Oklahoma Mesonet database at http://www.mesonet.org/. Volumetric water content data from the Mesonet station #55 closest to the experimental site (1.6 km west-southwest of Lahoma, Major County, Oklahoma) were used.

Correlation of NDVI (at Feekes 5) and INSEY (calculated as NDVI at Feekes 5/growing degree days (GDD>0) with winter wheat grain yield was assessed in this paper.

Also, 24 soil moisture indices were evaluated for correlation with winter wheat grain yield including:

1. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, at planting (NDVI*WC5plant),

2. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, at planting (NDVI*WC25plant),

3. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, at planting (NDVI*WC60plant),

4. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, at sensing (NDVI*WC5sens),

5. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, at sensing (NDVI*WC25sens),

6. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, at sensing (NDVI*WC60sens),

7. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around planting (NDVI*WC5av30plant),

8. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around planting (NDVI*WC25av30plant),

9. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around planting (NDVI*WC60av30plant),

10. NDVI at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around sensing (NDVI*WC5av30sens),

11. NDVI at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around sensing (NDVI*WC25av30sens),

12. NDVI at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around sensing (NDVI*WC60av30sens),

13. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, at planting (INSEY *WC5plant),

14. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, at planting (INSEY *WC25plant),

15. INSEY at Feekes 5multiplied by WC at the 60 cm depth, at planting (INSEY *WC60plant),

16. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, at sensing (INSEY *WC5sens),

17. INSEY at Feekes 5multiplied by WC at the 25 cm depth, at sensing (INSEY *WC25sens),

18. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, at sensing (INSEY *WC60sens),

19. INSEY at Feekes 5 multiplied by WC at the 5 cm depth, average of 30 days around planting (INSEY *WC5av30plant),

20. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around planting (INSEY *WC25av30plant),
21. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around planting (INSEY *WC60av30plant),
22. INSEY at Feekes 5multiplied by WC at the 5 cm depth, average of 30 days around sensing (INSEY *WC5av30sens),
23. INSEY at Feekes 5 multiplied by WC at the 25 cm depth, average of 30 days around sensing (INSEY *WC25av30sens),
24. INSEY at Feekes 5 multiplied by WC at the 60 cm depth, average of 30 days around sensing (INSEY *WC60av30sens).

This resulted in a total of 26 indices evaluated in this paper.

RESULTS AND DISCUSSION

Figure 1. shows that NDVI alone at the Feekes 5 growth stage was correlated with winter wheat grain yield (coefficient of correlation r^2=0.44). Incorporating WC at the 5 cm depth, at sensing, the correlation with grain yield was increased compared to using NDVI alone (Figure 2.). Fifty two per cent of the variation in winter wheat grain yield was explained by NDVI*WC25sens. NDVI*WC60sens index was also slightly better correlated with grain yield compared to NDVI alone (r^2=0.46) (Figure 3).

When WC at the 5 cm depth at the time of planting was used (NDVI*WC5plant), the correlation with winter wheat grain yield was improved significantly over using NDVI alone vs grain yield (Figure 4).

As illustrated in Figure 5., INSEY explained approximately 30% of the variation in winter wheat grain yield. Incorporating WC at the 5 cm depth, at sensing, greatly improved correlation with grain yield (Figure 6). Over 60% of the variation in grain yield was explained by the INSEY*WC5sens index. Volumetric water content at the25 cm depth, at sensing, was also useful: INSEY*WC25sens was highly correlated with grain yield (R^2=0.53) (Figure 7).

Other indices did not show a potential for improving on the prediction of mid-season grain yield.

CONCLUSIONS

Analysis of long-term grain yield, NDVI, and INSEY data proved that NDVI and INSEY can be used to accurately estimate YP_0 in winter wheat. The results indicated that knowledge of soil moisture (WC and FWI) at various depths can help to estimate YP_0 mid-season. Six of 24 soil moisture indices helped to improve NDVI and INSEY correlation with winter wheat grain yield. The results suggested that three indices – NDVI*WC5plant, NDVI*WC5sens and INSEY*WC5sens - have the potential to increase the accuracy of YP_0 estimation in winter wheat. Interestingly, all the indices that helped to improve the correlation with grain yield all incorporated WC at the 5 cm depth. This indicated the importance of adequate soil moisture within the top 5 cm of the soil for winter wheat. Soil moisture in the top 5 cm is probably the most variable, because it is most affected by environmental changes. The top layers of soil are the first to become saturated during a rainfall event, and also the first to dry out during dry periods. The knowledge of soil water status at the time of sensing and planting, especially at 5 cm depth, could assist in winter wheat YP prediction, which, in turn, could result in improved NUE in wheat production systems.

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FIGURES

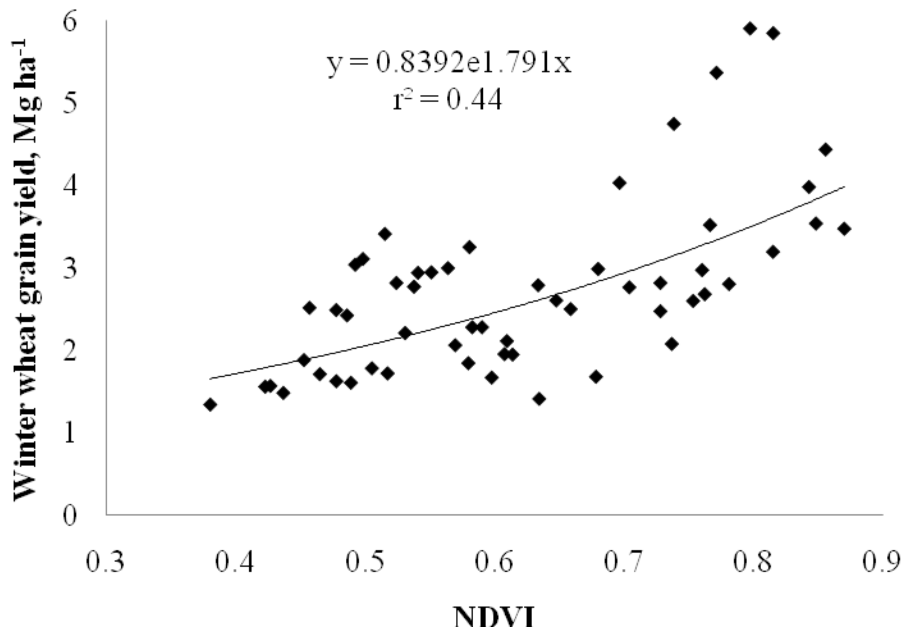

Figure 1. Relationship between NDVI at the Feekes 5 growth stage and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

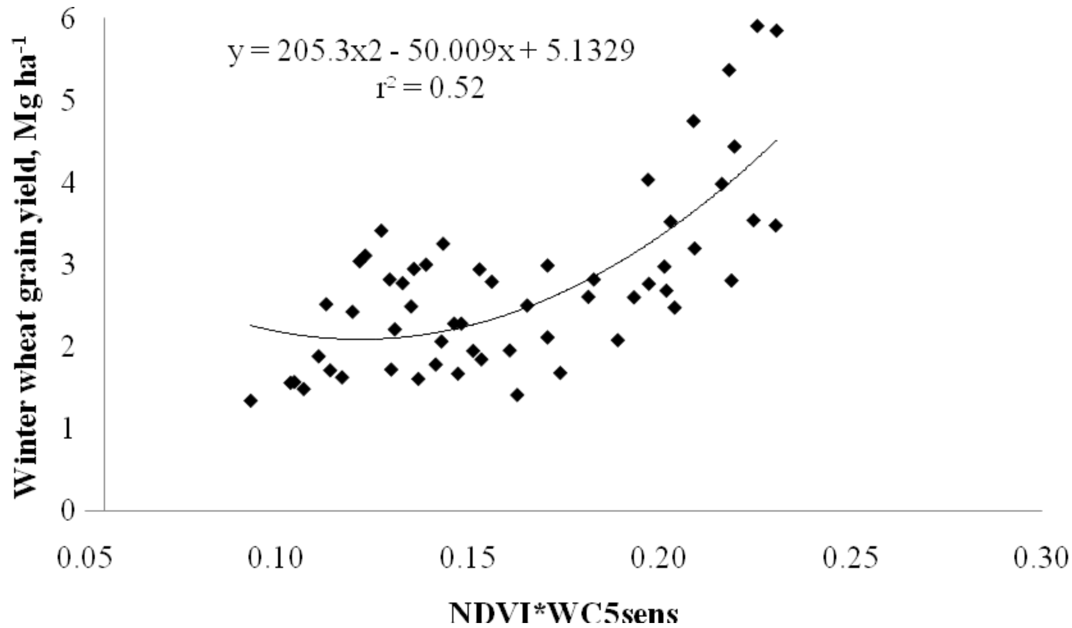

Figure 2. Relationship between NDVI at the Feekes 5 growth stage multiplied by volumetric soil water content at the 5 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

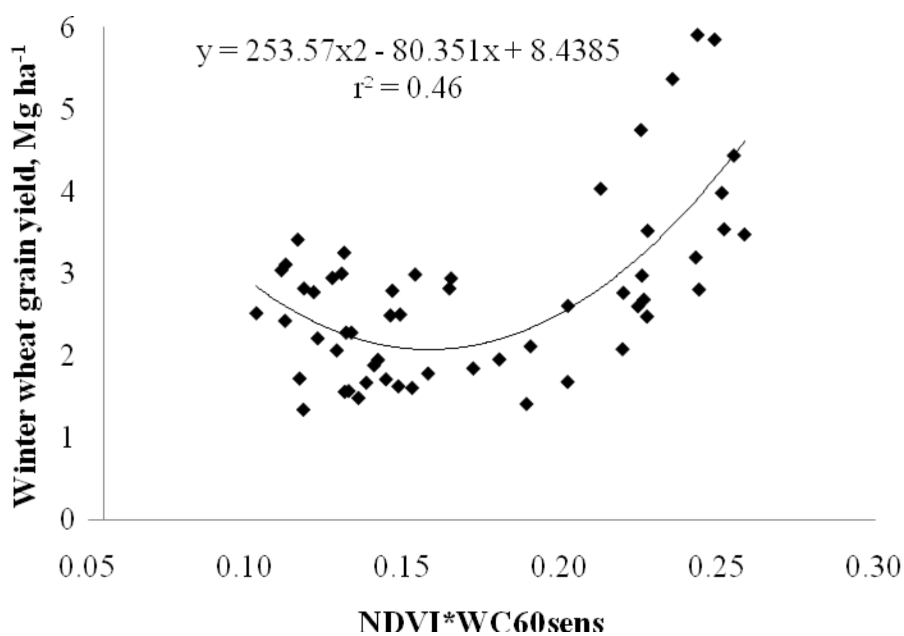

Figure 3. Relationship between NDVI at the Feekes 5 growth stage multiplied by volumetric soil water content at the 60 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

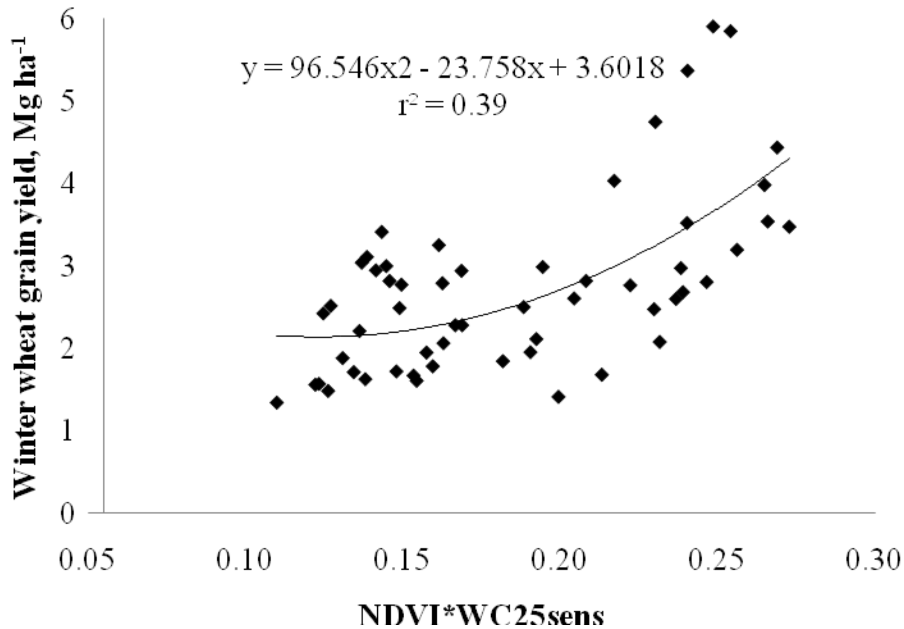

Figure 4. Relationship between NDVI at the Feekes 5 growth stage multiplied by volumetric soil water content at the 25 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

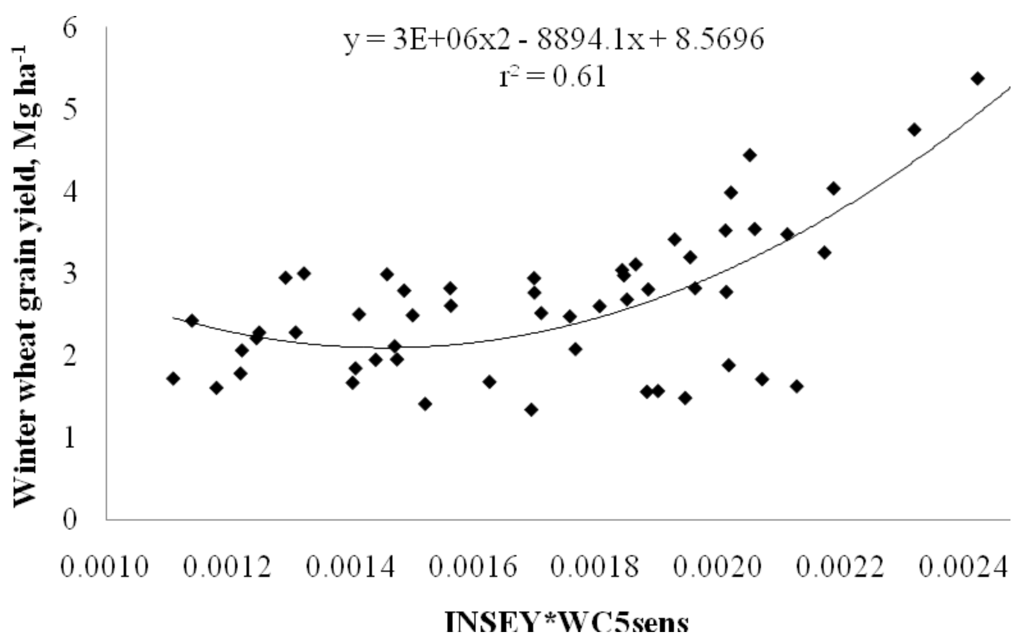

Figure 6. Relationship between INSEY at the Feekes 5 growth stage multiplied by volumetric soil water content at the 5 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

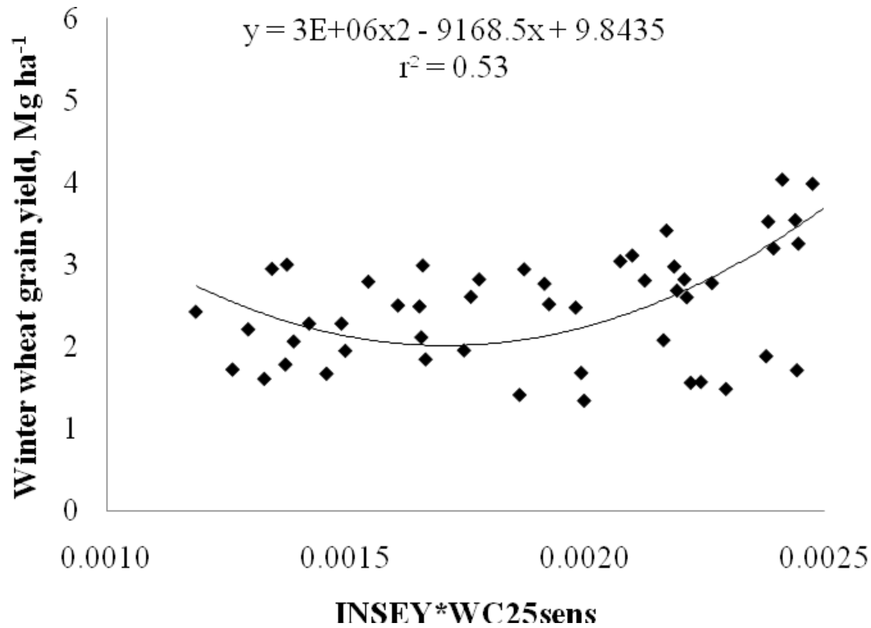

Figure 7. Relationship between INSEY at the Feekes 5 growth stage multiplied by volumetric soil water content at the 25 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

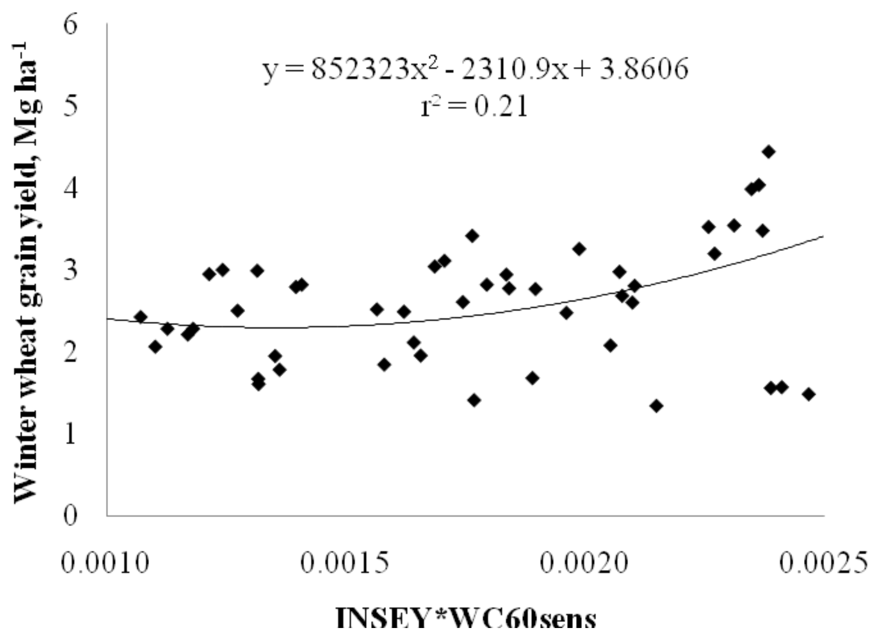

Figure 8. Relationship between INSEY at the Feekes 5 growth stage multiplied by volumetric soil water content at the 60 cm depth at the time of sensing and winter wheat grain yield, Lahoma, OK, 1999 – 2006.

APPENDIX B

DETERMINING N FERTILIZER REQUIREMENTS FOR NO-TILL WINTER WHEAT (*Triticum aestivum L.*) PRODUCTION.

ABSTRACT

No-till (NT) system offers multiple advantages including reduced labor requirements, time and fuel saving, reduced machinery wear, improved long-term productivity, improved surface water quality and reduced soil compaction and degradation, enhanced soil moisture retention and infiltration, decreased carbon gas release and reduced air pollution. Although several experiments were carried out to address the issue of adjusting fertilizer rates according to tillage practices, no widely accepted fertilizer management strategy has been developed for NT due to controversial results obtained. The objectives were to determine the preplant N application rate that will optimize winter wheat grain yields under NT system, and to determine the response of winter wheat grain yield to topdress N application at different levels of preplant N. Long-term experiment 601 was established at R.L. Westerman Irrigation Research Center (Lake Carl Blackwell) Stillwater, Oklahoma on a Pulaski fine sandy loam soil (coarse-loamy, mixed, nonacid, thermic Typic Ustifluvent) in the fall of 2002 to determine optimum N fertilization requirements in winter wheat (*Triticum aestivum L.)* under NT. The experiment employed randomized complete block design with 4 replications. A combination of 3

preplant N rates (0, 50.4, and 100.8 kg N ha^{-1}) and 4 topdress N rates (0, 33.6, 67.2, and 100.8 kg N ha^{-1}) were evaluated. Treatments with 0 kg N ha^{-1} and 50.4 kg N ha^{-1} followed by 67.2 kg N ha^{-1} topdress were repeated twice in each block, resulting in 14 treatments in total for the experiment. In 3 out of 4 cropping years, total rate of applied N fertilizer strongly affected final wheat grain yields (R^2 = 0.88, 0.84, and 0.92, respectively). In general, crop responded to fertilizer N up to 100.8 kg N ha^{-1} for treatments that received preplant N and treatments that had no preplant N applied. Independent of preplant N level, there were no statistically significant differences in mean wheat grain yield associated with method of topdress fertilizer N application (one time topdress fertilization vs split application in January/March). Based on the results of this study, it can be recommended to apply a total of approximately 100 kg N ha^{-1} to winter wheat under continuous NT. Results indicated that splitting fertilizer N between preplant and mid-season application might be beneficial compared to a one time fertilization.

