IN SEASON PREDICTION OF NITROGEN USE EFFICIENCY AND GRAIN PROTEIN IN WINTER WHEAT (*TRITICUM AESTIVUM L.*)

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Bachelor of Science in Agronomy

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2003

Submitted to the faculty of the Graduate
College of the Oklahoma State University
In partial fulfillment of the requirements for
The degree of
MASTER OF SCIENCE
May, 2012

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CHAPTER I

ABSTRACT & INTRODUCTION

Abstract

The algorithm presently used at Oklahoma State University for mid-season fertilizer recommendations utilizes an assumed nitrogen use efficiency (NUE) of 0.5. The recommended nitrogen (N) rate is calculated by subtracting N uptake without additional N from N uptake with additional N and dividing the difference by the NUE.

Also, many winter wheat producers in Oklahoma have at some point encountered protein related price deductions at the elevator. Knowing protein levels mid-season would allow farmers to make fertilizer adjustments in time to achieve optimal yield and protein levels. GreenSeeker NDVI readings have been successfully used to predict yield potential. In this two year study at three locations, GreenSeeker and SPAD meter readings were evaluated for their use in predicting NUE and grain protein in winter wheat. In addition, NUE, grain protein, and N uptake were evaluated as a function of rate and timing. Preplant treatments applied ranged from 28 kg ha^{-1} to 224 kg ha^{-1}. Selected treatments also included topdress rates of 28, 56, 84, 112 and 140 kg N ha^{-1}. GreenSeeker and SPAD readings were collected at Feekes (F) 3, 4, 5, and 7. Over two cropping seasons, Mid-season NDVI readings did not reliably predict NUE and were not highly correlated with

grain protein at all sites. Protein levels did increase with increasing N rate, and corresponding decreases in NUE.

Introduction

With the fast growing world population, which is projected to rise to 8.9 billion by 2050 (United Nations, 2004), and the subsequent increasing food demand, food producers worldwide have to think about and find more efficient ways to utilize agricultural resources. Fertilizer is without a doubt, one of the most expensive inputs in crop production (Baligar, 2001). As fertilizer nitrogen prices increase, it becomes important to carefully monitor the efficiency with which N is used by wheat and other crops. Nitrogen use efficiency (NUE) is a term used to indicate the relative balance between the amount of fertilizer taken up and used by the crop versus the amount of fertilizer lost (Nielsen, 2006). In other words, NUE implicates fertilizer recovery in a production system.

The algorithm for fertilizer recommendation developed at Oklahoma State University utilizes the predicted yield potential (YP0) and the response index (RI) to predict yield potential when N is applied (YPN). The fertilizer rate is calculated by dividing the difference in grain N uptake of YPN and YP0 by an estimated use efficiency (Raun et al. 2005). This NUE is subject to several environmental factors. Raun and Johnson (1999) noted that nitrogen (N) fertilizer losses due to gaseous plant emission, soil denitrification, surface runoff, volatilization and leaching are the main contributors to the low NUE in cereal grain production worldwide. Nielsen (2006) mentioned that the health of the crop and the combination of the frequency and severity of nitrogen loss are main factors affecting NUE. In other words the nitrogen balance and the response of the crop to added nitrogen are prime components in determining the NUE. A fact that producers should understand is that this nitrogen balance changes from year to year due to environmental factors. The year to year variability in the nitrogen balance and the changes in yield response cause variability in nitrogen use efficiency; a fact that has to be taken into consideration when making nitrogen recommendations.

Grain protein is an important quality component in cereal grains and is receiving increased attention due to protein discounts at the elevator. Research in Colorado has shown that grain protein content is a reliable indicator to determine nitrogen fertility in wheat production (Goos et al. 2008). According to Cassman et al. (1992) factors such as plant dry matter, accumulation of nitrogen, partitioning of dry matter and nitrogen between vegetative parts and grain determine the grain yield and N concentration or grain protein. The objectives of this study were to improve the estimation of NUE using mid-season NDVI readings at Feekes 3, 4, 5 and 7. A second objective was to evaluate the use of mid-season NDVI readings to predict grain protein levels.