INTRODUCTION

No-till (NT) is defined as “planting crops in previously unprepared soil by opening a hole, narrow slot, trench, or band of the smallest width and depth needed to obtain proper coverage of the seed” (Wall, 1998; Derpsch, 1999). Paulitz (2006) defined NT as “planting directly into residue of the previous crop without tillage that mixes or stirs soil prior to planting”. No-till is a complex agricultural management system that involves several practices such as planting, residue management, pest and weed control, harvesting, and crop rotation.

No-till was initially used as a method to prevent soil erosion. There are multiple advantages offered by NT system including reduced labor requirements, time and fuel saving, reduced machinery wear, improved long-term productivity, improved surface water quality and reduced soil compaction and degradation, enhanced soil moisture retention and infiltration, decreased carbon gas release and reduced air pollution (ISTRO, 2007). These advantages have lead to rapid expansion of NT adoption in the US (Weisz et al., 2003). Ekboir (2001) stated that maximum benefits of no-till are obtained only if the package follows the three principles mentioned earlier: that the soil is disturbed as little as possible, that the soil is covered by plants or plant residues, and that crops are rotated. Incentive programs developed in the U.S. to encourage NT adoption, keep producers informed on the latest issues, assists producers to invest in required technologies and equipment, provide guidance in the decision making process, and offer help with the economic analysis (www.lenrd.org, 2007; PA No-Till Alliance, 2007). Worldwide expansion of no-till acceptance is reflected in currently reported 57%, 56.9%, 55.2%, 20.8%, and 12.5% of total area of cultivated land under NT in Canada, Brazil, Argentina, USA, and Australia respectively (The 5th International NT-CA Conference, 2007). Adoption of NT has increased rapidly in many Australian grain-producing regions over the past decade (D'Emden and Llewellyn, 2004). A survey of Australian growers was conducted to evaluate NT adoption and determine growers' outlook on the long-term effects of NT systems. Results suggest a rapid increase in the acceptance of NT over the next five years. No-till technology has experienced almost a 60-fold increase in Latin America in the last 15 years from 670,000 ha in 1989 to 40.6 million ha in the year 2004 (Derpsch, 2007).

Due to continuous interest to NT management, it represents a subject of extended research. Most attention, however, is being paid to weed control (Brown et al., 1994; Swanton et al., 1998; Kettler et al, 2000), physical/chemical changes of soil properties (Blevins et al., 1983; Bowman and Halvorson, 1998; Hussain et al., 1999), and run-off (Glen and Angel, 1987; Lindstrom et al, 1998) in NT. Very little research has been done to assess crop's nitrogen (N) fertilizer requirements in NT production systems.

Although several experiments were carried out to address the issue of adjusting fertilizer rates according to tillage practices, no widely accepted fertilizer management strategy has been developed for NT due to controversial results obtained. Camara et al. (2003) stated: "historically, few if any technologies have increased winter wheat yield more than N fertilizer". Rasmussen (1981) and Rasmussen (1996) noted, however, that developing accurate N fertilizer recommendations is “not an exact science”. As reported by Camara et al. (2003), conflicting results of tillage trials are most likely because many researchers have made conclusions based on short-term experiments. They stated that long-term studies including various soil/climate conditions would be more valuable for interpreting data concerning benefits and disadvantages association with conservation tillage.

Rhoton (2000) conducted a long-term study to investigate how many growing seasons are required to improve soil properties with NT system. He concluded that NT can improve numerous fertility and erodobility-related soil characteristics within four years. This illustrates the extreme importance of evaluating data from long-term experiments in order to make recommendations and develop guidelines for NT operating production systems.

Improving N fertilizer recommendations and reducing tillage are important strategies for crop production and soil and water conservation. A combination of both practices may affect soil water, nutrient availability, N uptake, water use efficiency and grain yield (Angas et al., 2006). Optimum N fertilizer application rate, timing, and placement for developing improved fertilizer N recommendations are vital for maintaining profitable NT crop production with minimum environmental impact (Timmons and Baker, 1992).

OBJECTIVES

The objectives were:

1. To determine the preplant N application rate that will optimize winter wheat grain yields under NT system, and

2. To determine the response of winter wheat grain yield to topdress N application at different levels of preplant N.

MATERIALS AND METHODS

Long-term experiment 601 was established at R.L. Westerman Irrigation Research Center (Lake Carl Blackwell) Stillwater, Oklahoma on a Pulaski fine sandy loam soil (coarse-loamy, mixed, nonacid, thermic Typic Ustifluvent) in the fall of 2002 to determine optimum N fertilization requirements in winter wheat (*Triticum aestivum L.)* under NT. The experiment employed randomized complete block design with 4 replications. Treatment structure is summarized in Table 1. Plot size was 0.4 m by 0.8 m with 0.5 m alleys. A combination of 3 preplant N rates (0, 50.4, and 100.8 kg N ha^{-1}) and 4 topdress N rates (0, 33.6, 67.2, and 100.8 kg N ha^{-1}) were evaluated. Treatments with 0 kg N ha^{-1} and 50.4 kg N ha^{-1} followed by 67.2 kg N ha^{-1} topdress were repeated twice in each block, resulting in 14 treatments in total for the experiment. Preplant fertilizer N was applied as ammonium nitrate - NH_4NO_3 (34-0-0) and topdress N was applied as urea ammonium nitrate - UAN (28-0-0). Topdress N for treatments 13 and 14 were split applied in January/March. Field activities including planting dates, seeding rates, cultivars, preplant N fertilizer application dates, topdress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Lake Carl Blackwell, OK, 2003-2006 are reported in Table 2.

LITERATURE REVIEW

SOIL – A LIVING SYSTEM

Dokuchaev considered soil as an independent natural and historical body (Krasilnikov, 1958) and emphasized the importance of soils in environmental protection practices and management of natural resources (Gradusov, 2004). According to Dokuchaev, soil is an outer horizon of parental matter that is being continuously changed by complex effects of water, air and a variety of living and dead organisms. Recognition of the biospheric model of nature management proposed by Dokuchaev offered a solution to challenges associated with environmentally sustainable agriculture (Krasilnikov, 1958). Schonbeck (2006) discussed that, in a sustainable cropping system, the soil living fraction represents “the engine of soil fertility and crop production”; it also serves as “the guardian of long term soil health”. He talked about various ways of preserving soil’s health and fertility including: cover cropping, mulching and composting, returning crop residues to the soil, crop rotation, fertilization, and reducing intensity and frequency of tillage.

Soil conservation tillage practices, especially on slopping land, are critical for sustaining and maintaining soil life and organic matter levels sufficient to maximize crop yields. Converting from conventional tillage (CT) to NT resulted in net accumulation of over 1120 kg of soil organic matter (SOM) per hectare per year in some southern US soils (Schonbeck, 2006). Agricultural croplands containing 1% or less SOM are considered biologically dead, primary due to tillage pressure. Most soils in Oklahoma contain less than 1% SOM (Zhang and Stiegler, 1998). Soil managed under NT relies on soil organisms (bacteria, fungi, algae, protozoa, nematodes and larger organisms) to incorporate crop residue accumulated on the surface and to add it to the SOM complex, which is done by tillage in CT practice (Sullivan, 1999). Zhang and Stiegler (1998) listed reducing or eliminating tillage among the most effective practices to maintain or increase SOM levels.

NO-TILL BENEFITS

Smith et al. (1991) reported that intensive tillage resulted in annual sediment discharge of 15.9 Mg ha^{-1} in the southern Great Plains. McGregor et al. (1992) observed increasing soil losses over time under CT and decreasing soil loses in NT soils. Gaynor and Findlay (1995) investigated soil erosion with different tillage practices. The results indicated that with NT the average soil loss was reduced by almost 50% compared to CT.

In intensive row cropping systems, reduced tillage is often recommended to decrease soil erosion, compaction and degradation Burgess et al. (1996); Gaynor and Findlay (1995). Burgess et al. (1996) examined the effect of different tillage practices on corn (*Zea mays* L.) grain yields in a 3-year study in Canada. They concluded that NT might provide economically feasible alternatives to CT in silage production. They suggested that, due to residue buildup, special attention should be paid to the planting techniques to minimize the risk of grain yield loss in continuous corn production.

In a long-term tillage experiment in a continuous corn production system Blevins et al. (1983) observed higher SOM content, higher soil moisture content, significantly lower evaporation, better soil water movement, no problems with soil compaction, and no deterioration of soil physical properties under NT compared to CT.

Halvorson et al. (2006) stated that NT irrigated corn production has the potential to minimize soil degradation due to erosion, reduce fossil fuel use, and greenhouse gas emissions.

Effects of various tillage systems on SOM were evaluated in Central Illinois by Wander et al. (1998). No-till resulted in a 25% increase in organic C content at the soil surface; at lower depth (5-17.5 cm); however, organic C content was reduced by 4%. Tillage effects were site-specific and varied among soil types. Decreased crop residues, accelerated decomposition of SOM and loss of the SOM-rich topsoil due to water and wind erosion are among the most commonly discussed results of intensive and excessive tillage practices (Arshad et al., 1990). They examined changes in the quality of SOM in a long-term continuous barley (*Hordeum vulgare* L.) trial. The results showed that soil in NT plots had higher organic C and total N content compared to soil in CT plots. They observed that NT practice resulted in quantitative and qualitative improvements in SOM. Dick (1983) reported a decrease of 12-25% in organic C under CT compared to NT, noting that the intensity of degradation depends on soil type.

The availability of N fertilizer to crops under NT versus CT may be affected by position of applied N, N immobilization and N loss from soil. Nalhi and Nyborg (1991) evaluated the effect of tillage, time and method (placement) of application on the recovery of ^{15}N-labelled urea in barley plants and in soil. They observed the lowest N recovery in barley plants when urea was broadcast on the soil surface with no surface broadcasting with NT and with CT when urea was incorporated into the soil.

Substantially higher N recovery was achieved by banding urea. Spring application of urea resulted in markedly greater plant N recovery compared to fall application.

Rapid adoption of NT coupled with direct seeding technologies in Canada resulted in higher winter wheat (*Triticum aestivum* L.) grain yields, increased profitability and reduced the financial risk for the crop producers. In addition, adoption of NT has contributed to the sustainability of the soil resources in Canada (Brown et al., 1996). Aase and Pikul (1995) evaluated crop and soil response to various management practices (including annual cropping vs fallow-crop rotation, and CT vs NT) in spring wheat cropping systems in the northern Great Plains. Results suggested that NT annual spring wheat production to be the most efficient from the standpoint of grain yield, water use efficiency, and soil organic C.

Pasricha et al. (1989) investigated the possible benefits of NT practices in wheat in rotation with rice (*Ozyra sativa*, L.) in Bangladesh, finding energy savings, conservation of soil organic C, and lower fertilizer N and irrigation water inputs. Compared to CT, the amount of nutrients returned to the soil with NT system was increased by 40% for organic C and 45% for N, phosphorus (P), and potassium (K). Results indicated that NT resulted in a net saving of 32.64 L of diesel fuel per hectare, and increased water use efficiency by 16%. Lower total N uptake in wheat was recorded in NT (144.6 kg N ha^{-1}) compared to CT plots (184.37 kg N ha^{-1}). Fertilizer N use efficiency, however, was 8% greater with NT (45% for NT vs 36% for CT plots). Pasricha et al. (1989) concluded that NT is a more efficient practice, due to savings in fuel, irrigation water, and nutrients, and recommended NT as a sound agronomic strategy for soil quality improvement and sustainable crop production.

Plant-available water and soil degradation are major limiting factors in agricultural production. Thus, to maintain sustainable crop production, resource management practices such as reduced tillage and effective crop residue management, including NT systems, coupled with optimum N management, must be developed (Aase and Schaefer, 1996; Halvorson, 1990; Halvorson, 1999; Halvorson et al. 2006). Reetz (1992) noted that surface residue in NT systems holds soil in place, reduces evaporation by reflecting the sunlight, and increases water infiltration. Therefore, soil is cooler and wetter for most of the growing season, which increases crop response to starter fertilizer.

NO-TILL DISADVANTAGES

Several challenges associated with NT practices including lower crop yield (Cosper, 1983), poor weed control (Bolton, 1983) and inadequate planting equipment (Logan et al., 1987) are generally discussed in the literature. Poor wheat emergence and slow seedling development were reported to occur in NT systems due to additional crop residue left on the surface without tillage (Weisz et al., 2003). Several studies showed that less plant-available N is present in NT soil during early vegetative plant growth, affecting formation of tillers in wheat (Jacobsen and Westermann, 1988; Carefoot, et al., 1990; Halvorson et al., 1999; Halvorson et al. 2006).

TIMING OF FERTILIZATION IN NO-TILL

Fowler and Brydon (1989) evaluated timing of fertilizer N on wheat grain yields in NT system in Canada. They reported that application time of N fertilizer significantly affected wheat grain yields. Fertilization in the fall caused reduced grain yield, lower grain protein level, due to loss of soil profile N. On the other hand, delaying N application until late spring also limited both grain yields and grain protein concentrations, particularly, under wetter field conditions (Fowler and Brydon, 1989). Melaj et al (2003) proposed that wheat grain yield, N accumulation, and remobilization may be modified by adjusting fertilizer application timing and changing tillage practice. They conducted two field experiments for evaluation of tillage and fertilizer N application timing effects on winter wheat growth and grain yields. They achieved higher yields with application of urea at tillering. Delayed N fertilization resulted in higher N in wheat plants derived from fertilizer, especially in the NT treatments.

Weisz et al (2003) evaluated the potential benefits of N fertilization early in vegetative growth (at Zadok's Growth Stage 25). They suggested that N management guidelines for NT production need to be re-evaluated due to probable effects of surface residue on crop growth and development and N transformations within the plant-soil system.

N RATE IN NO-TILL

Camara et al. (2003) commented on disagreements concerning recommended N fertilizer application rates found in the literature. Some researchers state that NT production N fertilizer needs are lower that those of CT. Mrabet et al. (1995) evaluated results of an eleven-year study conducted in Morocco for the purpose of comparing NT with CT systems across five crop rotations. They found that NT helped to retain soil organic matter (SOM), increased plant-available N, extractable P and exchangeable K concentrations within the root zone. They proposed that larger amounts of soil nutrients are available to wheat in NT due to acidification of the seed zone and decomposition of SOM. Mrabet et al. (1995) hypothesized that, because of the greater efficiency of nutrient cycling, lesser amounts of fertilizer inputs should be needed in NT systems compared to

CT. In a tillage-fertilizer N management study in Spain, high fertilizer N rates resulted to 30% - 80% loss of fertilizer-derived N (Angas et al., 2006). They found that NT system's nutrient requirements are lower compared to CT.

Other researchers suggested the demand for higher N rates for NT systems compared to CT. Kolberg et al (1996) stated that N fertilizer management systems for wheat that have been developed under CT might not be applicable in a NT system. They conducted an experiment in Colorado to compare four N rates and four N fertilizer source/placement/timing treatments in various crops including winter wheat, corn and grain sorghum (*Sorghum bicolor* L. Moench). Results showed that N fertilizer recommendations were not sufficient to support maximum grain production under NT management. Some researchers found that application of higher N fertilizer rates can help to overcome problems associated with reduced tillering, often a grain yield-limiting factor associated with NT (Rasmussen et al., 1997).

Malhi et al. (1989) proposed that balance between fertilizer application rate, fertilizer use efficiency, soil conditions and moisture level, seedbed quality, equipment availability and cost, time and labor all should be taken into consideration when developing optimum fertilization guidelines for NT systems. They pointed out that fertilizer management strategies depend on the key limiting factors present within a crop production system. Staggenborg et al. (2004) discussed that wheat yield response to N fertilizer is highly influenced by the previous crop within a rotation.

Wells et al. (1997) evaluated N rates (0, 67, 135, 200, and 270 kg N ha^{-1}), N sources, and time of N fertilizer application in a long-term continuous NT corn study at Robinson Experiment Station in Kentucky. Detailed analysis showed that 120 kg of fertilizer N ha^{-1} plus 45 kg N ha^{-1} from mineralization in the soil was sufficient to achieve near maximum corn grain yields. They concluded that this optimum N rate is comparable with a fertilizer N rate recommendation of 140 to 170 kg N ha^{-1} for continuous NT corn grown on well-drained soils currently proposed at the University of Kentucky.

Minor et al. (2007) summarized fertilizer application guidelines suggested by the University of Missouri for NT corn and grain sorghum. Research in the Corn Belt showed that corn response to banded starter fertilizer during early vegetative growth is greater in NT systems than in CT. They noted that vigorous growth of corn early in the season helps to avoid pest problems and reduce grain moisture at harvest; however, it did not necessarily result in higher corn grain yields. Minor et al. (2007) recommended applying a starter fertilizer (containing both N and P) approximately 5 cm to the side of the seed and at least 5 cm below the seeding depth. They suggested that N requirements for NT corn systems should be similar to those under CT for well-drained soils. They mentioned that for imperfectly drained soils N fertilizer recommendations should differ for NT corn, however, they did not provide any specific fertilization guidelines. On the other hand, they suggested increasing fertilizer N rates by 10 – 15% for NT corn following soybeans. To avoid potential N loss, Minor et al. (2007) proposed injection of N (as anhydrous ammonia, ammonium nitrate, or UAN) into the soil.

The Manitoba-North Dakota Zero Tillage Farmers Association (1997) noted that nutrient cycling processes within a cropping system could be affected by tillage practices. Mineralization in NT soils is more uniformly spread over the growing season, unlike in regularly tilled soils, where mineralization increases greatly once soil has been tilled and then decreases quickly shortly after. Thus, to ensure best establishment of NT crops planted in the pring they should be adequately fertilized early in the season. Nitrification may occur in NT soils even under dry conditions due to higher soil moisture levels. Conversely, exceedingly wet conditions may result in very low oxygen levels in NT soils, therefore, inhibiting the nitrification process. The Manitoba-North Dakota Zero Tillage Farmers Association (1997) hypothesized that distribution of soil-mobile nutrients such as N may also be affected by tillage practices used. The extent of tillage effects on nutrient distribution is, however, difficult to access due to interaction of multiple factors including pore size, soil moisture, and the rate of SOM oxidation.

Halvorson et al. (2006) evaluated the effect of N fertilizer rate and tillage (CT vs NT) on irrigated continuous corn grain yields in a 5 year study with the objective of determining the feasibility of the NT system and N requirements for optimum yield. Average corn grain yields achieved under CT were 16% higher than in NT. They found that N required for production of 1 Mg corn grain was 19 and 20 kg N Mg^{-1} grain for the CT and NT systems, respectively. They hypothesized that lower corn grain yields under NT were due to lower soil temperatures observed in NT systems resulting in the slow early spring plant development compared to a CT system. Halvorson et al. (2006) concluded that NT continuous corn may be viewed as a viable alternative to CT system in the central Great Plains area, but with the slightly lower corn grain yield potential. They found that the corn crop responded to addition of N fertilizer similarly under NT and CT systems. They suggested that, due to lower yield potential and slightly higher N requirements, N rates should be adjusted if yield goal based N fertilizer recommendations (developed for CT systems) are used in the NT. Johnson (1991) and Dahnke et al. (1988) discussed the yield goal approach traditionally used for determining N application rates.

The yield goal based method entails relying on a recent 5-year crop yield average typically increased by 10 to 30% as an “insurance” of providing adequate N amounts for above-average growing conditions. Yield goal was defined by Dahnke et al. (1988) as the "yield per acre you hope to grow". Dahnke et al. (1988) pointed out that not accounting for great fluctuations of growing conditions year to year and field to field and setting unrealistic yield goals often results in failing to access the crops’ need for N. This failure to accurately estimate N requirements in some years may lead to supplying N in amounts not adequate for optimum yields, and often resulting in excessive N application.

RESULTS AND DISCUSSION

In the first cropping year, 2003, grain yields ranged from 2.5 Mg ha^{-1} for Treatment 1 (unfertilized check) plot to 4.1 Mg ha^{-1} for Treatment 8 that received a total of 151 kg N ha^{-1} (50 kg N ha^{-1} prior to planting followed by 101 kg N ha^{-1} topdress). Similar range of grain yields was observed in 2004: 2.5 Mg ha^{-1} for the check and 4.3 Mg ha^{-1} for Treatment 12 (202 kg N ha^{-1} total N rate applied, equally split between preplant and topdress) (Table 3). Overall, normal temperatures for Oklahoma prevailed during the 2002-2003 growing season (Oklahoma Climatological Survey, 2003). Drier than normal conditions were observed in the area of the experimental site; thus the experiment had to be irrigated as needed to support plant growth.

Unstable and variable weather conditions persisted during the 2003-2004 growing season. Higher than normal spring and summer temperatures, extremely wet May and exceptionally dry June, the environmental conditions influenced yield potential. However, a mild, wetter than usual winter allowed for successful germination and plant development (Oklahoma Climatological Survey, 2004).

Grain yields in 2005 were the lowest for the experiment ranging from 1.9 Mg ha^{-1} to 2.7 Mg ha^{-1}. Average grain yields of 2.3 Mg ha^{-1} were observed in 2005, compared to 3.6 Mg ha^{-1}, 3.8 kg N ha^{-1}, and 3.5 Mg ha^{-1} in 2003, 2004, and 2006 cropping years respectively (Table 3). Several factors could have affected yield potential of the crop resulting in a decrease of 1.3 Mg ha^{-1} compared to 3.6 Mg ha^{-1} average obtained for the other three cropping years.

September – early October is considered the best planting time for winter wheat in Oklahoma (Daniel Edmonds, personal communication, July 2008). In 2004, wheat was planted on October 20. Oklahoma experienced very wet conditions during the month of November with reported precipitation values 90.2 mm above normal (weather.gov). On December 14, 2004, the crop was replanted due to poor stands caused by the heavy rain (45 mm of rainfall in short time period on November 1). Total rainfall of 128 mm and 163 mm for October and November respectively was recorded for the experimental site area. The first freeze was registered for most parts of Oklahoma on November 25 (weather.gov). On November 25, 2004, at the experimental site the minimum air temperature of -3C° has been reported (mesonet.org). Considering overall wet and cold conditions during October – December, planting of wheat on December 14 probably did not allow the crop to adjust to the winter environment. Seeding at optimum time allows seedlings to germinate, grow two to three leaves and develop a crown, which is vital for winter survival. Later planting may cause poor stand, weak undeveloped plants, may cause delayed heading, later maturity, increased weed problems and lower grain yield potential. Recent research in Canada showed that winter wheat grain yields were decreased by 30% when planting date was delayed for just 2 weeks (from the second week of September to the first week of October) (McKenzie, R.H., 2007).

In 2006, the greatest difference between the minimum (1.9 Mg ha^{-1} for the check) and the maximum (4.4 Mg ha^{-1} for Treatment 10, received 134 kg N ha^{-1} N total, with 101 kg N ha^{-1} preplant followed by 34 kg N ha^{-1} topdress) wheat grain yields were observed (Table 3). Most of the state of Oklahoma experienced drought conditions throughout the 2006 growing season. According to Oklahoma Mesonet and Oklahoma Climatological Survey, most regions, the 2006 drought was among the modern climate record's 5 most severe events (Oklahoma Climatological Survey, 2006a). The intensity of the drought was complicated by the extreme summer heat wave (Oklahoma Climatological Survey, 2006b). While hot temperatures certainly have affected wheat yield potential to some extent, the experimental site was irrigated as needed, which buffered the negative influence of extreme weather conditions.

In 2003, 2004, and 2006 cropping years, total rate of applied N fertilizer strongly affected final wheat grain yields (R^2 = 0.88, 0.84, and 0.92 respectively (Figures 1, 2, and 3). No apparent trend between total N rate applied and grain yields was observed in 2005 (Table 3).

Analyzing the effect of fertilizer N rate on winter wheat grain yields for all growing seasons together, the following has been shown. When all N was applied prior to planting, with no addition of N mid-season (treatments 2, 3, and 4) (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1} preplant N respectively), clear crop response was apparent up to 100.8 kg N ha^{-1} showing overall demand for fertilizer N (Figure 4). Similarly, with no preplant N (treatments 2, 3, 4) and various topdress N fertilizer rates (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1} respectively), the response to N was evident up to 100.8 kg N ha^{-1} confirming strong mid-season demand for N (Figure 5).

Noticeable response to fertilizer N was observed up to 33.6 kg N ha^{-1} topdress, for the treatments that received 50.4 kg N ha^{-1} preplant (treatments 5, 6, 7and 8) (Figure 6). However, when preplant N rate was doubled to 100.8 kg N ha^{-1} (treatments 9, 10, 11, and12) there was no significant increase in grain yield associated with the addition of topdress N fertilizer at any rate (Figure 7).

In 2003 and 2004, statistically significant ($p<0.05$) increases in grain yields of 1.2 Mg ha^{-1}, 0.8 Mg ha^{-1} were achieved by increasing the preplant N rate from 50.4 to 100.8 kg N ha^{-1} (Figures 8, 9). There were no significant differences between grain yield mean values associated with preplant N in 2005 (Figure 10). A considerable, though not statistically significant, increase in grain yield of 0.6 Mg ha^{-1} was observed in 2006 due to increase in preplant N rate (Figure 11).

In 2003 and 2006 growing seasons, 0.8 Mg ha^{-1} and 0.7 Mg ha^{-1} increase in grain yield was obtained by increasing topdress fertilizer N rate from 67.2 to 100.8 kg N ha^{-1} (Figures 12 and 15).

In 2004, the overall demand for N was lower compared to 2003 and 2006, since significantly greater ($p<0.05$) grain yield was obtained with an increase in topdress N rate from 33.6 kg N ha^{-1} to 67.2 kg N ha^{-1}. However, statistically similar grain yields were observed by further increasing the topdress N rate to 100.8 kg N ha^{-1} (Figure 13).

Again, there were no significant differences between winter wheat grain yield mean values associated with topdress N rate in 2005 (Figure 14).

Independent of preplant N level, there were no statistically significant differences in mean wheat grain yield associated with method of topdress fertilizer N application (one time topdress fertilization vs split application in January/March). Thus, for all cropping years, mean grain yields were the same for Treatment 3 (no preplant, 67 kg N ha^{-1} one-time topdress) and Treatment 14 (no preplant, 67 kg N ha^{-1} split-applied topdress) (Table 3). Likewise, similar yields were observed for Treatment 7 (50 kg N ha^{-1}

preplant, 67 kg N ha^{-1} one-time topdress) and Treatment 13 (50 kg N ha^{-1} preplant, 67 kg N ha^{-1} split-applied topdress) (Table 3).

Overall, crop response to fertilizer N was observed in all cropping years, except 2005. Results of linear, quadratic, and cubic polynomial orthogonal contrasts for mean wheat grain yield showed that in 2003, 2004, and 2006, grain yields increased linearly as the rate of applied N fertilizer increased (Table A-1).

CONCLUSIONS

In 3 out of 4 cropping years, total rate of applied N fertilizer strongly affected final wheat grain yields (R^2 = 0.88, 0.84, and 0.92, respectively). In general, crop responded to fertilizer N up to 100.8 kg N ha^{-1} for treatments that received preplant N and treatments that had no preplant N applied. Independent of preplant N level, there were no statistically significant differences in mean wheat grain yield associated with method of topdress fertilizer N application (one time topdress fertilization vs split application in January/March). Based on the results of this study, it can be recommended to apply a total of approximately 100 kg N ha^{-1} to winter wheat under continuous NT. Results indicated that splitting fertilizer N between preplant and mid-season application might be beneficial compared to one time fertilization.

TABLES

Table 1. Treatment structure for experiment at Lake Carl Blackwell, OK, 2003 - 2006.

Treatment	*Preplant N fertilizer application	† Topdress N fertilizer application	Total fertilizer N rate applied
		kg N ha $^{-1}$	
1	0	0	0
2	0	34	34
3	0	67	67
4	0	101	101
5	50	0	50
6	50	34	84
7	50	67	118
8	50	101	151
9	101	0	101
10	101	34	134
11	101	67	168
12	101	101	202
13	50	††67	118
14	0	††67	67

* Preplant N was applied as ammonium nitrate (34-0-0).
† Topdress N was applied as urea ammonium nitrate (28-0-0).
†† Topdress for Treatments 13 and 14 split-applied in January and March.

Table 2. Field activities including planting dates, seeding rates, cultivars, preplant N fertilizer application dates, topdress N fertilizer application dates, herbicide application dates and harvest dates for Lake Carl Blackwell, OK, 2003-2006.

Field activity	Cropping year 2003	Cropping year 2004
Planting date	October 1, 2002	September 10, 2003
Cultivar	Custer	Jagalene
Seeding rate (kg ha^{-1})	112	112
Preplant N fertilization date†	September 2002	September 10, 2003
Herbicide application date⁎	January 14, 2003	January 14, 2004
Topdress N fertilization treatments 13 and 14 (I)	January 21, 2003	January 20, 2004
Topdress N fertilization treatments 13 and 14 (II)	March 5, 2003	March 8, 2004
Topdress N fertilization treatments 2 - 12	February 21, 2003	February 26, 2004
Harvest date	June 19, 2003	June 6, 2004
Field activity	**Cropping year 2005**	**Cropping year 2006**
Planting date	October 20, 2004¥	October 21, 2005
Cultivar	Jagalene	Jagalene
Seeding rate (kg ha^{-1})	112	112
Preplant N fertilization date†	September 21, 2004	October 18, 2005
Herbicide application date⁎	January 15, 2005	January 12, 2006
Topdress N fertilization treatments 13 and 14 (I)	January 24, 2005	January 25, 2006
Topdress N fertilization treatments 13 and 14 (II)	March 12, 2005	March 6, 2006
Topdress N fertilization treatments 2 - 12	February 22, 2005	April 10, 2006
Harvest date	June 23, 2005	June 16, 2006

† Preplant N fertilizer was applied as ammonium nitrate (34-0-0);

‡ Topdress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0).

⁎ Herbicide – Losban applied at 1.17 l ha^{-1}. * Rainfall, average air and average soil temperatures for the period from planting through harvest.

¥ Planting on October 20, 2004 resulted in a bad stand; the experiment was replanted on December 14, 2004.

Table 3.Treatment, preplant N, topdress N, total N rate, winter wheat mean grain yields and SED's for Lake Carl Blackwell 2003 – 2006.

Treatment	Preplant N	Topdress N	Total N	Mean grain yield Mg ha $^{-1}$			
	N rate, kg N ha $^{-1}$			2003	2004	2005	2006
1	0	0	0	2.5	2.5	2.4	1.9
2	0	34	34	2.9	3.1	2.4	2.6
3	0	67	67	3.0	3.6	2.1	3.0
4	0	101	101	3.8	3.9	1.9	3.7
5	50	0	50	2.7	2.5	1.9	2.9
6	50	34	84	3.5	3.9	2.5	3.8
7	50	67	118	4.1	3.9	2.7	4.1
8	50	101	151	4.1	4.1	2.4	4.1
9	101	0	101	3.9	3.3	1.9	3.5
10	101	34	134	4.0	3.9	2.6	4.4
11	101	67	168	3.9	4.1	2.2	4.1
12	101	101	202	4.0	4.3	2.1	4.0
13	50	67	118	3.9	3.8	2.5	4.2
14	0	67	67	3.3	3.1	2.3	3.2
SED				0.3	0.3	0.3	0.2

* SED – Standard error of the difference between two equally replicated means.

FIGURES

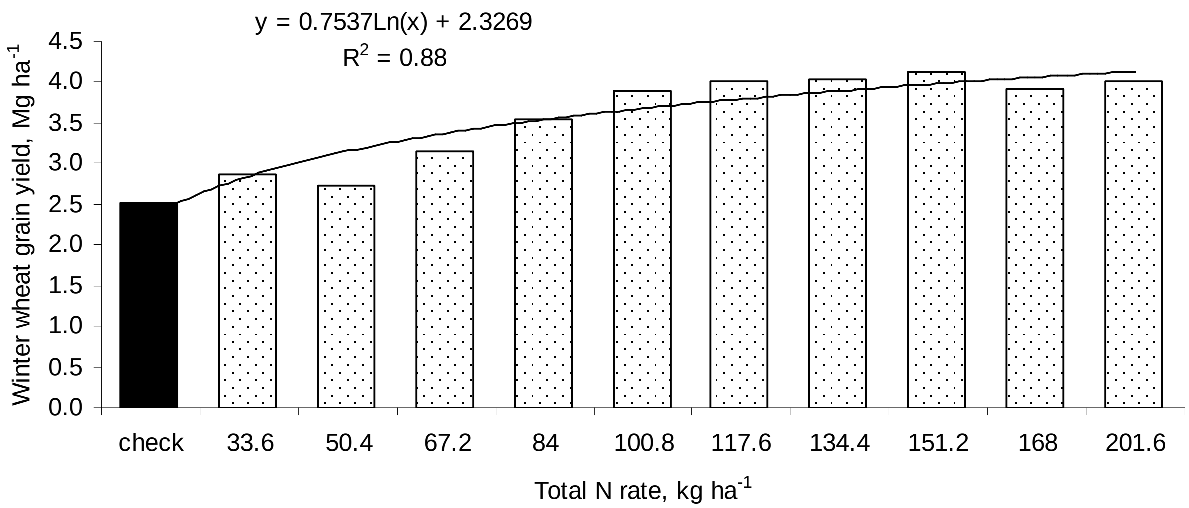

Figure 1. Winter wheat grain yield as affected by total N rate of fertilizer at Lake Carl Blackwell, OK, 2003.

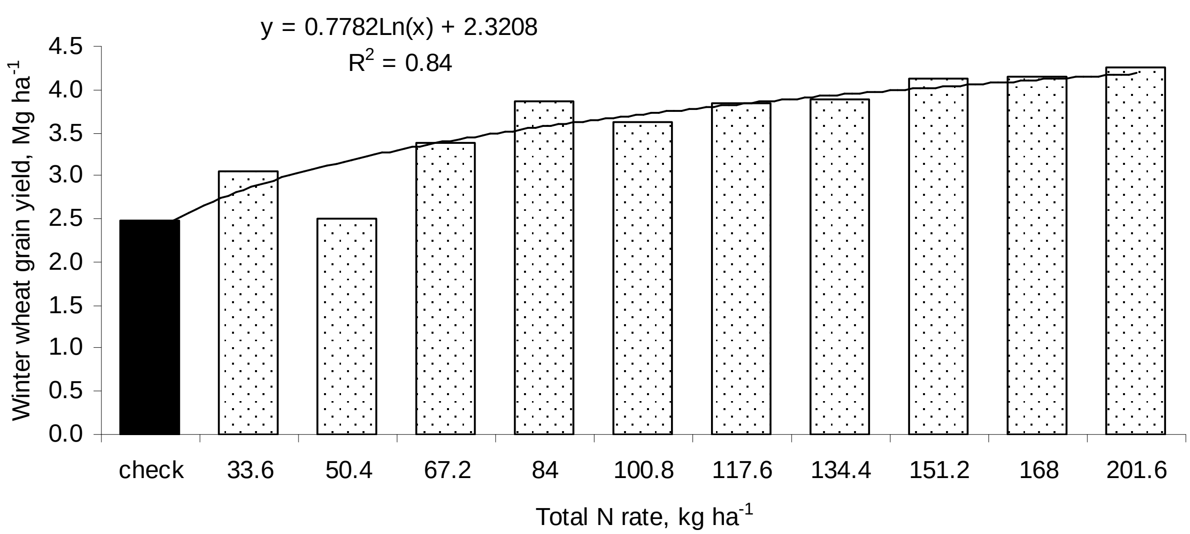

Figure 2. Winter wheat grain yield as affected by total N rate of fertilizer at Lake Carl Blackwell, OK, 2004.

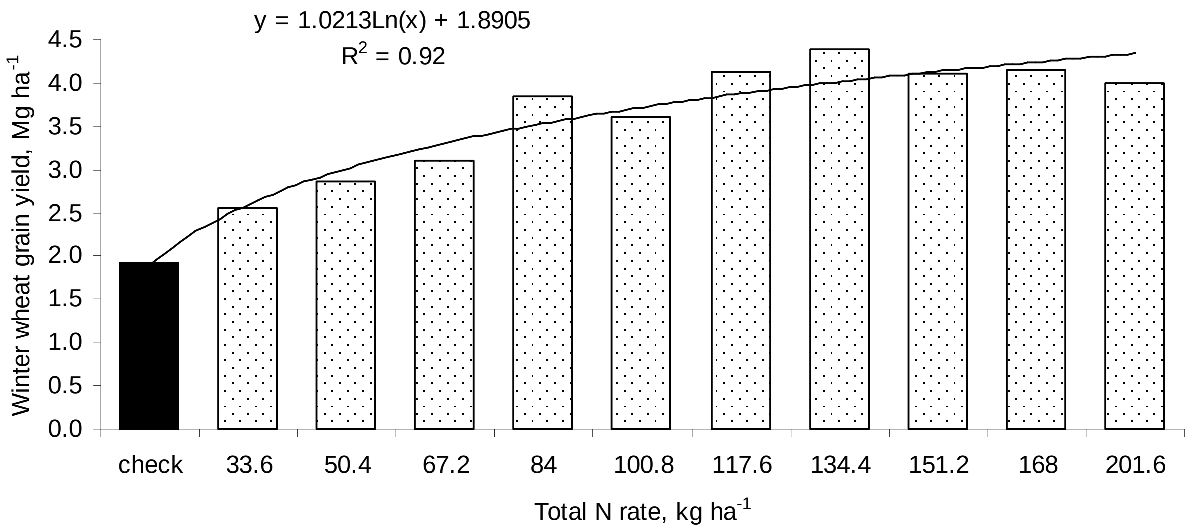

Figure 3. Winter wheat grain yield as affected by total N rate of fertilizer at Lake Carl Blackwell, OK, 2006.