CHAPTER II

LITERATURE REVIEW

The world cereal grain NUE is estimated at about 33%, with NUE’s of 42% and 29% in developed and developing countries respectively (Raun and Johnson, 1999). NUE’s in Sub Saharan Africa are found to be extremely high, with NUE’s of over 100 %, indicating mining of the N sources (Edmonds et al. 2009). Numerous definitions for NUE can be found in literature. Fageria and Baligar (2005) defined NUE as the maximum economic yield produced per unit of N applied, absorbed, or utilized by the plant to produce grain and straw. Other work described NUE as the grain dry weight or grain nitrogen as a function of N supply (Van Sanford and MacKown, 1986). Monitoring NUE is essential to guarantee optimum economic returns and for protection of the environment. Several factors affect NUE. Nielsen (2006) noted that crop health and the combined effect of the frequency and severity of nitrogen loss play a major role in affecting NUE. Several pathways in the uptake and utilization of N fertilizer cause a decrease in NUE (Huggins et al 2010; Moll et al. 1982; Huggins and Pan 1993). Fischer et al. (1993) mentioned that the inefficient utilization of applied nitrogen, might be due to a sufficient soil N supply, inhibited response affected by disease, water shortage or lodging.

NUE as Affected by Time and Rate of Application

It is well known that applying the right rate of fertilizer at the appropriate time is critical in determining NUE, as applying fertilizer in excess of what the plant needs or can take up, decreases NUE. Several workers reported increasing NUE's with low levels of applied N and decreasing NUE's with increasing levels of applied N (Gauer et al. 1992; Campbell et al. 1977). Campbell et al. (1993) found that NUE increased with cropping years at fertilizer rates smaller than 50 kg N ha^{-1} but would decrease when rates exceeded 50 kg N ha^{-1}. Gauer et al. (1992) observed a decreasing NUE with increasing N rates; ranging from 40 to 200 kg N ha^{-1}. This work reported an average NUE of 32.03% at 40 kg N ha^{-1} and an NUE of 15.49% at 200 kg N ha^{-1}under moderate moisture conditions. Delogu et al. (1998) noted a decrease in nitrogen utilization efficiency (defined as the ratio of grain yield and total N uptake) with increasing N rate. This study showed nitrogen utilization efficiency of 44 kg of grain per kg of N at 0 N, 36 at 140 kg N ha^{-1}and 31 at 210 kg N ha^{-1}.

Several works reported an increased NUE with split application of N fertilizer (Mahler et al. 1994; Destain et al. 1993; Papakosta and Gagianas, 1991). Other work reported higher N fertilizer loss when N was split applied (Randall and Mulla 2001; Baker and Melvin 1994). Blakenau et al. (2002) noted that increased N availability to the crop at critical growth stages increased NUE. Destain et al. (1993) found an increased NUE if the total amount of N fertilizer was applied in three separate portions instead of applying all at once. This work reported that N applied at ear emergence was more efficiently utilized by the grain (66%) compared with applications at tillering (30%) and at shooting (52%). The lower NUE's were attributed to increased levels of denitrification and leaching. Ellen and Spiertz (1980) found that split application between fall and spring increased NUE in hard red winter wheat. Wuest and Cassman (1992) found a greater NUE for late season versus preplant fertilizer N supply. Sowers et al. (1994) found equal or increased NUE values when fertilizer N was spring applied with point injection or topdressing at 84 and 112 kg ha^{-1} compared with all fertilizer N fall applied.

NUE as Affected by Environmental Factors

Several environmental factors, such as rainfall and temperature affect NUE, not only because of their effect on crop growth but also because of their role in soil-plant nutrient cycling processes. Hirel et al. (2007) argued that NUE is a function of factors such as climate, soil texture, the interaction between soil and microbes (Hirel et al. 2007; Walley et al., 2003; Burger and Jackson 2004) and attributes related to the available N pool (Hirel et al., 2007; Schulten and Schnitzer, 1998).