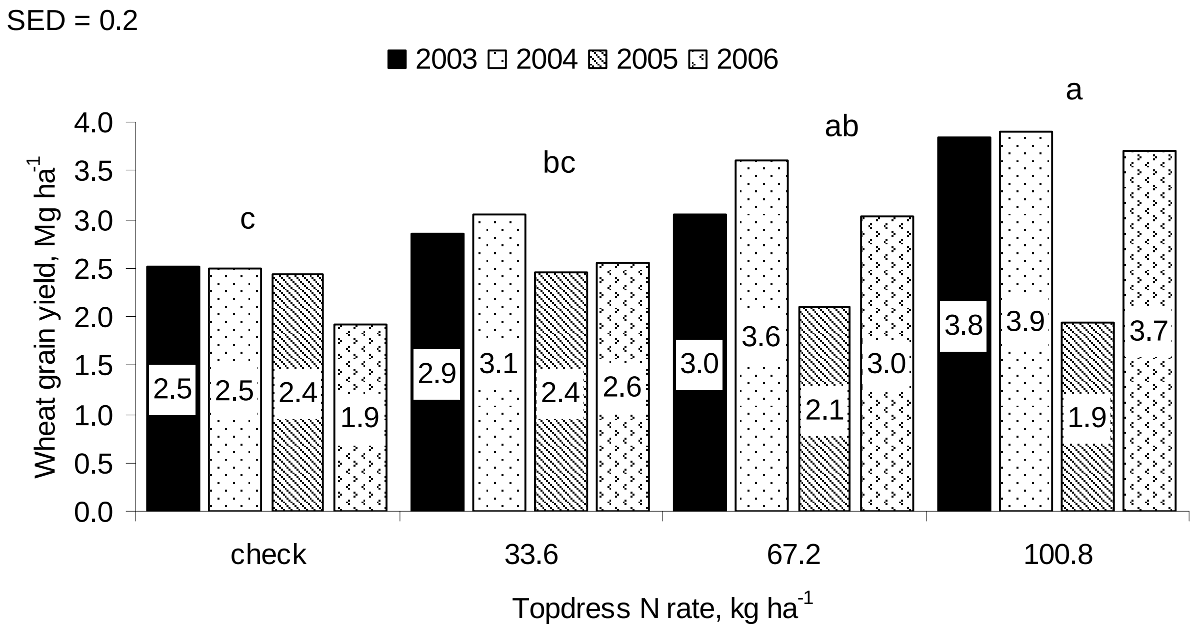

Figure 4. Winter wheat grain yield of check plot (treatment 1) and treatments with no preplant (treatments 1, 2, 3, 4) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003, 2004, 2005, and 2006. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

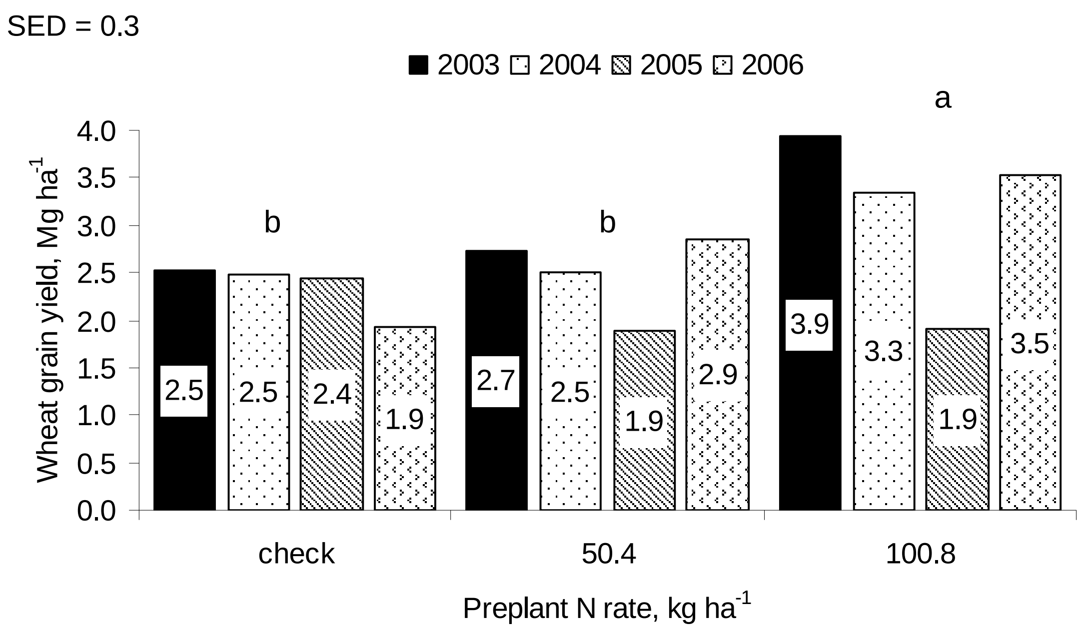

Figure 5. Winter wheat grain yield for check plot (treatment 1) and treatments with no topdress (treatments 1, 5, 9) as affected by preplant N fertilizer rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003, 2004, 2005, and 2006. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

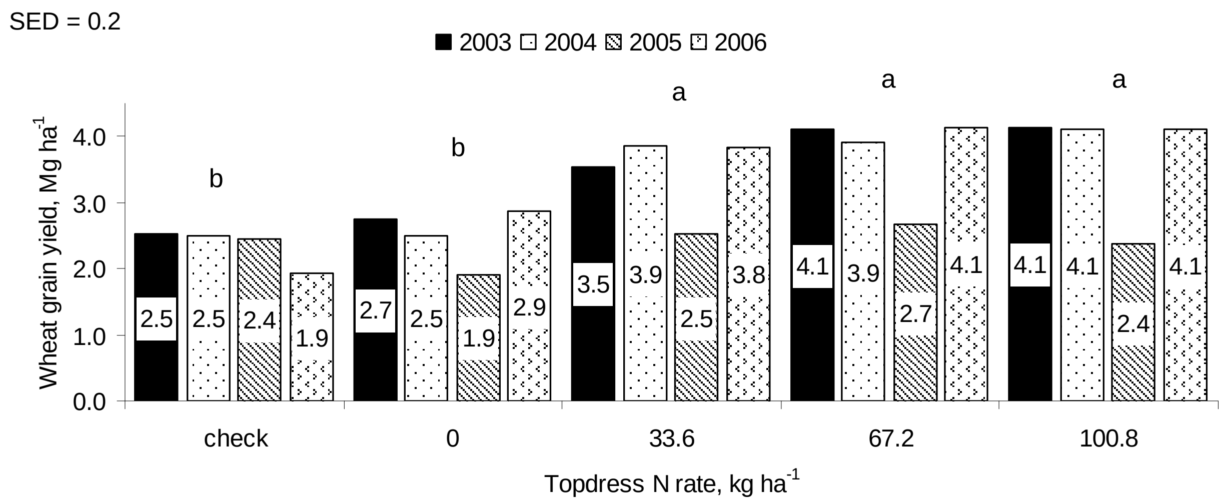

Figure 6. Winter wheat grain yield of check plot (treatment 1) and treatments with 50.4 kg N ha^{-1} preplant (treatments 5, 6, 7, 8) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003, 2004, 2005, and 2006. Bars followed by the same letter are not significantly different at p<0.05 using Least Significant Difference (LSD) mean separation procedure.

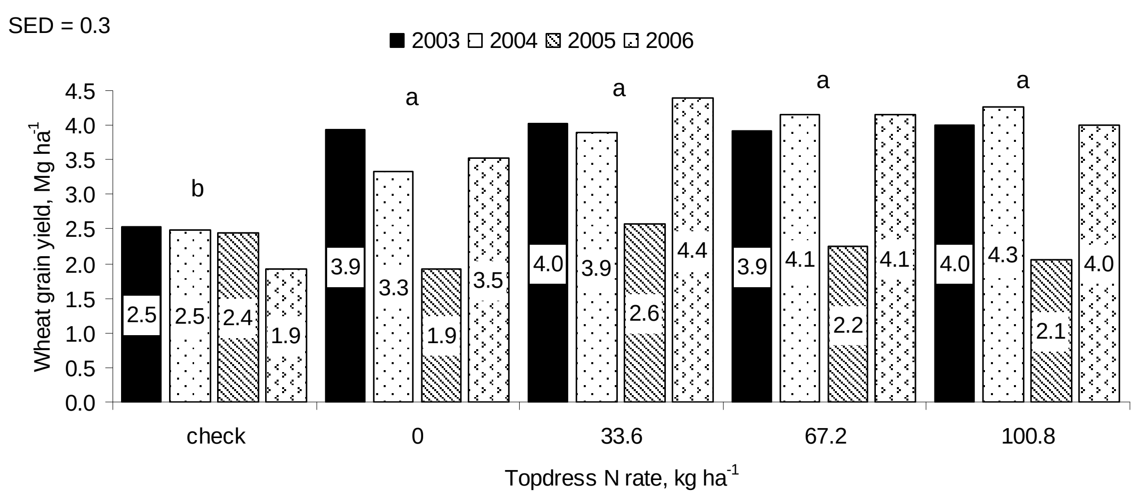

Figure 7. Winter wheat grain yield of check plot (treatment 1) and treatments with 100.8 kg N ha^{-1} preplant (treatments 9, 10, 11, 12) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003, 2004, 2005, and 2006. Bars followed by the same letter are not significantly different at p<0.05 using Least Significant Difference (LSD) mean separation procedure.

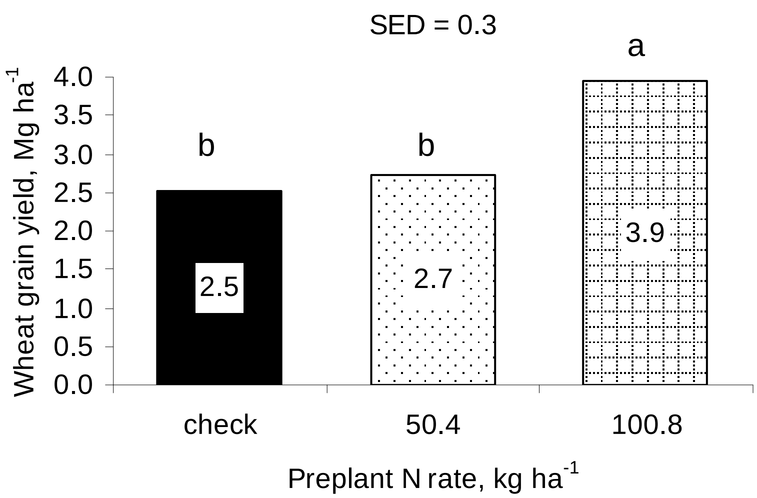

Figure 8. Winter wheat grain yield for check plot (treatment 1) and treatments with no topdress (treatments 1, 5, 9) as affected by preplant N fertilizer rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

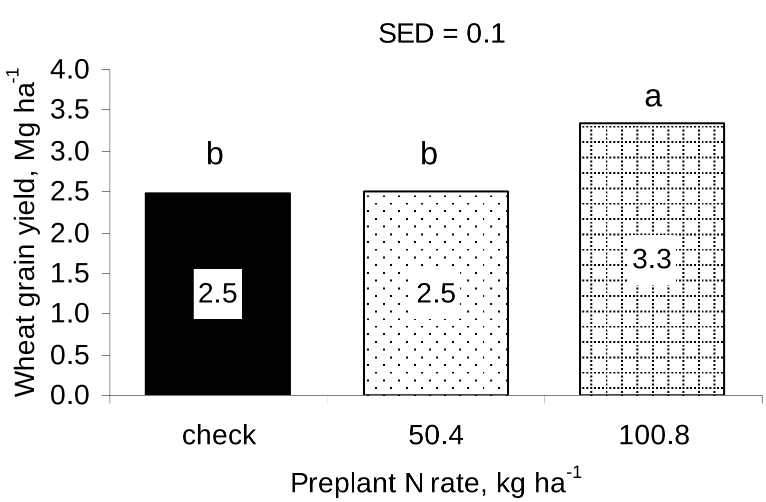

Figure 9. Winter wheat grain yield for check plot (treatment 1) and treatments with no topdress (treatments 1, 5, 9) as affected by preplant N fertilizer rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2004. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

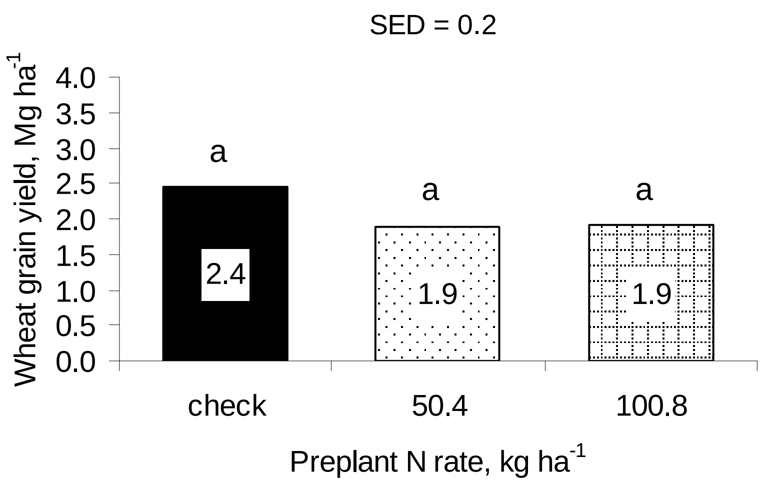

Figure 10. Winter wheat grain yield for check plot (treatment 1) and treatments with no topdress (treatments 1, 5, 9) as affected by preplant N fertilizer rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2005. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

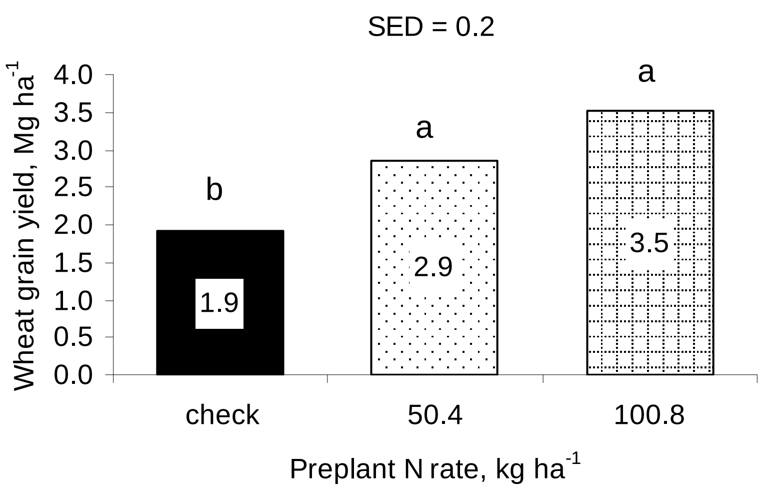

Figure 11. Winter wheat grain yield for check plot (treatment 1) and treatments with no topdress (treatments 1, 5, 9) as affected by preplant N fertilizer rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2006. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

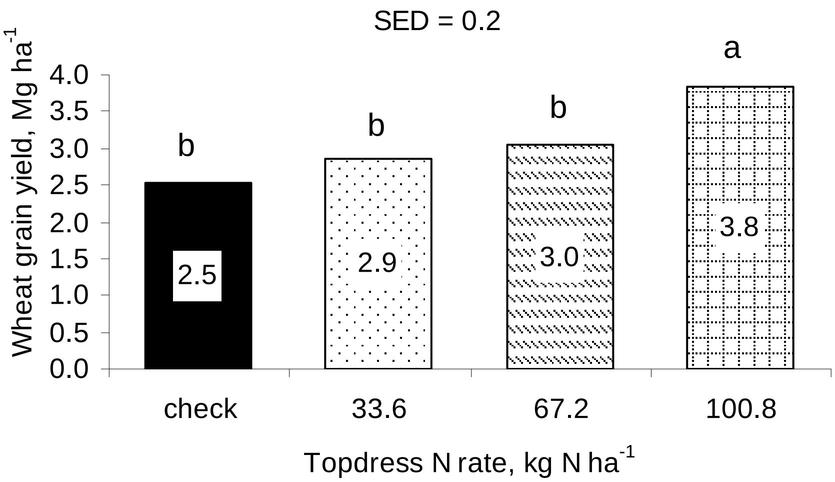

Figure 12. Winter wheat grain yield of check plot (treatment 1) and treatments with no preplant (treatments 1, 2, 3, 4) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2003. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

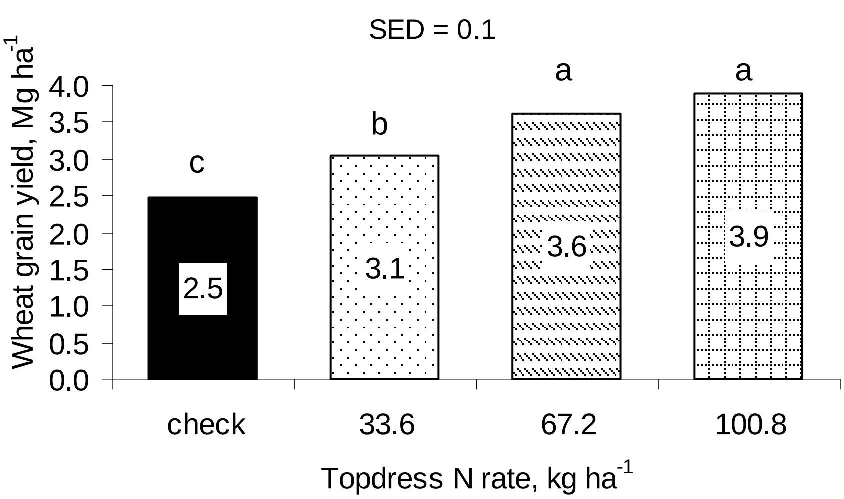

Figure 13. Winter wheat grain yield of check plot (treatment 1) and treatments with no preplant (treatments 1, 2, 3, 4) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2004. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

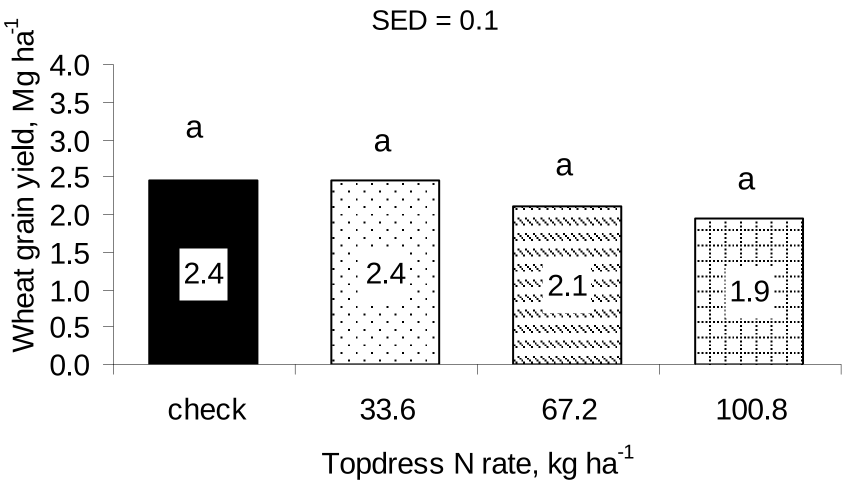

Figure 14. Winter wheat grain yield of check plot (treatment 1) and treatments with no preplant (treatments 1, 2, 3, 4) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2005. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

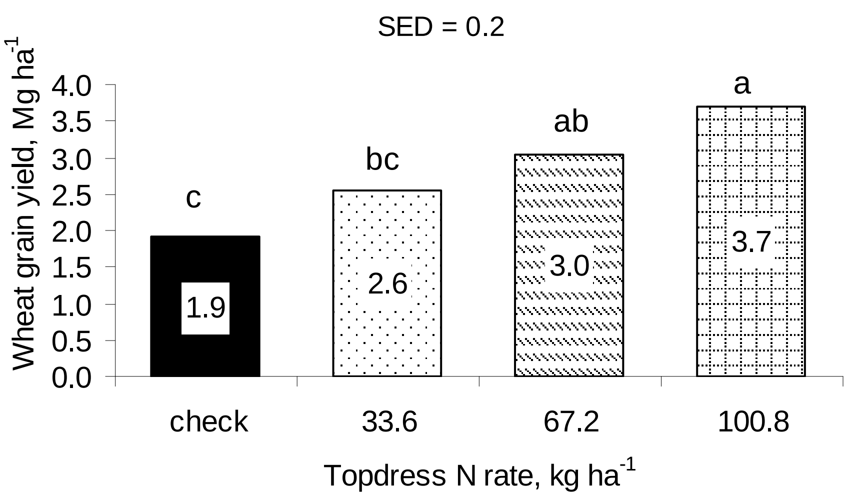

Figure 15. Winter wheat grain yield of check plot (treatment 1) and treatments with no preplant (treatments 1, 2, 3, 4) as affected by topdress N fertilizer application rate (33.6 kg N ha^{-1}, 67.2 kg N ha^{-1}, 100.8 kg N ha^{-1}) at Lake Carl Blackwell, OK, 2006. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

APPENDIX

Table A-1. Results of linear, quadratic, and cubic polynomial orthogonal contrasts for mean wheat grain yield at Lake Carl Blackwell, OK, 2003 – 2006.

Contrast	2003	2004	2005	2006
Linear: topdress no preplant	**	***	ns	***
Linear: preplant no topdress	**	**	ns	***
Linear: topdress low preplant	**	***	ns	
Cubic: topdress low preplant			*	***
Linear topdress high preplant	**	***	ns	***

* - Significant at p< 0.05; ** - Significant at p< 0.01; *** - Significant at p< 0.001; p < 0.1 – Significant at 0.05<p<0.1; ns – Not statistically significant.