There are several pathways of loss such as denitrification, volatilization, gaseous plant losses (Harper et al., 1987; Francis et al., 1993), leaching (Randall and Mulla, 2001; Olson and Swallow, 1984) and surface run off that lead to lower NUE’s. Cassman et al. (2002) included moisture- and temperature regimes among other factors that affect NUE. Gauer et al. (1992) noted that an increase in soil moisture content could improve the NUE due to an increase in yield potential and improvement of the mobility of N in the soil. Campbell et al. (1993) noted an increase from 5 to 18 kilogram (kg) grain kg^{-1}N^{-1} at increasing moisture levels ranging from 150-300 mm with 100 kg ha^{-1}additional N. Another study showed NUE of 20.7 grams per gram of applied N when 15 grams of N m^{-2} was applied under irrigation (Asseng et al., 2001; Whitfield and Smith, 1992). Randall and Mulla (2001) noted that drainage water leaving the landscape is mainly a function of climatic conditions such as, temporal precipitation distribution, and soil properties. Aulakh and Singh (1997) noted that the two main factors controlling leaching losses of nitrate (NO_3^-) are the soil NO_3^- and the amount of water through the soil profile. However, not only N loss is governed by environmental factors, but N uptake as well. Factors such as temperature, pH and nitrate concentration in the soil solution affect nitrate uptake by the crop (Novoa and Loomis, 1981; Bassioni, 1971).

Plant Related Factors

When discussing NUE, processes within the plant, such as, assimilation, translocation and remobilization of N, have to be taken into consideration. Huggins and Pan (2003) subdivided NUE in several components, these included, economic indicators, environmental indicators and factors related to soil and plant physiology. In studies done with maize, Hirel et al. (2001) noted that variation in NUE at high levels of N was largely affected by variation in the ability of the crop to take up nitrogen. This same work showed that at low N levels variations in NUE were largely explained by nitrogen utilization efficiency (grain yield/nitrogen uptake). Cassman et al. (2002) showed that physiological N efficiency was mainly determined by the magnitude of variation in grain yield due to one increment change in N accumulation in the crop's vegetative parts. The authors argue that physiological N efficiency was mainly affected by the genetically predetermined photosynthetic pathway (C3 or C4) and by the grain N concentration, which can be determined by both genetics and N availability. Other studies have also shown that between different genotypes there can be significant differences in nitrogen absorption, assimilation and N recycling (Hirel et al., 2001; Masclaux et al., 2000). Craswell and Godwin (1984) found an average N recovery of 32% at N rates of 144 kg ha^{-1} between 1952 and 1967. With the introduction of high yielding varieties and several other improved cultural practices however, N recovery increased to 65%. According to studies, 60-95% of the grain N originates from stored N in roots and shoots accumulated prior to anthesis (Hirel et al. 2007; Palta and Fillery, 1995; Habash et al. 2006). Novoa and Loomis (1981) noted that part of the carbon and nitrogen in grain originated from assimilatory processes in leaves and from senescing plant biomass.

In addition to accumulation and storage of N, there are also several factors that contribute to the loss of N on a plant level thus rendering it unavailable for redistribution throughout the plant. Papakosta and Gagianas (1991) listed volatilization and leaching of mobile N from the tops of plants as being the most significant pathway of loss

Grain Protein

Grain protein is an important quality characteristic in cereal crops and largely determines their suitability for various end use purposes such as malting and baking. Low protein is desired for crisp or tender products such as crackers and snacks, while protein levels above 12.5%, such as found in hard red spring wheat, are desirable for bread making (US Wheat Associates, 2012). Soft white wheat varieties, mainly used for pastries, have low protein levels and are considered inferior if the protein exceeds 10% (Hunter et al., 1958). Grain protein levels in wheat thus determine its marketability and consequently the price that farmers receive at the elevator.

Grain protein levels are determined by a combination of genotypic and environmental factors such as nitrogen fertility, water and temperature (Terman et al., 1969; Stark et al., 2001). Several workers reported that N availability has proven to be the most important factor affecting grain protein levels (Woolfolk et al., 2002; Daigger et al., 1976).

Fertilizer Nitrogen and Timing of Application

Nitrogen is critical in the synthesis of amino acids which are the main components of all proteins (Brown, 2000). Research in Colorado has shown that grain protein was a good indicator to determine if nitrogen fertility was a limiting factor in the production of wheat (Goos et al., 2008). At N rates 0, 40, 80, 120, 160 and 200 kg ha^{-1} Gauer et al. (1992) found that protein concentrations increased from 12.90 to 15.82% under moderate moisture conditions. Under very wet conditions protein levels decreased at 40 kg N ha^{-1}, but increased at N levels higher than 40 kg ha^{-1}.

Protein concentrations in wheat are affected by the availability of nitrogen fertilizer and by application timing. According to Ellen and Spiertz (1980), nitrogen availability late in the season increases grain protein and yield. Cassman et al. (1992) stressed the importance of time of fertilization as an influential factor on yield goal and grain protein content. Split application increased the efficiency with which the crop utilized applied fertilizer (Woolfolk et al., 2002; Boman et al., 1995; Mascangi and Sabbe, 1991). Gauer et al. (1992) noted that applying higher N rates to increase the grain protein content was relatively inefficient, especially under dry soil conditions. Work by Wright et al. (2003) has shown that midseason N application at anthesis increased grain protein content by 0.3-0.4%. Rawluk et al. (2000) found consistently increasing grain protein levels, under different conditions, when fertilizer N was applied at anthesis. Fowler et al. (1990) reported that trials with variable timing of N application showed declining grain protein concentrations with late spring fertilizer N application.

Grain Protein and Weather Related Factors

Various works reported the influence of climatic factors such as temperature, radiation and soil moisture on grain protein levels (Woodard and Bly, 1998; Gauer et al. 1992; Sajo et al. 1992; Benzian and Lane, 1986). McNeal et al. (1978) concluded that environmental conditions affecting photosynthesis play an important role in regulating the synthesis of carbohydrates that become available for transport from leaves to the grain. Work by Terman et al. (1969) has shown that low moisture levels result in low protein content. Gauer et al. (1992), found a negative relationship between the moisture supply and protein content. This finding was in agreement with other studies showing an increase in grain protein levels with decreasing water supply (Fowler et al., 1990; Fowler et al., 2003; Rezeai et al., 2010). A study by Campbell et al. (1977) showed higher protein levels in spring wheat under conditions of moisture stress with additional N supply compared to irrigated field conditions. Under dryland conditions with no additional N application protein levels as high as 15.4% were reached, while under irrigated conditions with no additional N, the grain protein level was 14.1%. A study by Fernandez and Laird (1959) showed that at soil moisture levels of 34, 49 and 61%, respectively only N applications as high as 151 kg ha^{-1}would significantly increase grain protein content. Whereas under dry soil conditions, (soil moisture of 1%), an N rate as low as 51 kg ha^{-1} would significantly increase grain protein.

Grain Protein and Plant Related Factors

An increase in grain protein content may not only come from an increase in N fertility but also from an enhanced capacity of the grain to acquire N (Martre et al., 2003). Heitholt et al. (1990) noted that there are several plant traits, such as post anthesis N uptake, nitrogen harvest index and the leaf nitrate reductase activity, that affect grain nitrogen content. The significance of nitrate reductase as a factor affecting grain protein content was explained by Croy and Hageman (1970). This work explained that the assimilation of N to amino acids starts with reduction of nitrate by the enzyme nitrate reductase. The level of activity of this enzyme then becomes an indicator of the reduced nitrate that was available for protein synthesis in the plant.

Spiertz and Vos (1985) reported that 50 to 80% of the grain protein N originates from N present in vegetative parts, acquired prior to anthesis. Masclaux- Daubresse et al. (2010) reported that there is a close relationship between flag leaf senescence and grain nitrogen content. At senescence N was translocated from the stalk and leaves to the developing grain (Andersson and Johansson, 2006). Chloroplasts are an important source of N for movement to the grain and they also show the first signs of breakdown during senescence (Masclaux- Daubresse et al., 2010).

Grain Protein and Grain Yield

The inverse relationship between grain protein and yield is well documented (Evans, 1993; Woodard and Bly, 1998; Terman 1979; Loffler and Bush, 1982; Cox et al., 1985; Costa and Kronstad, 1994; Glenn et al., 1985; Terman et al., 1969; Schlehuber and Tucker, 1959). Huggins et al. (2010) reported that, in an optimal yield environment, higher levels of fertilizer N, decreased yield responses and increased grain protein levels. Sander et al. (1987) found that the amount of fertilizer N needed for maximum yields and the amount that will yield maximum protein levels are different.