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APPENDIX C

EFFECT OF DELAYED NITROGEN FERTILIZATION ON CORN (*Zea mays L.*) GRAIN YIELDS AND NITROGEN USE EFFICIENCY

ABSTRACT

Sidedress nitrogen (N) delayed until V8 to V10 growth stages facilitates in-season plant nutrient evaluation and the determination of fertilizer N needed to be applied to achieve maximum grain yields based on the crop's yield potential (YP). Corn grain yield potential can be accurately estimated mid-season using NDVI at the V8 growth stage. Delaying sidedress N fertilizer application until later in the growing season has potential for increasing N use efficiency (NUE). This study was conducted from 2005 to 2007 at three experimental sites in Oklahoma to determine if application of fertilizer N can be delayed until mid-season without decreasing grain yields. Several combinations of preplant and sidedress N fertilizer applications at various growth stages were evaluated. Higher corn grain yields and NUE's were achieved with preplant N applications followed by mid-season sidedress fertilization at V6-V10 growth stages. Generally, corn grain yields were maximized with 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at V6 or V10 (8 of 9 site-years). Analysis of data from 9 site-years demonstrated that there was no significant decrease in grain yields associated with delaying sidedress N application until

V10 growth stage and tasseling when preplant was applied. Delaying N fertilizer until mid-season supplies N at the time when the crops need for N and N uptake are at the maximum, and thus facilitates more efficient N fertilizer use. Nitrogen use efficiency was generally improved with mid-season N application at lower N rates. Highest NUE's were achieved with 45 kg N ha^{-1} preplant followed by 45 kg N ha^{-1} sidedress applied at V6 growth stage (8 of 9 site-years) and at V10 (6 of 9 site-years). Lowest NUE's were observed with higher N fertilizer rates and when all N was applied preplant. The results of this study suggest that the optimum fertilizer recommendation in corn may be formulated as follows: apply 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at or before V10 growth stage. This provides a window of opportunity for sidedress fertilizer N application of approximately 15 to 20 days.

INTRODUCTION

The typical world-wide NUE reported by Raun and Johnson (1999) for most cereal crops including corn (Zea mays L.), wheat (Triticum aestivum L.), rice (Oryza sativa L.), barley (Hordeum vulgare L.), oats (Avena sativa L.), sorghum (Sorghum bicolor, L.), rye (Secale cereale L.), and millet (Pennisetum glaucum L.), is approximately 33% with estimated averages of 29% and 42% for the developing and the developed countries, respectively. Such a low NUE reflects ineffective N management in agriculture and causes both great economic loss to producers and negative impact on the environment. On a global scale, the question of whether NUE can be increased above the average 33% becomes crucial considering the continuous pressure on agricultural producers to meet the demands of a rapidly growing population worldwide.

The highly intensive crop production worldwide results in large amounts of N being removed with the harvested grain, and, therefore, results in natural nutrient depletion year after year. On the other hand, one of the most harmful ecological problems, known to be caused by accelerated agriculture, is run-off from croplands. This results in deterioration of water quality and declining sea-life. One of the most difficult challenges researchers and crop producers face today is to sustain global food security, and minimize the negative impact of intense agriculture on the environment.

To improve fertilizer recommendations, it is necessary to determine the effects of the delayed N application and how long is it possible to delay N application for corn without compromising maximum grain yields. The following hypotheses were tested in this study. (i) NUE can be increased by delaying fertilizer N application to corn until later in the season without compromising grain yield; (ii) supplying all of the N to the established crop at V6 will enable corn to overcome the stress caused by N deficiency earlier in the season, when no preplant fertilizer is applied; (iii) it is possible to achieve high yield with the minimum amount of preplant fertilizer followed by N application delayed until the V10 growth stage; and (iv) corn will fail to recover if no preplant fertilizer is applied and all of the N is supplied to the crop at the V10 growth stage.

OBJECTIVES

The objectives of this study were:

1. To evaluate the effects of delayed N fertilization on corn grain yields,
2. To identify the minimum preplant N needed to achieve maximum yields if sidedress N fertilizer is applied later in-season, and
3. To determine how late in the growing season fertilizer N can be applied without decreasing corn grain yields.

LITERATURE REVIEW

Wittwer (1998) referred to crop production as “the world’s most important renewable resource”; to be able to sustain global food security, while using natural resources wisely and minimizing the negative impact of intense agriculture on the environment, represents, perhaps, the most difficult challenge which researchers and crop producers are facing today. As stated by Basra (1998), “crops stand between people and starvation” because cereal grains such as rice, wheat and corn supply the majority of calories (approximately 60%) and protein (50%) for human consumption.

One of the most harmful ecological problems, known to be caused by accelerated agriculture, is run-off from croplands. It results in deterioration of water quality and declining sea-life. The mean annual input of N as a result of fertilizer run-off (61% of which is due to nitrate N) to the Gulf of Mexico has tripled in the last 30 years (Goolsby et al., 2000). This illustrates the damaging effects of improper fertilizer management.

Highly intense crop production worldwide results in large amounts of N being removed with the harvested grain, and, therefore, causes natural nutrient supply of soils to deplete year after year. Maintaining the balance between N lost from the soil and naturally occurring N fixation is not possible, as it previously was, during the pre-chemical era. The use of slow-release organic fertilizers such as manure, application of green manure coupled with adoption of agricultural systems, such as crop rotation and intercropping, allowed for more efficient use of residual N (Joji Arihara National Agriculture Research Center, 2000).

As stated by Evans (1998), because of the need for continuous nutrient inputs to the soil, simply reducing the rates of N fertilizer used in agriculture would obviously prevent crop producers from achieving their major goal – higher yields. Therefore, creating the effective N management system and improving N recommendations and increasing NUE are critical issues, which should be addressed to maintain and increase the sustainability of crop production in the future.

The conventional practices historically used by most crop producers do not address the issue of successfully managing resources. Traditional approaches to fertilizing corn after harvest in the fall is still considered to be more advantageous by many crop producers because it enables them to better distribute their time and labor (Randall et al., 2003) and benefit from better soil conditions and lower fertilizer N prices at this time (Bundy, 1986; Randall and Schmitt, 1998). However, it is necessary to evaluate the risks imposed by fall post-harvest application versus spring application and split N fertilization (40% at planting followed by 60% mid-season).

Recently, Bruns and Abbas (2005) stated that application of full amounts of N fertilizer prior to planting may result in better economic returns than carrying out split N applications. They concluded that the economic loss due to decreased grain yield may be insignificant when compared to additional production costs associated with split fertilization, such as several trips to the field.

Aiming to determine how fertilizer N application timing effects corn grain yield, Torbert et al. (2001) found split and spring fertilization to increase yields compared to fall application. Significantly lower N uptake recorded for fall application (40-60 kg ha^{-1}) compared with spring and split fertilization (90-105 kg ha^{-1}) could be explained because of leaching, erosion, and denitrification that are active during the fall-winter periods (Torbert et al., 2001).

According to Wells and Blitzer (1984) and Wells et al. (1992), the most efficient time for N application is at growth stage V6, when corn plants active development significantly increases N plant needs. N uptake rate is known to be affected by many factors such as weather, planting date, and time of fertilizer application but is usually highest between V8 and V12 (Russelle et al. 1981). Fast development of corn plants during middle vegetative stage (growth stage V6 and later) results in maximum N uptake, meaning that even N-deficient corn should be able to respond to delayed N application (Binder et al., 2000).

Aldrich (1984), Olson and Kurtz (1982), Russelle et al. (1981), Stanley and Rhoads (1977), and Welch et al. (1971) all agree that the best practice in managing corn is the application of N fertilizer at the time (or near the time) when both the need for N and N uptake are maximum for corn plants because it promotes higher NUE by reducing denitrification, N immobilization and leaching.

Studies in winter wheat and soybean production showed similar results in some cases. Nelson et al. (1984) reported that supplying N to the soybean plant during the time of peak seed demand prevents premature senescence, and increases seed yield. Morris et al. (2005) found that the highest grain yield for winter wheat was achieved by application of N fertilizer to the established crop. Fertilization delayed until Feekes 5 enabled the crop to overcome N stress present earlier in the growing season and achieve maximum or near maximum yields (Morris et al. 2005).

Evaluating the impact of in-season fertilization of soybean, Barker and Sawyer (2005), found that, even though N fertilizer applied during reproductive stages increased plant N concentration, it did not result in increased grain N concentration, grain yield or grain quality.

Mixed and site-specific results of split N fertilization of corn indicate that more extensive data is needed to confirm or contradict the effectiveness of this method of corn fertilization. Miller et al. (1975) and Olson et al. (1986) evaluated the efficiency of in-season N application and concluded that both NUE and grain yields can be increased by delaying N fertilization for corn. Results of a seven-year study on timing of N application in corn and soybean production, conducted by Randall et al. (2003), demonstrated that the lowest grain yield was achieved by fall N application versus the highest grain yield with split N fertilization. Evaluation of the economic return for fall and split N application clearly showed advantages for split N application (\$166.70 $ha^{-1}year^{-1}$ for fall applied N; \$239.40 $ha^{-1}year^{-1}$ for split applied N) (Randall et al. 2003).

The effectiveness of split N applications is largely dependent on site-specific conditions such as soil properties and climate (Bundy 1986). Even though fall application of N can be acceptable for some soil types (medium-to-fine-textured soils) combined with specific climate conditions (low winter temperatures decrease nitrification), this early fertilization can cause decreased fertilizer-N effectiveness (10-15% less effective when compared with N fertilizer applied in spring)(Bundy 1986).

Vetsch and Randall (2004) found a significant difference in N recovery: 87% for spring N application compared with only 45% when N was applied in fall. Relative leaf chlorophyll measurements taken at different growth stages were not significantly different for fall and spring applied N. However, starting from growth stage V6, N deficiency was recorded for the plants fertilized in the fall (Vetsch and Randall, 2004).

A wide range of factors affects the decision about when is the best time to apply N fertilizer so that the crop will benefit the most. Among them are fertilizer rate, fertilizer type, method of application, climatic conditions, amount of residual N present in soil prior to fertilization, and the level of N deficiency imposed on the crop.

Evaluating corn grain yield response to N fertilizer applied at various rates and times, Schmidt et al. (2002) achieved a maximum grain yield by applying at least 130 kg ha^{-1} of N fertilizer. Greater organic matter (OM) content did not decrease corn need in fertilizer N, since the fields with higher OM did not require less N to maximize grain yields. While corn grain yields varied depending on the rate of N applied, higher fertilizer rates did not necessarily increase availability of N to the plant and, consequently, increase grain yield. Schmidt et al. (2002) recommended sidedress application of N fertilizer during the growing season as a means to improve NUE.

In 1999, Ma et al. recorded the highest loss of N during the growing season at the location with the highest rate of N fertilizer applied; net gain of mineral N had occurred throughout the growing season at the check location where there was no N fertilizer applied. This showed that significant amounts of mineralized plant-available N can be contributed to the soil from the atmosphere via precipitation and dry deposition (Ma et al., 1999). Therefore, it is necessary to evaluate the amount of residual N present in soil by conducting a preplant soil test.

Blackmer et al., (1989) found that delaying N fertilization until mid-season allows for more accurate determination of crop need for N, and they suggested carrying out in-season soil test to avoid over application and minimize N loss.

One of the problems associated with the application of N later in the growing season is the suppression of corn grain yield due to N deficiency. Understanding the effects imposed to corn by delayed N application is extremely important for improvement of fertilizer recommendations because the effectiveness of delayed N application to corn is strongly dependent on the degree of N deficiency at that time (Binder et al., 2000). Lower grain yield was achieved by late fertilization of slightly N deficient corn; slight increase in yield was observed for severely deficient corn fertilized late in season, but the maximum yield was not achieved. Severely N-deficient corn showed high N response compared with less N-deficient corn, but did not result in higher grain yield (Binder et al., 2000).

Using chlorophyll meter readings, Varvel et al. (1997) calculated a SI (sufficiency index) to determine the appropriate timing for in-season N fertilization for corn. N was applied when index values were below 95%. They further reported that maximum yields for corn could not be achieved by late in-season fertilization if sufficiency index values at V8 were below 90%. Therefore, the suggestion was made that N fertilization before V8 growth stage was critical for corn.

Scharf et al. (2002) found, that N fertilization even as late as stage V11 did not result in irreversible yield loss, even for corn showing very significant N stress. Delaying

N application until growth stages V12 and V16 caused a loss of just 3% in grain yield. Scharf et al. (2002) concluded that the benefits of the delayed N fertilization in corn outweigh the risk of grain yield loss.

Evaluating NUE and N response in winter wheat production, Wuest and Cassman (1992) observed higher N recovery (55% to 80%) when fertilizer was applied mid-season compared to N recovery of 30% - 55% in the case of preplant N application.

Supplying only the necessary amount of N to satisfy the crop need at the specific fertilizer application time would result in lesser amounts of residual NO^{-}_{3} in soil and, therefore, decrease the risk of N being lost from soil (Andraski et al. 2000).

Results from Solie et al. (1996) and Stone et al. (1996) show that on-the-go optical sensing and variable rate application are practical and reliable tools for determining optimum N rate, placement methods and timing of mid-season fertilization. They showed that it is possible to successfully address the issue of spatial variability present in the field by using sensors which measure reflected light and determine normalized difference vegetative index (NDVI). Precision sensing at high resolutions (one square meter) enables accurate prediction of yield potential and estimation of N fertilizer needed, increasing N uptake and decreasing the risk of N loss, and, therefore, increasing NUE (Stone et al. 1996).

Teal et al. (2006) showed that corn grain yield potential can be accurately estimated mid-season using NDVI at the V8 growth stage. There is a need to investigate whether sidedress N fertilization in corn can be delayed until mid-season without leading to irreversible grain yield loss.

MATERIALS AND METHODS

This study was conducted at three locations in 2005, 2006 and 2007: Stillwater Research Station near Lake Carl Blackwell (irrigated), OK, Efaw Research Farm (rainfed), near Stillwater, OK, and Haskell, OK at the Eastern Oklahoma Research Station (rainfed). A completely randomized block design with 3 replications was used to evaluate 14 treatments at all sites. Various combinations of preplant and sidedress N fertilizer applications at several growth stages (V6, V10, and VT) were evaluated to determine the optimum nutrient management strategy for corn production. Treatment structure is shown in Table 1. At all sites the size of the individual plots was 3.1 x 6.2 m with 3.1 m alleys. Initial surface (0-15cm) soil chemical characteristics and classification are reported in Table 2.

Field activities including planting dates, seeding rates, cultivars, preplant soil sampling dates, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, for 2005, 2006, and 2007 are summarized in Tables 3, 4, and 5 respectively. In 2005, “Pioneer 33B51” variety was planted at Efaw and Lake Carl Blackwell, and “Triumph 1416Bt” at Haskell. In 2006, “Pioneer 33B51” was planted at all sites. In 2007, the varieties were “Dekalb DKC 50-20”, “Dekalb DKC 66-23”, and

‘’Pioneer 33B54” for Efaw, LCB, and Haskell respectively. The seeding rates were 59,280 plants ha^{-1} for Efaw and Haskell), and 74,100 plants ha^{-1} for Lake Carl Blackwell in 2005. In 2006, the seeding rates were 54,340 plants ha^{-1} at Efaw, 79,040 plants ha^{-1} at Lake Carl Blackwell, and 61,750 plants ha^{-1} at Haskell. In 2007, the seeding rates were 54,340 plants ha^{-1} at Efaw, 79,040 plants ha^{-1} at Lake Carl Blackwell and 59,280 plants ha^{-1} at Haskell.

Preplant N fertilizer as ammonium nitrate (34% N), urea (46%N), and urea ammonium nitrate (UAN) (28% N) were broadcast manually and incorporated into the soil at planting in 2005, 2006, and 2007, respectively. Sidedress fertilizer N was applied mid-season as urea ammonium nitrate (UAN) (28-0-0). Sidedress N was applied along each row at the base of the plants in a continuous stream using 50-200 ml syringes.

The center 2 rows from each 4-row plot were harvested with a Massey Ferfuson 8XP self-propelled combine. Grain sub-samples were collected, oven-dried at 70°C for 72 hours and processed to pass a 106 μm (140 mesh screen) and analyzed for total N content using a Carlo Erba NA 1500 dry combustion analyzer (Schepers et al. 1989). Total N uptake (kg ha^{-1}) was determined by multiplying grain yield (kg ha^{-1}) by grain percent N. N use efficiency was determined using the difference method (Varvel and Peterson, 1991).

Statistical analysis was performed using SAS for Windows (SAS, 2002). Analysis of variance (ANOVA) was used to evaluate the effect of treatments on grain yield and NUE. Multiple comparisons of treatment means were also evaluated. Linear and quadratic polynomial orthogonal contrasts were used to assess trends in grain yield to N fertilizer rates.

RESULTS

2005

GRAIN YIELD

EFAW

Grain yields responded to fertilizer N, giving a 2000 kg ha^{-1} increase from 90 kg N ha^{-1} when compared to the 0-N check (Treatments 1 and 2) (Table 6). At Efaw, when the sidedress N fertilizer rates were increased from 0 to 180 kg ha^{-1}, grain yields increased linearly regardless of the sidedress application timing (Treatments 1, 4, 5 vs 1, 6, 7 vs 1, 8, 9) (Table 6). Comparison of one time sidedress application at the three growth stages (V6, V10 and VT) with split application (half of total N applied preplant and the remaining half sidedressed at each respective growth stage) generally showed a significant increase in grain yield when N fertilizer was split applied (Treatments 4 and 14, 6 and 13, 5 and 10, 7 and 11, 9 and 12) (Table 6). In general, the highest grain yields at Efaw were obtained with split fertilization and higher total N application (Table 6). There were no statistically significant differences in grain yield associated with timing of sidedress fertilizer applications.

LAKE CARL BLACKWELL

Grain yields at Lake Carl Blackwell increased linearly with an increase in sidedress N fertilizer rate from 0 to 180 kg N ha^{-1} when sidedress applications were made at the V10 growth stage (Treaments 1, 6, and 7) (Table 7). When no preplant N was applied and the sidedress applications were made at V6 and VT stages, yields peaked at the 90 kg N ha^{-1} rate (Treatments 4, 5 vs 8, 9) (Table 7). At V6, plots with 90 kg N ha^{-1} yielded 647 kg ha^{-1} more than plots that received 180 kg N ha^{-1}. Similarly, when fertilization was delayed until the VT growth stage, application of 90 kg N ha^{-1} resulted in 1117 kg ha^{-1} additional yield compared with 180 kg N ha^{-1}. The significant reduction in grain yields observed with higher N fertilizer rates may be explained by imbalance between vegetative biomass production and grain production. Preplant application of 90 kg N ha^{-1} followed by 90 kg ha^{-1} sidedress N at VT resulted in 3057 kg ha^{-1} more grain yield than the single 180 kg N ha^{-1} sidedress application (Treatments 12 and 9) (Table 7). Treatments with split applications at various growth stages also generally resulted in increased grain production at Lake Carl Blackwell.

At the fertilizer N rates evaluated, grain yields for treatments with sidedress applications at V6 were significantly higher ($p<0.05$) compared to those with delayed fertilization at the VT growth stage (Treatments 4, 5, 10, 14 vs 8, 9, 12) (Table 7). Overall, treatments where fertilizer N was applied earlier in the growing season (V6 growth stage) yielded more than treatments where sidedress N was delayed until tasseling (VT growth stage) (Figure 1).

HASKELL

Yield levels were low at this site and as such, response to N fertilization was more difficult to discern. However, preplant N applications demonstrated a linear response to applied N (Treatments 1, 2, and 3) (Table 8). Preplant applications, as well as fertilization earlier during the growing season, were important in grain production at Haskell in 2005. The highest yields were generally obtained with the application of 180 kg N ha^{-1} prior to planting with no additional sidedress fertilization and with the 90-90 split sidedressed at V6 (Treatments 3 and 10) (Table 8).

With the 180 kg N ha^{-1}, treatment that received 90 kg N ha^{-1}preplant and 90 kg N ha^{-1} at V6, yields were 4742 kg ha^{-1} and significantly superior ($p<0.05$) to applying all N at V6 (Treatments 10 and 5) (Table 8).

Grain yields gradually decreased from 4641 kg ha^{-1} (plots receiving all N preplant) to 4107 kg ha^{-1} (sidedress fertilizer applied at V6) to 3852 kg ha^{-1} (sidedress application at V10) to 3535 kg ha^{-1} (sidedress at VT) (Figure 2). Delaying fertilizer N application until the VT growth stage resulted in a significant reduction in grain yields compared to treatments that were fertilized at V6 growth stage (Figure 2) independent of the fertilizer rate.

2005

NITROGEN USE EFFICIENCY

EFAW

The highest fertilizer N use efficiency of 48% was obtained at Efaw with 90 kg N ha^{-1} split applied (preplant plus sidedress at V10) (Treatment 13) (Table 9). The lowest NUE's were achieved for treatments that received no N preplant and where high rates of sidedress N were delayed until late mid-season (V10-VT growth stages) (Treatments 7 and 9) (Table 9). Since the need for fertilizer during crop establishment and rapid development was not satisfied earlier in the growing season, even the application of large amounts of N later on did not allow the crop to “catch up” and achieve maximum yields.

Increased NUE was generally observed with split fertilizer application compared to treatments that received all fertilizer N at one time (Treatments 13 vs 6, and 14 vs 4) (Table 9).

LAKE CARL BLACKWELL

The highest NUE of 96% was achieved for the treatment that received no N preplant and N applied early in the growing season, which allowed the crop to "catch up" and produce near maximum grain yields (Treatment 4) (Table 10). The lowest NUE was obtained for the treatment with no N applied preplant, and where sidedress was delayed until tasseling (VT growth stage), which also resulted in loss of potential grain yield (Treatment 9) (Table 10). This shows that fertilizer use efficiency is proportional to the achieved grain yield and gradually decreases with increased fertilizer rates applied.

In general, split fertilizer applications resulted in greater NUE's compared to treatments with no N preplant, and all fertilizer N applied mid-season. Consequently, NUEs for treatments with the total N rate of 90 kg ha^{-1} were 82% (no preplant) compared to 94% obtained with preplant followed by sidedress at the V10 growth stage (Treatments 6 and 13)(Table 10). When a total of 180 kg ha^{-1} fertilizer N was applied, 62% NUE was achieved with split fertilizer application, while only 39% NUE was observed when no N was applied preplant and all fertilizer was applied at VT growth stage (Treatments 12 and 9) (Table 10).

HASKELL

Greater NUEs were achieved when all fertilizer was supplied as preplant (27%) and with the split application when sidedress applied early in the growing season (V6 growth stage) (29%) (Treatments 2 and 14) (Table 11). However, since the application of higher N rates later in the season did not improve yields, the fertilizer N use efficiency was lower. The NUEs tended to gradually decrease with delayed N application, averaged over N rates (Figure 3).

Omitting preplant N and applying 90 kg N ha^{-1} sidedress at V10 resulted in significantly lower ($p<0.05$) NUE (11%) compared to treatments with split application (18%) (Treatments 6 and 13) (Table 11).

2006

GRAIN YIELD

EFAW

A linear increase in grain yield was observed when sidedress N rates were increased from 0 kg ha^{-1} to 180 kg ha^{-1}, regardless of application timing (Treatments 1, 4, 5 vs 1, 6, 7 vs 1, 8, 9) (Table 6).

The highest grain yield of 7116 kg ha^{-1} was produced when N was split applied at V6 (Treatment 10) (Table 6). Another high-yielding treatment (6913 kg ha^{-1}) was where all fertilizer was supplied at 180 kg N ha^{-1} preplant (Treatment 3) (Table 6). Comparable grain yields of 6835 and 6813 kg ha^{-1} were obtained with split fertilization (sidedress at V6 and V10 growth stages, respectively) (Treatments 14 and 13) (Table 6). This showed that although the response to fertilizer N was clearly present at Efaw, the 90 kg ha^{-1} rate was adequate to satisfy crop needs for N, but when split applied.

When a total of 90 kg N ha^{-1} was applied, significantly greater ($p<0.05$) grain yields (6835 kg ha^{-1}) were obtained by splitting N applications compared to only 5467 kg ha^{-1} for the treatment with no preplant N (Treatments 13 and 6)(Table 6).

LAKE CARL BLACKWELL

Statistical analysis indicated a quadratic relationship between N fertilizer rate and grain yield at Lake Carl Blackwell. A significant ($p<0.05$) reduction in grain yield was observed when fertilizer N was doubled. The magnitude of grain yield loss, however, was much larger in 2006, since plots that received 90 kg N ha^{-1} yielded more than twice as much (7482 kg ha^{-1}) than plots with 180 kg N ha^{-1} (3141 kg ha^{-1}) (Treatments 4 and 5)(Table 7).

Likewise, split fertilization resulted in significantly greater ($p<0.05$) grain yield compared to treatments that did not receive any N preplant, and all fertilizer was applied at V6 growth stage (Treatments 5 and 10) (Table 7). The amount of grain yield achieved with split applications was more than 2.5 times greater than that obtained with single sidedress fertilization.

HASKELL

At Haskell, no statistically significant differences in grain yields were observed regardless of N fertilizer rates and/or timing of sidedress application in 2006. Also, yields were generally lower in 2006 compared to the yields achieved in the previous growing season (Table 7).

Yield levels were the lowest compared to any other site-year obtained in this study. No response to N fertilizer was observed at this location in 2006. The 0-N check plots that did not receive fertilizer N yielded more than most of the fertilized treatments, regardless of N rate and fertilizer timing (Treatments 1, 3, 4, and 12)(Table 7).

2006

NITROGEN USE EFFICIENCY

EFAW

Greater NUEs were obtained at Efaw in 2006 via split fertilization (53%) of 90 kg N ha^{-1} compared to one time mid-season application at V10 (38%) (Treatments 13 and 6) (Table 9).

A similar trend was apparent when fertilizer N was applied at 180 kg N ha^{-1}. Treatments receiving preplant N had significantly greater ($p<0.05$) NUEs than where fertilizer application was delayed until V10 (Treatments 11 and 7) (Table 9). Considerable variability existing within the field may explain the greater NUE of 30% obtained with the later one time sidedress fertilization at VT compared to 28% NUE observed with split fertilization (Treatments 9 and 12) (Table 9).

Overall, sidedress application timing did not contribute significantly to differences in fertilizer N use efficiency at Efaw.

LAKE CARL BLACKWELL

Unlike 2005, method (split versus one time fertilization) of fertilizer application did not affect NUE (Table 10). However, treatments with no preplant N, and 90 kg N ha^{-1} applied at V6 produced the highest fertilizer N use efficiency of 68% (Treatment 4) (Table 10). The NUE's for treatments with no preplant N and high sidedress N (180 kg ha^{-1}) at V6 were only 11% (Treatment 5) (Table 10). This significantly lower ($p<0.05$) fertilizer N use efficiency is explained by the fact that much lower grain yields (3141 kg ha^{-1}) were obtained with 180 kg N ha^{-1} than with 90 kg N ha^{-1} (7482 kg ha^{-1}) (Treatments 5 and 4) (Table 8).

HASKELL

At Haskell, fertilizer N use efficiencies were extremely low in 2006 due to very low grain yields even for treatments with higher fertilizer N rates. Plots with highest NUE (only 6%) received 45 kg ha^{-1} fertilizer N preplant and another 45 kg ha^{-1} N at V6 (Treatment 14) (Table 11). These plots produced near maximum yields for this location in 2006 (Table 8). In general NUEs at this site were low, since grain N uptake in the check plot was high, thus limiting what could be interpreted from subtle treatment differences. Low NUE's can be explained by lack of crop's response to fertilizer N at this location in 2006.

2007

GRAIN YIELD

EFAW

In general, grain yields were low at Efaw in 2007; no pronounced response to applied fertilizer was observed. Preplant application of 90 kg N ha^{-1} and 180 kg N ha^{-1} resulted in the lowest grain yields (1977 and 2171 kg ha^{-1}) close to that of the check plot (1966 kg ha^{-1}). The highest grain yield of 3231 kg ha^{-1} was achieved with no preplant N and 180 kg N ha^{-1} applied at V6 growth stage. Grain yield decreased considerably from 3231 kg ha^{-1} to 2533 and 2241 kg ha^{-1} when sidedress N was delayed until V10 and VT growth stages, when no preplant N was applied (Table 6).

Split application of 90 kg N ha^{-1} and 180 kg N ha^{-1} (treatments 10 through 14) all resulted in comparable yields. Comparable yields (2405, 2927, and 2647 kg ha^{-1}) were obtained when sidedress was applied at V6, V10, and VT respectively at 90 kg N ha^{-1}. A noticeable increase in yield (from 2405 to 3231 kg ha^{-1}) associated with increase of fertilizer N rate from 90 kg N ha^{-1} to 180 kg N ha^{-1} was observed only when no preplant was applied and sidedress fertilization was carried out at V6 growth stage (Table 6). With no preplant N and delayed sidedress N at V10 and VT growth stages produced very similar grain yields independent of the N rate applied.

Independent of fertilizer N rate applied, significantly lower ($p<0.05$) corn grain yields were obtained when all N was applied preplant (2074 kg ha^{-1}), compared to grain yield for the treatments for which sidedress was delayed until V6 (2799 kg ha^{-1}), V10 (2799 kg ha^{-1}) or VT (2541 kg ha^{-1}) growth stages compared to grain yield of 2799 kg ha^{-1} with sidedress fertilization at V6. No significant differences associated with the time of sidedress N application time (V6, V10, and tasseling) were observed (Figure 4).

LAKE CARL BLACKWELL

In 2007, grain yields at LCB were higher than at Efaw but considerably lower than at Haskell. With split application of 90 kg N ha^{-1}, grain yields slightly decreased from 6830 to 6598 to 6270 kg ha^{-1} when sidedress was applied at V6, V10, and VT growth stages respectively (Table 7).

With no preplant N, delaying 180 kg N ha^{-1} sidedress from V6 to V10 application caused a decrease in grain yield of 990 kg ha^{-1}. However, no further decrease in yield was observed when sidedress fertilization was further delayed until tasseling. Similar to results from Efaw, with no preplant followed by sidedress N at V6 growth stage, grain yields increased considerably (from 7679 to 8362 kg ha^{-1}) when sidedress N was doubled from 90 kg N ha^{-1} to 180 kg N ha^{-1}. On the other hand, when sidedress N was delayed until V10 and VT growth stages, similar grain yields were obtained independent of N rate applied (Table 7).

Overall, there were no significant differences among grain yield treatment means associated with the time of sidedress application.

HASKELL

Even though the check plot at Haskell in 2007 yielded almost 1500 kg ha^{-1} more than the check plot at LCB, the overall grain yields were significantly higher ($p<0.05$) at Haskell ranging from 7897 to 12776 kg ha^{-1} (Table 8). The demand for N is illustrated by increased grain yields (from 4644 to 10067 to 12776 kg ha^{-1}) as preplant fertilizer N rates increased from 0 to 90 to 180 kg N ha^{-1}.

Pronounced response to N for treatments with no preplant resulted in higher yields achieved with the highest sidedress N rate of 180 kg N ha^{-1} compared to 90 kg N ha^{-1}. Doubling sideddress N applied at V6 increased grain yield from 9843 to 11025 kg ha^{-1} (Table 8). Grain yields increased from 7897 to 10121 kg ha^{-1} when N was sidedress at VT at 180 kg N ha^{-1} compared to 90 kg N ha^{-1}. When N was split-applied, comparable grain yields were obtained independent of rate and/or time of fertilization. For example, 45 kg N ha^{-1} preplant followed by 45 kg N ha^{-1}sidedress at V6 growth stage yielded 10559 kg ha^{-1}, and 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} at V10 and VT growth stages yielded 10572 and 10646 kg ha^{-1} respectively (Table 8).

Unlike at Lake Carl Blackwell, in 2007 at Haskell, significantly higher ($p<0.05$) corn grain yields were obtained when all N was applied preplant (11422 kg ha^{-1}) compared to treatments that received sidedress N at tasseling (9555kg ha^{-1}). However, there was no statistically significant difference in mean corn grain yields between treatments that were sidedressed at V6, V10, or even tasseling (Figure 5).

2007

NITROGEN USE EFFICIENCY

EFAW

In general, very low fertilizer NUEs (ranging from 5% to 20%) were observed at Efaw in 2007 (Table 9). This could be explained by lack of response to fertilizer N and low corn grain yields. The highest NUE of 20% was obtained at Efaw with 90 kg N ha^{-1} applied at V10 growth stage with no preplant N (Treatment 6). Similar NUEs were observed for Treatments 6 (no preplant N followed by 90 kg N ha^{-1} applied at V10 growth stage), Treatment 8 (no preplant N, 90 kg N ha^{-1} applied at VT growth stage) and Treatment 6 (total 90 kg N ha^{-1} split applied at V6 growth stage) (Table 9).

Overall, higher NUEs were obtained with lower N rates. For example, Treatment 6 (no preplant, 90 kg N ha^{-1} applied at V10 growth) had NUE of 20%, whereas Treatment 7 (no preplant, 180 kg N ha^{-1} applied at V10 growth) had NUE of only 5%.

In general, when no preplant N was applied, sidedress N fertilizer application affected NUE to a greater extent than time of fertilization. For Treatment 8 (no preplant, 90 kg N ha^{-1} applied at tasseling) NUE was 17% compared to only 8% for Treatment 9 (no preplant, 90 kg N ha^{-1} applied at tasseling). Similar, but slightly lower NUE of 5% was observed for Treatment 3 (180 kg N ha^{-1} applied all preplant) compared with 7% for Treatment 2 (90 kg N ha^{-1} applied all preplant) (Table 9).

When a total of 180 kg N ha^{-1} was split applied, NUEs were the same (10%) whether sidedress N was applied at V6 growth stage (Treatment 10) or delayed until V10

(Treatment 11). However, delaying sidedress N until tasseling (Treatment 12) led to a 3% decrease in NUE (from 10% to 7%). Neither N fertilizer application rate nor N application time significantly affect NUEs.

LAKE CARL BLACKWELL

The highest NUEs (up to 98%) were achieved at LCB in 2007 compared to any other site-year. As at Efaw, greater NUE's were obtained with lower N rates applied. For example, Treatment 2 (90 kg N ha^{-1} applied all preplant) had NUE of 35% compared to 28% for Treatment 3 (180 kg N ha^{-1} applied all preplant) (Table 8). Similarly, when no preplant N was applied, treatments with 90 kg N ha^{-1} sidedress (Treatments 4, 6, and 8) had higher NUE's (89%, 96%, and 83% respectively) compared with treatments with 180 kg N ha^{-1} sidedress (Treatments 5, 7, and 9) that had NUE's of 65%, 16%, and 57%.

At 180 kg N ha^{-1} split applied, there was a pronounced decrease in NUE's when sidedress N was delayed from V6 to V10 to VT growth stage (from 56% to 30% to 20% respectively) (Table 10).

The opposite trend was noticed for 90 kg N ha^{-1} split applied. Treatment 14 (no preplant N, sidedress N at V6) had NUE of 61%; when sidedress N was delayed until V10 growth stage (Treatment 15) a greater NUE (98%) was achieved (Table 10). Overall, there were no significant differences among NUE treatment means associated with the time of sidedress N application.

HASKELL

At Haskell in 2007, relatively high N fertilizer use efficiency was achieved. NUEs ranged from 36% to 90% (Table 11). The greatest NUE was recorded for Treatment 13

(90 kg N ha^{-1} total split between preplant and sidedress at V10), whereas Treatment 7 (180 kg N ha^{-1} all applied at V10).

With no preplant N, and 90 kg N ha^{-1} applied sidedress at V6, V10, and VT (Treatments 4, 6, and 8 respectively) higher NUEs of 72%, 67%, and 45% were observed compared to NUE's of 44%, 36%, and 38% for treatments that received 180 kg N ha^{-1} (Treatments 5, 7, and 9) (Table 11). Similarly, Treatment 2 (90 kg N ha^{-1} applied all preplant) had a greater NUE of 75% compared to 56% for Treatment 3 (180 kg N ha^{-1} applied all preplant).

There were no significant differences among NUE treatment means associated with the time of sidedress N application. The fertilizer N rate affected the NUEs to a greater extent than the timing of fertilizer application. However, in general NUE's decreased slightly as sidedress N was delayed until later in the season when no preplant was applied for 90 kg N ha^{-1} and 180 kg N ha^{-1}. For the treatments with 90 kg N ha^{-1} rate, NUE's decreased from 72% (Treatment 4) to 67% (Treatment 6) to 45% (Treatment 8). This meant a drop in NUE of 27% (sidedress at V6 vs at VT) (Table 11). Similarly, for the treatments with 180 kg N ha^{-1} rate, NUE's decreased from 44% (Treatment 5) to 36% (Treatment 7) and 38% (Treatment 9) resulting in a drop of 6% (sidedress at V6 vs at VT).

On the other hand, when fertilizer N was split applied, this trend was not observed. For example, Treatment 14 (90 kg N ha^{-1} rate split applied at V6) had NUE of 82%; when sidedress N was delayed until V10 growth stage (Treatment 13) a greater NUE of 90% was achieved. Also, with 180 kg N ha^{-1} rate split applied (Treatments 10, 11, and 12) (sidedress at V6, V10, and VT respectively), comparable NUEs (46%, 41%, and 42%) were observed (Table 11).

DISCUSSION

GRAIN YIELD

The preliminary results by Aref et al. (1997) supported the argument and conventional understanding that climate is particularly important in estimating of corn grain yields. They found that fertilizer N rate alone accounted for approximately 40% of the variation in corn grain yield. However, when climatic factors are considered, about 91% of the variation is accounted for. They noted that as well as amount of precipitation, the air temperature during grain fill strongly affected corn grain yield.

Higher corn grain yields were generally achieved in the 2005 season compared to 2006 (Table 6). Beneficial climatic conditions such as more abundant rainfall (509mm, 590mm, and 577mm for Efaw, Lake Carl Blackwell, and Haskell, respectively in 2005) compared to only 417mm, 380mm, and 412mm in 2006 for Efaw, Lake Carl Blackwell, and Haskell, respectively contributed to higher grain yields in 2005 cropping year, especially at the rainfed sites (Tables 3, and 4). Low levels of soil moisture at all sites (especially in 2006) both pre-season and during the growing season resulted in moisture stress, which may have decreased N uptake. Higher soil and especially - air temperatures also decreased grain yields in 2006 (Tables 3, and 4). Corn pollen is known to be sensitive to high temperatures (Hopf et al., 1992). Thus, heat stress present during most of the 2006 cropping year may have affected pollination and grain development.

2007 was an extremely wet year with several periods of continuous rainfall, numerous floods (32 floods reported for the period of March to July). The month of June was the wettest month for the state of Oklahoma (record since 1985) with 20 days of continuous rain June 13 to July 2 (Arndt, 2007). All 3 experimental sites received much greater rainfall compared to the other crop years (1139mm, 906mm, and 795 mm) for Lake Carl Blackwell, Efaw, and Haskell respectively (Tables 3, 4, and 5).

Statistical analysis of three years of data showed that both year and site location significantly affected grain yields at all three sites ($p<0.05$). No year-by-treatment or site-by-treatment interaction was found at any of the site-years (averages over site and year not reported).

Overall, grain yields responded to 90 kg N ha^{-1}. Split fertilizer applications generally resulted in higher grain yields at most sites. The increase in N fertilizer rate from 0 to 180 kg N ha^{-1} almost always led to greater grain yields (Table 6).

Even though the obvious response to N fertilizer was observed comparing the 0-N check treatment, a significant decrease in yield was observed when N was increased from 90 to 180 kg N ha^{-1} at some sites. For instance, in both 2005 and 2006 cropping years, treatment 4 (no N preplant, sidedress N at 90 kg ha^{-1} applied at V6 growth stage) produced significantly higher ($p<0.05$) grain yields versus treatment 5 (no N preplant, sidedress at 180 kg N ha^{-1} at the V6 growth stage) (Table 6). Likewise, comparing treatments 8 and 9 at Lake Carl Blackwell in 2005, when the sidedress application was delayed until the VT growth stage, application of higher N fertilizer rates resulted in decreased grain yields (Table 6).