Precision Sensing and Grain Protein

Several studies have assessed the use of remote sensing to estimate crop parameters such as leaf chlorophyll (Wright et al., 2004; Thomas and Gausmann, 1977; Curran et al., 1991; Munden et al., 1994), leaf area index (LAI) (Li et al., 2011; Serrano et al., 2000; Asrar et al., 1985), plant greenness (Wiegand et al., 1991; Pinter et al., 1987) and dry matter accumulation (Wright et al., 2004; Tucker 1981). Wright et al. (2004) reported that remote sensing could be an effective tool to evaluate the nitrogen status, and manage the protein content in wheat over large areas. Plant pigments, chlorophyll *a*, chlorophyll *b*, and β-carotene absorb blue and red light as energy source for photosynthesis (Jensen 2000; Wiegand et al., 1991). Under N limiting conditions, plants absorb less, which means they reflect more of the red light in the spectral region, due to the lower chlorophyll content (Serrano et al., 2003). Healthy vigorous plants with adequate N supply reflect less of the red light and more of the NIR light. Currently, remote sensing technology such as the global positioning system (GPS), Geographical

Information System (GIS) and soil- and crop sensors are being used in precision agriculture (Seelan et al., 2002). Lukina et al. (2001) found a positive correlation between NDVI readings, collected between Feekes growth stages 4 and 6, and final grain yield. Work by Raun et al. (2001) showed that in-season estimation of yield (INSEY), NDVI divided by the number of days from planting to sensing, was better correlated with wheat grain yield than was NDVI.

CHAPTER III

MATERIALS AND METHODS

Three winter wheat field experiments were established in 2009 and 2010 to evaluate NUE, grain protein, and N uptake as a function of rate and timing. These experiments were located at Lake Carl Blackwell, Lahoma and Hennessey. The experimental site at Lake Carl Blackwell is located on a Port silt loam; fine-silty, mixed, thermic Cumulic Haplustolls. The experimental site at Lahoma is located on a Grant silt loam; fine-silty, mixed, superactive, thermic Udic Argiustolls and the site at Hennessey is located on a Bethany silt loam; fine, mixed, superactive, thermic Pachic Paleustoll. The sites were planted in the fall of 2009 and 2010 using a 3 (m) meter Kincaid drill with row spacing of 15.24 centimeters. In 2009 planting at Lake Carl Blackwell took place on November 7, using the wheat variety ‘Endurance’. The Lahoma experiment was planted on October 28, using the ‘OK Bullet’ variety and planting in Hennessey was on October 6 with the ‘Overley’ variety. Plots were 6.096 m long and 3.048 m wide. The treatment structure was a randomized block design with 10 treatments in 4 replications. Treatments 2 through 10 all received a preplant treatment with urea ammonium nitrate, (UAN), (28-0-0) (N-P-K). Preplant N rates were 0, 28, 56, 112 and 168 kg ha^{-1}. Treatments 4 through

9 received an additional topdress application at rates of 28, 56, 84, 112, and 140 kg N ha^{-1} (Table 1a).The planting dates in 2010 were as follows: Lake Carl Blackwell planted on September 29, 2010 with ‘Centerfield’; Hennessey planted on October 1, 2010 with ‘Centerfield’; and Lahoma planted on October 6, 2010 using ’OK Bullet’. In 2010, 4 additional treatments were added. Treatment 11, 12, 13, and 14 received preplant N rates of 56, 84, 140, and 224 kg ha^{-1}(Table 1b), respectively with no additional topdress application. Preplant N at Lake Carl Blackwell, Lahoma and Hennessey, was applied on September 27, October 1, and September 29, respectively. Topdress applications were made on March 17 at Lake Carl Blackwell, March 16 at Lahoma and March 1 at Hennessey. UAN was applied with an ATV sprayer with a 3 m boom. NDVI and chlorophyll measurements were collected at growth stage F3, F4, F5 and F7 (Large 1954). NDVI measurements were taken with the GreenSeeker Hand Held Sensor (Trimble Navigation, Sunnyvale, CA). Chlorophyll readings were collected using a SPAD-502 (Konica Minolta sensing Inc.). The GreenSeeker calculates the NDVI as follows:

$$\frac{\rho NIR - \rho Red}{\rho NIR + \rho Red}$$

where, ρNIR and ρRed respectively are the fractions of emitted near infrared (NIR) and red radiation reflected back from the sensed area.

At maturity, plots were harvested using a Massey Ferguson 8XP self-propelled combine. Planting dates, variety planted, seeding rates, days after planting (DAP), and growing degree day (GDD) at sensing for each location are summarized in Table 2. Grain subsamples from each plot were collected for total N analysis using a LECO Truspec CN dry combusition analyzer (Schepers et al., 1989).

Nitrogen use efficiency was calculated using the formula:

$$\frac{(Grain\ N\ uptake\ treated - \ Grain\ N\ uptake\ check)}{N\ Rate\ applied}$$

Sensor readings collected at all stages, were combined with the use of climatological data available via the Mesonet (Oklahoma mesonet) and were evaluated for their use in predicting NUE and final grain protein content.

Statistical analysis was performed using SAS (SAS, 2003). Using the variables NDVI, SPAD , N rate and the in season estimation of yield (INSEY) as independent variables, regression and correlation were performed to see which variable best predicted yield, NUE and grain protein. INSEY was calculated as follows:

$$\frac{NDVI}{GDD}, \text{ where GDD} > 0$$

Linear models were generated for yield, NUE, protein and N uptake versus NDVI. To evaluate the change in N status in the crop over growth stage a delta NDVI (Δ NDVI) between growth stages was computed as:

$$\Delta NDVI = NDVI\ F7 - NDVI\ F3.$$

The use of ΔNDVI as a predictor of NUE and grain protein was evaluated by regressing delta NDVI versus NUE and grain protein.

Orthogonal contrasts were used to determine if there were significant differences between split- and single application.

CHAPTER IV

RESULTS

Since treatments differed between the 2009-2010 and 2010-2011 cropping seasons, the results of this study were analyzed by year and are reported by year and by location. The treatment structures for 2009-2010 and 2010-2011 are depicted in Tables 1a and 1b, respectively. Field activities including, planting dates, seeding rates, growth stage and growing degree days (GDD) at sensing at each location for both cropping years are reported in Table 2. Initial soil chemical properties for Lahoma, Lake Carl Blackwell and Hennessey for the 2010-2011 cropping season are reported in Table 3. Total rainfall numbers obtained from Lahoma and Lake Carl Blackwell Mesonet© stations are presented in Table 4. Treatment means and analysis of variance for Lahoma, Lake Carl Blackwell, and Hennessey for the 2009-2010 cropping season are reported in Tables 5, 6, and 7 respectively. Nitrogen uptake, grain yield, protein and NUE values as a function of total N rate are summarized in Table 8. Results for the Lahoma, Lake Carl Blackwell and Hennessey sites for the 2010-2011 season are reported in Tables 9, 10, and 11. A summary of the parameters N uptake, grain yield, protein and NUE for the 2010-2011 copping season, as it relates to total N rate is presented in Table 12. The results of linear, quadratic and orthogonal contrast for the 2010-2011 season are summarized in Table 13. In Table 14a and 14b the regression equations and the coefficients of determination between NDVI and SPAD readings collected at F3, F4, F5, and F7 with NUE are displayed. The results of linear, quadratic and orthogonal contrast for the 2010-2011 season are summarized in Table 13. In Table 14a and 14b the regression equations and the coefficients of determination between NDVI and SPAD readings collected at F3, F4, F5, and F7 with NUE are displayed.

Cropping Season 2009-2010

In January 2010, the Lake Carl Blackwell Mesonet ©station recorded 15 days with average temperatures below 0ºC, ranging from -12 ºC to -4 ºC.   The Lahoma Mesonet© station recorded 14 days with average temperatures between -12 ºC and -2 ºC for January 2010. In the following months temperatures and rainfall gradually increased, creating favorable conditions for recovery and growth of the crop.

Lahoma

Grain Yield

Grain yield levels ranged from 1724 kg ha^{-1} for the control treatment to 2674 kg ha^{-1}at 28 kg N ha^{-1} preplant combined with 140 kg N ha^{-1}topdress (Table 5). Yields were significantly different between treatments. The highest grain yields were obtained with split applications of fertilizer and the highest total N rate. These treatments include treatments 2, 5, 7, 8, 9, and 10 (Table 5). When grain yield was evaluated as a function of total N rate the results show an increase in grain yield up to 84 kg N ha^{-1}, and added N did not cause a further increase in yield (Table 8).

Nitrogen Use Efficiency

The highest NUE at Lahoma (33%), for the 2009-2010 cropping season was with an application of 28 kg N ha^{-1} preplant and a topdress application of 56 kg N ha^{-1}. When split versus single applications for a total N rate of 112 kg N ha^{-1} were compared, it was noted that greater NUE values were obtained when 112 kg N ha^{-1} was applied as 56 kg N ha^{-1} preplant and 56 kg N ha^{-1} topdress (27 %) or 28 kg N ha^{-1} applied preplant and an additional 84 kg of N ha^{-1} topdress (23%). Contrary to what was expected the application of only 28 kg N ha^{-1}preplant yielded the lowest NUE.