NITROGEN USE EFFICIENCY

Statistical analysis showed that there was no year-by-treatment or site-by-treatment interaction associated with fertilizer N use efficiency for any crop year. Higher NUEs were achieved in 2005 and in 2007 compared to the 2006 cropping year (Tables 9, 10, and 11). The Lake Carl Blackwell site generally had higher NUE's than Efaw and Haskell in all years (Tables 9, 10, and 11). Greater than average worldwide estimated NUEs were achieved for 6 of 9 site-years. The lowest N use efficiencies were observed at Haskell 2005 and 2006, with extremely low NUEs in 2006 due to the low grain yield produced at this location regardless of the fertilizer N applied (Table 8). Similar results were observed at Efaw in 2007, where extremely low corn grain yields coupled with no pronounced response to fertilizer N resulted in very low NUEs. Overall, N use efficiencies increased with mid-season fertilizer N applications and with preplant applications followed by sidedress N at or before the V10 growth stage.

Positive response to preplant fertilizer apparent for the majority of site-years is exemplified in higher NUEs achieved with split N fertilizer applications compared to treatments that received no preplant and a one-time fertilizer application mid-season. Overall, higher NUE's were achieved with mid-season (growth stages V6-V10) N fertilizer applications. Decreased NUE's were observed when sidedress N was delayed until tasseling and higher fertilizer N rates.

Application of preplant N followed by a mid-season sidedress fertilizer N application at or before the V10 growth stage is recommended for corn.

Delaying N fertilization until mid- season supplies N at the time when the crops need for N and N uptake are at maximum, and thus facilitates more efficient N fertilizer use.

CONCLUSIONS

Generally, corn grain yields were maximized with 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at V6 or V10 (8 of 9 site-years).Therefore, when no preplant fertilizer N was applied, supplying sidedress N early in the growing season allowed for crop recovery. Analysis of data from 9 site-years demonstrated that there was no significant decrease in grain yield associated with delaying sidedress N application until V10 growth stage and tasseling when preplant N was applied. Application of preplant N provides essential nutrients for crop emergence and establishment.

However, delaying N fertilizer applications until later growth stages (V10-VT) generally resulted in decreased grain yields (6 site-years of 9) when no preplant N was applied, meaning that the crop failed to recover from N stress and failed to “catch-up” and produce maximum grain yields. Lower corn grain yields were observed for the treatments that received all fertilizer N preplant (3 site-years of 9). This could be due to N loss from the soil via leaching, erosion, and denitrification processes that are active during the fall-winter periods.

Nitrogen use efficiency was generally improved with mid-season N application at lower N rates. Highest NUE’s were achieved with 45 kg N ha^{-1} preplant followed by 45 kg N ha^{-1} sidedress applied at V6 growth stage (8 of 9 site-years) and at V10 (6 of 9 site-years). Lowest NUE’s were observed with higher N fertilizer rates and when all N was applied preplant.

Sidedress N delayed until V8 to V10 growth stages facilitates in-season plant nutrient evaluation and the determination of fertilizer N needed to be applied to achieve maximum grain yields based on the crop's yield potential.

The results of this study suggest that the optimum fertilizer recommendation in corn may be formulated as following: apply 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at or before V10 growth stage.

TABLES AND FIGURES

Table 1. Treatment structure for experiments conducted at Efaw, Lake Carl Blackwell, and Haskell, OK, 2005 - 2007.

Treatment	*Preplant N fertilizer application	†Sidedress N fertilizer application	
	N rate (kg ha $^{-1}$)	N rate (kg ha $^{-1}$)	Growth stage
1	0	0	-
2	90	0	-
3	180	0	-
4	0	90	V6
5	0	180	V6
6	0	90	V10
7	0	180	V10
8	0	90	VT
9	0	180	VT
10	90	90	V6
11	90	90	V10
12	90	90	VT
13	45	45	V10
14	45	45	V6

* Preplant N applied as ammonium nitrate (34-0-0) in 2005, as urea (46-0-0) in 2006, and as urea ammonium nitrate (28-0-0) in 2007.
† Sidedress N applied as urea ammonium nitrate (28-0-0).

Table 2. Initial surface (0-15cm) soil chemical characteristics and classification at Efaw, Lake Carl Blackwell, and Haskell, OK, 2005.

Location	pH	NH_4-N	NO_3-N	P	K	Total N	Organic C
		mg kg $^{-1}$				g kg $^{-1}$	
Efaw	5.87	13.86	3.74	20.14	89.50	0.65	10.24
Lake Carl Blackwell	5.63	28.40	4.35	45.10	144.00	0.76	9.87
Haskell	6.11	22.85	2.17	25.33	61.00	0.75	8.93

* pH – 1:1 soil: water; K and P – Mehlich III; NH_4-N and NO_3-N – 2 M KCl, Total N and organic C – dry combustion.

Table 3. Field activities including planting dates, seeding rates, cultivars, preplant soil sampling dates, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2005.

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 30	April 12	April 4
Cultivar	Pioneer 33B51	Pioneer 33B51	Triumph 1416Bt
Seeding rate (plants ha^{-1})	59,280	74,100	59,280
Preplant soil sampling date	March 30	March 28	April 4
Preplant N fertilization date†	March 30	March 28	April 4
Herbicide application date*	April 8	May 12	April 6
Sidedress N fertilization at V6‡	May 19	May 19	May 24
Sidedress N fertilization at V10‡	June 2	June 2	June 9
Sidedress N fertilization at VT‡	June 14	June 21	June 20
Harvest date	August 27	September 7	August 29
Rainfall (mm) *	509	581	449
Average air temperatures (C°)*	23	23	23
Average soil temperatures (C°)*	25	27	24

† Preplant N fertilizer was applied as ammonium nitrate (34-0-0). ‡ Sidedress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0). * Herbicide – Bicep II Magnum was applied at 930ml ha^{-1}. * Rainfall, average air and average soil temperatures for the period from planting through harvest.

Table 4. Field activities including planting dates, seeding rates, cultivars, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2006.

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 30	March 31	April 13
Cultivar	Pioneer 33B51	Pioneer 33B51	Pioneer 33B51
Seeding rate (plants ha^{-1})	61,750	79,040	54,340
Preplant N fertilization date†	March 30	March 31	April 13
Herbicide application date⁕	March 30	March 31	April 13
Sidedress N fertilization at V6‡	May 19	May 16	May 23
Sidedress N fertilization at V10‡	June 2	May 29	June 8
Sidedress N fertilization at VT‡	June19	June 12	June 21
Harvest date	September 1	August 18	August 31
Rainfall (mm)*	415	414	412
Average air temperatures (C°)*	25	24	27
Average soil temperatures (C°)*	26	27	26

† Preplant N fertilizer was applied as urea (46-0-0). ‡ Sidedress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0). ⁕ Herbicide – Bicep II Magnum was applied at 930ml ha^{-1}.

* Rainfall, average air and average soil temperatures for the period from planting through harvest.

Table 5. Field activities including planting dates, seeding rates, cultivars, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2007.

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 21	April 6	April 12
Cultivar	Dekalb DKC 50-20	Dekalb DKC 66-23	Pioneer 33B54
Seeding rate (plants ha^{-1})	54,340	79,040	59,280
Preplant N fertilization date†	March 21	March 19	April 12
Herbicide application date*	March 21	April 6	April 16
Sidedress N fertilization at V6‡	May 26	May 28	May 29
Sidedress N fertilization at V10‡	June 11	June 6	June 13
Sidedress N fertilization at VT‡	June 21	June 19	July 5
Harvest date	August 29	August 23	September 19
Rainfall (mm)*	1139	906	795
Average air temperatures (C°)*	21	21	21
Average soil temperatures (C°)*	20	21	21

Table 6. Treatment, preplant N, sidedress N, and mean grain yields and SED's for Efaw, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		Mean grain yield kg ha^{-1}		
	kg ha^{-1}		Growth stage	2005	2006	2007
1	0	0	-	6187	3799	1966
2	90	0	-	8181	6343	1977
3	180	0	-	8546	6913	2171
4	0	90	V6	7570	5754	2405
5	0	180	V6	9049	6577	3231
6	0	90	V10	7691	5467	2927
7	0	180	V10	7970	6370	2241
8	0	90	VT	8175	5829	2647
9	0	180	VT	8433	6713	2533
10	90	90	V6	9104	7116	2892
11	90	90	V10	9144	6600	2879
12	90	90	VT	9056	6153	2443
13	45	45	V10	8543	6835	2558
14	45	45	V6	8272	6813	2667
*SED				679	660	485

* SED – Standard error of the difference between two equally replicated means.

Table 7. Treatment, preplant N, sidedress N, and mean grain yields and SED's for Lake Carl Blackwell, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		Mean grain yield kg ha $^{-1}$		
	kg ha $^{-1}$		Growth stage	2005	2006	2007
1	0	0	-	8842	3001	6119
2	90	0	-	12862	6586	6496
3	180	0	-	13814	6405	7285
4	0	90	V6	14210	7482	7679
5	0	180	V6	13563	3141	8362
6	0	90	V10	12852	4141	7900
7	0	180	V10	13927	7468	7163
8	0	90	VT	12571	6158	7476
9	0	180	VT	11454	4868	7367
10	90	90	V6	14228	7971	6830
11	90	90	V10	14345	9073	6598
12	90	90	VT	14502	8127	6270
13	45	45	V10	13405	5579	6852
14	45	45	V6	13683	6094	7007
*SED				759	1983	3338

* SED – Standard error of the difference between two equally replicated means.

Table 8.Treatment, preplant N, sidedress N, and mean grain yields and SED's for Haskell, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		Mean grain yield kg ha $^{-1}$		
	kg ha $^{-1}$		Growth stage	2005	2006	2007
1	0	0	-	3029	3726	4644
2	90	0	-	4562	3079	10067
3	180	0	-	4720	2732	12776
4	0	90	V6	3889	2970	9843
5	0	180	V6	3279	3153	11025
6	0	90	V10	3537	3116	9487
7	0	180	V10	4168	3708	9807
8	0	90	VT	3483	3474	7897
9	0	180	VT	3401	3397	10121
10	90	90	V6	4742	3938	11332
11	90	90	V10	3730	3013	10572
12	90	90	VT	3720	2782	10646
13	45	45	V10	3973	3000	11127
14	45	45	V6	4519	3793	10559
*SED				476	463	1128

*SED – Standard error of the difference between two equally replicated means.

Table 9. Treatment, grain N uptake, and NUE for Efaw, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		2005		2006		2007	
	kg ha $^{-1}$		Growth stage	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %
1	0	0	-	78	.	44	.	19	.
2	90	0	-	113	37	83	42	26	7
3	180	0	-	129	28	95	28	31	5
4	0	90	V6	110	35	78	37	31	13
5	0	180	V6	143	36	97	29	50	12
6	0	90	V10	111	35	79	38	42	20
7	0	180	V10	119	22	96	28	36	5
8	0	90	VT	113	37	86	46	41	17
9	0	180	VT	128	27	100	30	41	8
10	90	90	V6	143	35	105	34	40	10
11	90	90	V10	142	35	99	30	44	10
12	90	90	VT	139	33	95	28	38	7
13	45	45	V10	123	48	92	53	35	15
14	45	45	V6	116	41	90	51	37	17
*SED				12	9	10	8	7	5

SED – Standard error of the difference between two equally replicated means.

Table 10. Treatment, grain N uptake, and NUE for Lake Carl Blackwell, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		2005		2006		2007	
	kg ha $^{-1}$		Growth stage	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %
1	0	0	-	106	.	40	.	50	.
2	90	0	-	181	81	84	49	101	35
3	180	0	-	201	53	98	33	130	29
4	0	90	V6	201	96	102	68	202	89
5	0	180	V6	207	56	53	11	263	65
6	0	90	V10	181	82	65	33	196	96
7	0	180	V10	210	58	112	38	100	16
8	0	90	VT	181	82	94	59	182	83
9	0	180	VT	176	39	78	20	254	57
10	90	90	V6	218	62	125	48	186	56
11	90	90	V10	222	64	132	50	131	30
12	90	90	VT	217	62	113	40	102	20
13	45	45	V10	195	94	85	48	194	98
14	45	45	V6	190	87	84	47	147	61
*SED				16	11	26	22	82	37

*SED – Standard error of the difference between two equally replicated means.

Table 11. Treatment, grain N uptake, and NUE for Haskell, OK, 2005 – 2007.

Treatment	Preplant N	Sidedress N		2005		2006		2007	
	kg ha $^{-1}$		Growth stage	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %	Grain N uptake, kg ha $^{-1}$	NUE, %
1	0	0	-	39	.	55	.	51	.
2	90	0	-	63	27	48	3	118	75
3	180	0	-	63	14	44	0	174	56
4	0	90	V6	56	20	46	0	124	72
5	0	180	V6	48	6	51	1	149	44
6	0	90	V10	48	11	48	0	132	67
7	0	180	V10	61	12	59	3	140	36
8	0	90	VT	47	10	53	2	110	45
9	0	180	VT	52	7	54	2	157	38
10	90	90	V6	69	17	61	5	153	46
11	90	90	V10	55	9	49	0	142	41
12	90	90	VT	54	8	46	1	155	42
13	45	45	V10	55	18	47	2	142	90
14	45	45	V6	65	29	58	6	134	82
*SED				7	6	7	3	20	15

* SED – Standard error of the difference between two equally replicated means.

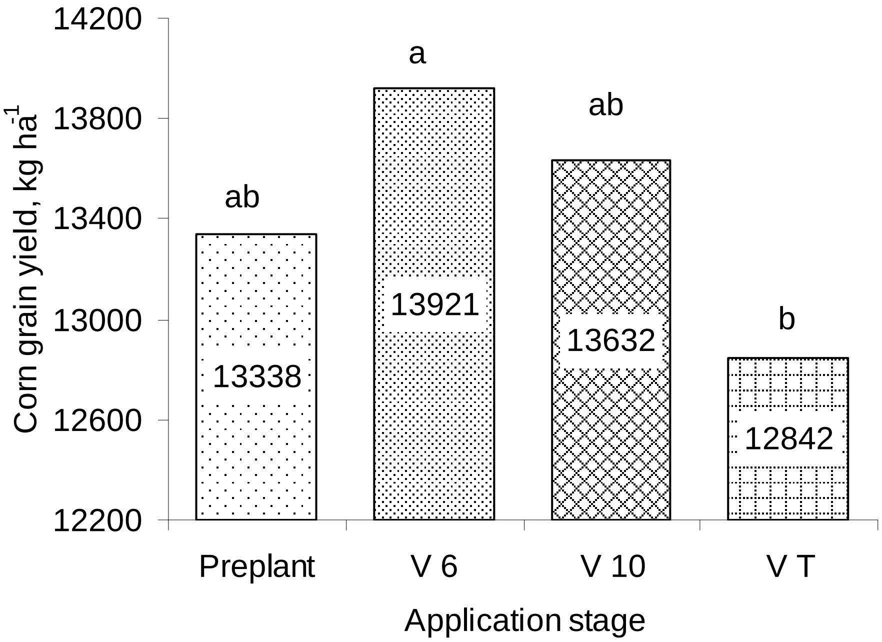

Figure 1. Corn grain yield as affected by time of fertilizer N application at Lake Carl Blackwell, 2005 averaged over N rates. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

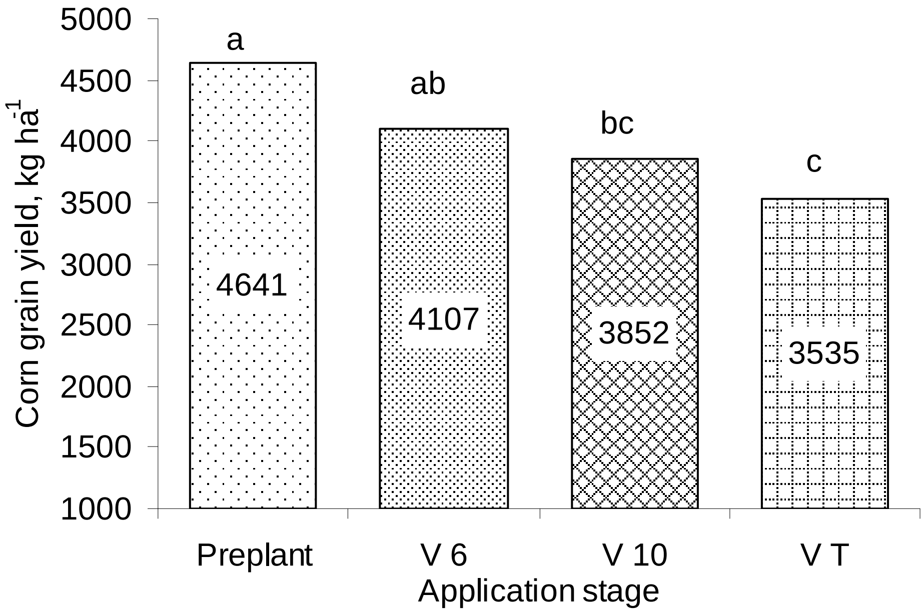

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Figure 2. Grain yield as affected by time of fertilizer N application at Haskell, 2005. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

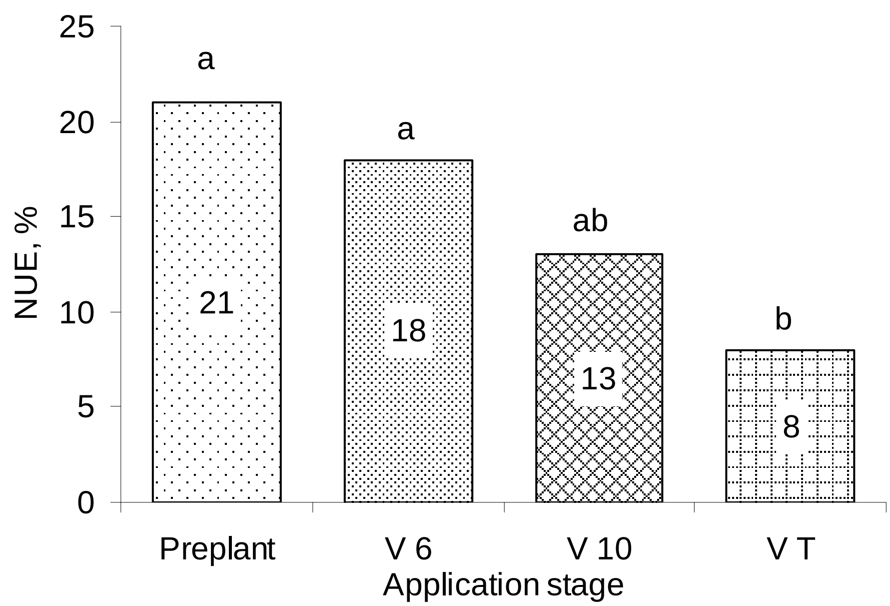

Figure 3. Fertilizer N use efficiency as affected by time of fertilizer N application at Haskell, 2005. Bars followed by the same letter are not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

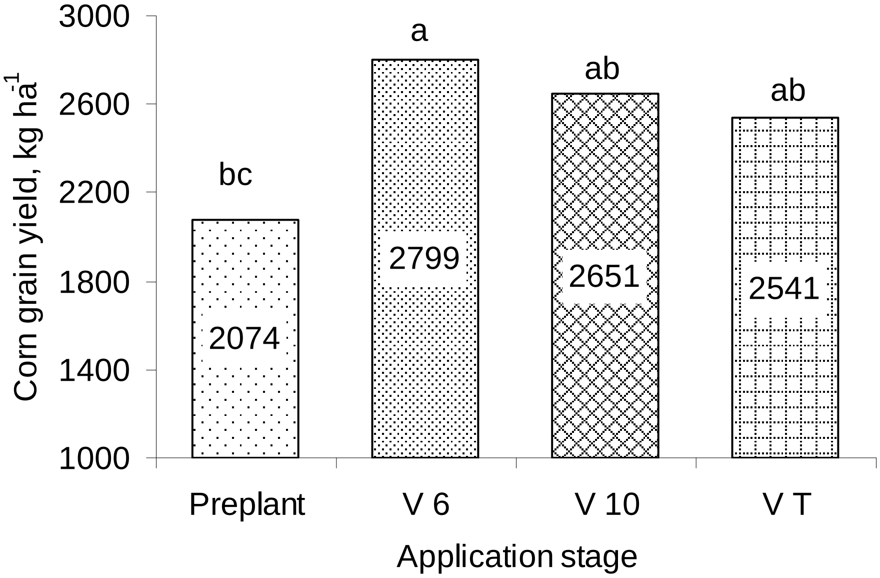

Figure 4. Corn grain yield as affected by time of fertilizer N application at Efaw, 2007 averaged over N rates. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

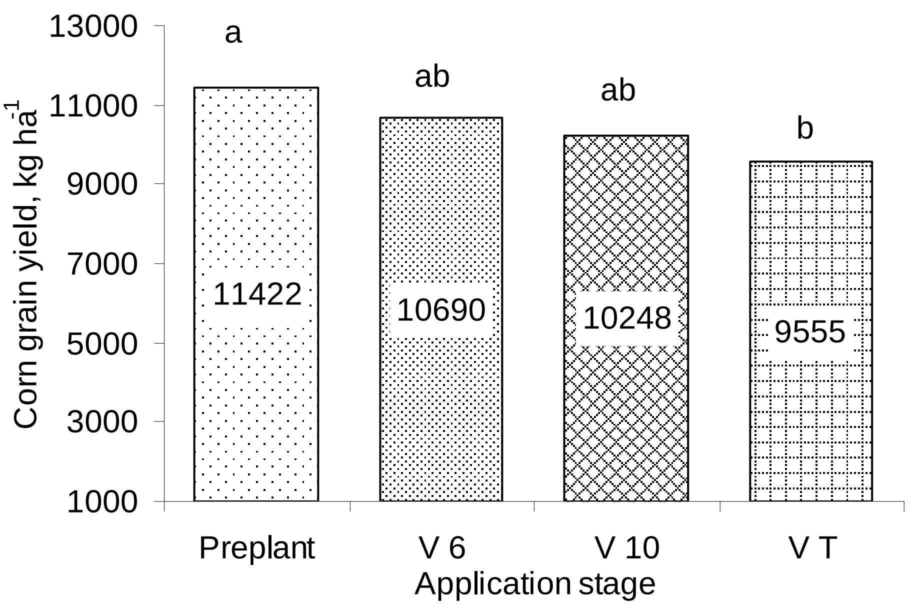

Figure 5. Corn grain yield as affected by time of fertilizer N application at Haskell, 2007 averaged over N rates. Bars followed by the same letter were not significantly different at $p<0.05$ using Least Significant Difference (LSD) mean separation procedure.

APPENDICES

Table A-1. Results of linear and quadratic polynomial orthogonal contrasts for corn grain yield at Efaw, Lake Carl Blackwell, and Haskell, 2005 – 2007.

Treatment	2005			2006			2007		
	Efaw	LCB	Haskell	Efaw	LCB	Haskell	Efaw	LCB	Haskell
Linear: sidedress at V6	***	***	ns	***	ns	ns	p<0.1	p<0.1	***
Quadratic: sidedress at V6	ns	***	p < 0.1	ns	*	ns	ns	ns	p<0.1
Linear: sidedress at V10	**	***	*	***	*	ns	ns	ns	***
Quadratic: sidedress at V10	ns	*	ns	ns	ns	ns	p<0.1	p<0.1	p<0.1
Linear: sidedress at VT	**	**	ns	***	ns	ns	ns	p<0.1	***
Quadratic: sidedress at VT	ns	**	ns	ns	ns	ns	ns	ns	ns
90 sidedress vs split at V6	ns	ns	ns	ns	ns	p < 0.1	ns	ns	ns
90 sidedress vs split at V10	ns	ns	ns	*	ns	ns	ns	ns	ns
180 sidedress vs split at V6	ns	ns	**	ns	*	ns	ns	ns	ns
180 sidedress vs split at V10	p < 0.1	ns	ns	ns	ns	ns	ns	ns	ns
180 sidedress vs split at VT	ns	***	ns	ns	ns	ns	ns	ns	ns

* - Significant at p< 0.05; ** - Significant at p< 0.01; *** - Significant at p< 0.001; p < 0.1 – Significant at 0.05<p<0.1; ns – Not statistically significant.

Table A-2. Results of orthogonal contrasts for NUE at Efaw, Lake Carl Blackwell, and Haskell, OK, 2005 – 2007.

Treatment	2005			2006			2007		
	Efaw	LCB	Haskell	Efaw	LCB	Haskell	Efaw	LCB	Haskell
90 sidedress vs split at V10	*	*	*	*	ns	ns	*	ns	**
180 sidedress vs split at V6	ns	ns	ns	ns	ns	ns	*	p<0.1	p<0.1
180 sidedress vs split at V10	ns	ns	ns	*	ns	ns	p<0.1	p<0.1	ns
180 sidedress vs split at VT	ns	*	ns	*	ns	ns	ns	ns	**

* - Significant at p< 0.05; ** - Significant at p< 0.01; *** - Significant at p< 0.001; p < 0.1 – Significant at 0.05<p<0.1; ns – Not statistically significant.

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APPENDIX D

EFFECT OF N FERTILIZER RATE AN APPLICATION TIME ON NITROGEN MINERALIZATION IN A CONTINUOUS WINTER WHEAT (*Triticum aestivum L.*) PRODUCTION

INTRODUCTION

Nitrogen mineralization (NM) - the process of decomposition of organic matter (OM) is the key process in the soil-plant nitrogen (N) cycle governing N availability to plants (Barraclough 1997). Bohm (2007) emphasized that the dynamic nature of NM and its great spatial and temporal variability complicate the development of N fertilization recommendations. Shepherd et al. (1996) emphasized that deeper understanding of NM process is vital for generating accurate N fertilizer recommendations and to minimize environmental pollution risk due to overfertilization. Comprehension of microbial processes affecting NM rate would allow managing cycling of N within an agroecosystem more efficiently. An estimate of soil mineralizable N is needed to adjust N fertilizer recommendation (Kolberg et al., 1999). Carpenter-Boggs et al. (2000) emphasized the importance of accurate estimation of mineralizable soil N for determining crop's requirements for fertilizer N in any given cropping year. Benbi and Richter (2002) agree that estimates of N fertilizer rates should be based on crop N needs and the soil's ability to supply N, which is difficult to quantify exactly. They pointed out that inability to accurately assess the amount of N supplied by the soil in any give year are partly due to the fact that both the soil organic N and the soil microorganisms involved in NM are poorly characterized.

Soil fertility research has been mainly focused on optimizing N fertilizer rate and application time, whereas little attention has been paid to background N gains and losses due to N cycling processes within the soil (Nelson and Griffith, 2000). Developing site-specific N fertilizer recommendations is vital to understand how the existing field conditions affect NM. Mullen et al. (2003) discussed the importance of developing indices for evaluation of NM potential. They noted that more accurate N fertilizer application recommendations could be made if NM potential for every given growing season was known. Most recently, Luxhoi et al (2006) stated that estimation of net NM is vital for synchronization of N supply with plant N requirements.

Ma et al. (1999) described nitrogen use efficiency (NUE) as a “measure of the extent to which a crop transforms available N to economic yield”. They hypothized, that mineralization of organic amendments may improve NUE by increasing available N in the soil and minimizing soil N losses.

OBJECTIVE

The objective of this study is to evaluate the effect of N fertilizer rate and application time on NM in the soil.

MATERIALS AND METHODS

Long-term experiment 506 was established at Lahoma in the fall 2002 to evaluate the effect of N fertilizer rate and application time on NM in the soil. The experiment employed a split plot design with 4 replications. Five main plots within each replication (4.9 by 21.9 m with 6.1 m alleys) were split into 3 subplots (4.9 by 6 m with 1.8 m alleys). Five N rates (0, 33.6, 67.3, 100.9, and 134.5 kg N ha^{-1}) and two application times (preplant and topdress at Feekes 4-5 growth stage) were evaluated. Preplant fertilizer N was applied as ammonium nitrate - NH_4NO_3 (34-0-0) and topdress N was applied as urea ammonium nitrate - UAN (28-0-0). Phosphorus (P) and potassium (K) fertilizer was supplied to achieve a 100% sufficiency level. The treatments were rotated annually such that the subplots were treated the same over a 3 year period.

LITERATURE REVIEW

N MINERALIZATION – GENERAL INFORMATION

Nitrogen mineralization is the microbial-driven two-step process of transforming organic N into inorganic plant-available forms. Step one – ammonification - is carried out by both aerobic and anaerobic soil microorganisms and results in the formation of ammonium (NH^{+}_{4} -N). In step two -nitrification - ammonium can be further converted into nitrate (NO^{-}_{3} -N) mainly by aerobic microorganisms such as *Nitrosomonas* and *Nitrobacter*. The NM rate is the rate "at which organic N is made plant-available" (Crohn, 2004). It has been noted that ammonification rate in most soils is slower than the nitrification rate (Bohm, 2007).

TEMPORAL/SPATIAL VARIABILITY OF N MINERALIZATION

Nintrogen mineralization is influenced by multiple factors, mostly due to their affect on activity in the soil microbial community. Among the key factors are temperature (Myers, 1975; Marion and Black, 1987), soil water content (Myers et al., 1982; Bohm, 2007), organic composition of the crop residue, and soil properties (Whitmore, 1996; Gabrera et al, 2005). Several studies showed that an interaction exists between soil temperature and water content with regards to NM (Goncalves and Carlyle, 1994; Sierra, 1997; Knoepp and Swank, 2002).

Crohn (2004) stated that temperature fluctuations throughout the year cause variation in mineralized N release within a growing season "in a predictable pattern", and pointed out that knowledge of the temperature patterns is important for matching crop N demand with the soil plant-available N. He discussed the "idealized steady-state" which is reached when continuous addition of N fertilizers (such as manure) gradually increases the N pool in the soil, but then reaches a plateau. At steady-state, the amount of organic N added with fertilizer applications is approximately equal the amount mineralized N. Crohn (2004) pointed out that an idealized steady-state can be used as a tool for predicting the total amount of N mineralized in any given growing season since concentrations of organic N (even though they fluctuate during the year) are approximately the same on a particular date from year to year. On the other hand, Crohn (2004) emphasized that while the steady-state concept can be used as a general guide for N management, it does not reflect the crops response to N at any given time. He pointed out that both crop response to fertilizer N and N uptake vary greatly from establishment to maturity.

Bohm (2007) assessed spatial and temporal patterns of N mineralization throughout the growing season. He observed N mineralization to be the highest in May and declining rapidly later in the season. He noted that patches of high and low N mineralization "appear and disappeared during the season" and that they "were not found in the same areas month after month". Results by Bohm (2007) illustrated great complexity of processes within the plant-soil system affecting N mineralization potential in any given growing season.

Johnson and Raun (2003) evaluated grain yield response to applied N fertilizer in a 30 year long-term replicated trial. Grain yields and crop response to applied fertilizer N varied greatly year to year independent of the yield achieved in the previous growing season. Check plots yields did not show an apparent trend to decrease over time despite the fact that no fertilizer N was applied to these plots for over 30 years. They stated that response to N is highly dependent on non-fertilizer supply of N, including N contributed from the atmosphere with rainfall, and N mineralized from soil organic matter. Johnson and Raun (2003) proposed using a reliable mid-season predictor of response index (RI) to increase nitrogen use efficiency (NUE) in crop production.

N MINERALIZATION AND NUE

The difference method is often used for estimation of fertilizer N recovery by crops in field studies. The difference method entails subtracting the total N uptake from check plots from the total N uptake from the fertilized plots, and dividing by the amount of N applied with fertilizer. The assumption that NM, N immobilization, and other soil processes involving N, are the same for the check and the fertilized plots, may, however, lead to misinterpretation of fertilizer recovery data (Schindler and Knighton, 1999). Thus, assessing how fertilizer N application affects N transformations within the soil-pant system is crucial for refining N fertilizer recommendations as well as NUE estimation.

Developed at Oklahoma State University, calibration stamp and calibration ramp technology implies that applying various N rates prior or soon after planting provides a visual interpretation of N deposition and N mineralization for the period from planting to the time of mid-season topdress N application. Prescribing topdress fertilizer N application rates based on the crop's need for N and adjusting for the amount already present in the soil would increase NUE (Raun et al., 2005).

A qualitative understanding of soil and crop management effects on N supply and NM facilitated the development of Codes of Good Agricultural Practice and fertilizer application guidelines in the UK (Shepherd et al, 1996). A deeper quantitative understanding of NM process would allow N fertilizer recommendations to be refined.

N FERTILIZER APPLICATION AND N MINERALIZATION

Grower applied N fertilizer and soil mineralized organic N - are two key sources for crop N nutrition. Westerman and Kurtz (1973) stated that application of N fertilizer results in a priming effect on N mineralization rates. Results by Olson et al. (1979), however, did not confirm the priming affect hypothesis. More recently, Ma et al. (1999) observed the priming effect on soil mineral N in all treatments during the period of active vegetative plant growth.

Soil N fortification has the potential to promote NM and to increase plant-available soil N by direct fertilization and by changing soil OM and plant residue quality (Marion and Black, 1988; Fenn et al., 1996; Fenn et al., 2003; Vitousek et al., 1997; Currie, 1999; Padgett et al., 1999; Korontzi et al., 2000; Li et al., 2006; Vourlitis and Zorba, 2007).

Kolberg et al. (1999) studied the effects of N fertilizer rate and cropping intensity on soil N mineralization, including their relationship with precipitation, soil moisture, and air temperature. Results indicated that rotation with legumes increased the N mineralized from soil. They found that greater amounts of N were mineralized from unfertilized plots compared to plots with a history of N fertilization.

Application of N fertilizer may alter the pool of labile N in the soil (by decreasing residence time of plant residue in the soil) and temporarily increased activity of the soil microbial community. Carpenter-Boggs et al. (2000) evaluated soil net N mineralization in various crop production systems including continuous corn (Zea mays L.), corn - soybean (Glycine max (L.) Merr.), and corn – soybean - wheat (Triticum aestivum L.)/alfalfa (Medicago sativa L.) - alfalfa rotations. Results indicated that more net N was mineralized from check plots (no N applied) compared to fertilized plots.

A laboratory incubation study was carried out to assess the effects of NH_4 and NO_3 on mineralization of N from ^{15}N-labelled vetch (Vicia villosa Rotn) in Illinois. The addition of NH_4 and NO_3 significantly amplified mineralization of vetch N during a 40 day incubation (Azam et al., 1995). While N mineralization is rarely measured directly in agricultural soils, N mineralization is normally based on laboratory soil incubation results. Laboratory-based estimates obtained under stable controlled conditions are often poorly correlated to the actual net mineralization observed in agricultural soils under various climate and management conditions throughout the growing season (Nelson and Griffith, 2000).

Ma et al. (1999) conducted a study to quantify the effects of inorganic and organic N fertilizer application on seasonal N mineralization in the plant-soil system. They found that application of manure at high rates (100 kg N ha^{-1} of mineral N and up to 800 kg N ha^{-1} of total N) resulted in approximately 120 kg N ha^{-1} mineralized, compared to 130 to 170 kg ha^{-1} N mineralized after application of 200 kg inorganic N ha^{-1}. In general, the amount of net N mineralized during the growing season accounted for up to 50% of the plant N uptake in all treatments. Ma et al. (1999) showed that the potential loss of mineralized N was lower for organic fertilizer applied compared to inorganic fertilizer due to synchronization of soil N release with active N uptake by corn plants.

Christensen et al. (2001) discussed the fact that winter wheat (grown in rotation other crops) response to early-spring applied N fertilizer is strongly affected by the previous crop. Findings by Kjelgren (1985), Sebastian (1995), and Baloch (1998) suggest that variability in mineralizable soil N impact the effect of the previous crop on winter wheat N requirements.

Crohn (2004) suggested the addition of inorganic N fertilizer at higher rates during the winter to compensate for slow NM rates due to cool weather. He recommends reduced rates when inorganic N is applied during the summer in order to "meet overall farm nutrient management goals." This approach does not seem rational considering that fall-planted crops are in the state of dormancy in winter, and spring-planted crops are not likely to benefit from winter-applied N, since a considerable portion of it will be lost from the soil through various pathways including leaching (Sanchez and Blackmer, 1988), denitrification (Yadvinder-Singh et al, 1994), and immobilization (Malhi and Nyborg, 1991). On the other hand, mid-season sidedress N fertilization is more sensible since it entails basing N fertilizer rates on the actual crop needs and allows to supply N at the time when plants need it most and N uptake is at a maximum, which increases NUE.

Glendining et al. (1996) evaluated N mineralization data obtained from the 135-year long-term experiment at Rothamsted (UK). Using a computer model, they estimated after applying 144 kg N ha^{-1} for 140 years, approximately 50% of the N mineralized each year was fertilizer N-derived. They observed that NM was up to 60 % greater for the high-N rate treatment (144 kg N ha^{-1}) compared to unfertilized check plots.

Rasmussen et al. (1998) reported that mineralized N, as a portion of the total soil N, was increased by addition of higher fertilizer N rates, with greater cropping frequency, and reduced tillage. They observed a linear increase in NM as a function of previous N fertilizer application. Rasmussen et al. (1998) hypothesized that a substantial portion of N applied in the past may be gradually recovered in the crop over time. They noted that, due to the effect of residual N on plant growth, the fertilizer N demand for optimum yield may not increase as rapidly as expected.

Evaluation of short- and long-term fertilizer N management on grazed pasture soils showed that NM (gross and net) was higher in a long-term fertilized soil compared to a soil which had never received fertilizer N. Short-term (one growing season) changes in fertilizer N input such as application of N to previously unfertilized soil, and withholding N from soil fertilized in the past, did not influence gross NM (Hatch et al., 2000).

Olff and Bakker (1991) noted that amount of plant-available N is determined by external inputs (including depositions from the atmosphere and application of N fertilizer) and by internal turnover within the plant-soil system governed by NM. They proposed that in soils heavily fertilized in the past, annual NM rates would continue to be high, declining not suddenly but gradually over time, meaning that N availability would also decrease gradually, until the “high quality” soil OM is used up.

Fertilizer application timing is important to consider and to adjust according to other agricultural practices such as tillage system used. Brouder (1998) suggested that application of starter fertilizer is considerably more important for no-till (NT) than tilled conditions because of slower NM and higher N immobilization occurring early in the growing season in NT systems.

Magdoff et al. (1984), Fox et al. (1989), and Magdoff et al. (1990) all agreed that monitoring NM rate would assist to better synchronize soil N availability with crop N requirements by adjusting mid-season fertilizer N recommendations. Tests such as pre-sidedress soil nitrate test (PSNT) or the late-spring nitrate test (LSNT) are often used to help account for the net effects of NM, leaching, and immobilization that may have taken place since the last crop harvest (Dinnes et al, 2005).

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Pages in Study: 249 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and Method of Study: I. The hypothesis was that soil moisture measurements would allow for more precise prediction of yield potential and more efficient N fertilizer use efficiency. The objectives were: to determine the effect of mid-season soil profile moisture on prediction of yield potential in winter wheat, and to establish the functional relationship for adjusting fertilizer N recommendations based on profile moisture and to refine the on-line Sensor Based Nitrogen Rate Calculator. Correlation of 64 parameters that incorporated soil moisture (WC and FWI) at 4 depths (5, 25, 60, and 75 cm) were evaluated to assess if soil moisture can assist to estimate winter wheat grain yield. II. The objectives were: 1. to determine whether foliar applications of P can result in increased corn grain yields and P uptake, and improve use efficiency; 2. to determine the optimum time for foliar P application in corn. Combinations of 2 P rates, 2 fertilizer application times, and 4 P sources were evaluated.

Findings and Conclusions: I. The results of this study showed that NDVI and INSEY were good predictors of grain yield in winter wheat for all site-years. All of the 64 indices incorporating volumetric water content and fractal water index were equally as good in predicting winter wheat grain yield for all site-years. II. In 2006 there were no statistically significant differences between any of the treatments. Many factors significantly affected corn grain yields in 2008. Phosphorus use efficiencies were very low for both growing seasons. This was due to lack of response to P fertilizer applied.

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