Grain Protein Content

Grain protein levels were significantly different between treatments. A split application of 28 kg N ha^{-1} and 140 kg N ha^{-1} yielded a grain protein content of 15.7% (Table 5). The lowest protein content observed at this location was 11.9% with an N fertilizer application of 28 kg ha^{-1}preplant. Grain protein content increased linearly with increasing total N rates, between 28 kg N ha^{-1} and 168 kg N ha^{-1}(Table 8).

Feekes 3, Feekes 5, and Feekes 7 NDVI

Feekes 3 NDVI values ranged from 0.39 to 0.49 with an average of 0.43. Feekes 5 NDVI values ranged from 0.37 to 0.55 with an average of 0.46, while F7 NDVI values ranged from 0.54 to 0.73 with an average of 0.66. At F3 and F5 the lowest NDVI values were measured in the control treatments, while the highest NDVI values were measured for the highest N rate (treatment 2). This was not the case for F7 NDVI, as no significant difference was observed for NDVI values between treatments (Table 5).

Lake Carl Blackwell

Grain Yield

Grain yields at Lake Carl Blackwell ranged from 2698 to 4007 kg ha$^{-1.}$ The highest yield, 4007 kg ha^{-1} was obtained with a preplant application of 168 kg N ha^{-1} (treatment 2) without additional topdress application (Table 6); while a split application of 28 kg N ha^{-1} preplant and 140 kg N ha^{-1} topdress only yielded 3190 kg ha^{-1}. A preplant application of 112 kg N ha^{-1} yielded 3844 kg ha^{-1}, while this same rate split applied as 28 kg N ha^{-1} and 84 kg N ha^{-1} yielded almost the same 3870 kg ha. This proofs that split application did not necessarily increase yield. One increment of added N (28 kg ha^{-1}) increased the grain yield by 1025 kg ha^{-1} compared to the control treatment. The highest yield corresponded with the highest amount of grain N uptake. Grain yield levels were not significantly different among treatments.

Nitrogen Use Efficiency

Notable, was a very high NUE of 86% for treatment 3, which included a preplant N rate of 28 kg N ha^{-1} without additional topdress application. The lowest NUE (17%) was found at a fertilizer application of 28 kg N ha^{-1} preplant combined with a topdress application of 140 kg N ha^{-1}(Table 6). A total N rate of 56 kg N ha^{-1} yielded an NUE value of 33%, a value similar to the NUE at Lahoma at this N rate (Table 8).

Grain Protein Content

As was observed at Lahoma, the highest grain protein content of 13.5% was obtained with a split application of 28 kg N ha^{-1} and 140 kg N ha^{-1}(Table 6). The lowest protein content of 9.8% corresponded with the lowest grain yield, in the control treatment. Grain protein levels increased with increasing total N rates. The highest grain yield of 3723 kg ha^{-1} corresponded with a protein content of 10.6% (Table 8). A total N rate of 168 kg N ha^{-1} yielded the highest grain protein content.

Feekes 3, Feekes 5, and Feekes 7 NDVI

Feekes 3 NDVI values ranged from 0.35 to 0.40, and were not significantly different. This might have been caused by limited N uptake early in the growing season due to the colder temperatures because as observed by Arkin and Taylor (1981) nutrient uptake is limited at low soil temperatures. Feekes 5 NDVI values ranged from 0.64 to 0.79, with an average of 0.72, while F7 NDVI values ranged from 0.67 to 0.86, with an average value of 0.77. At F5 and F7 growth stages, the lowest NDVI values were measured in the control treatment, while the highest NDVI values were measured at the highest N rate, 168 kg N ha^{-1}(Table 6).

Hennessey

Grain Yield

Grain yields were significantly different between treatments. Yields increased with 468 kg ha^{-1}compared to the control treatment, when only 28 kg of N ha^{-1} was applied preplant without additional topdress application (Table 7). Grain yield levels ranged from 2581 kg ha^{-1} to 4131 kg ha^{-1}. The highest yield was attained with 28 kg N ha^{-1} applied preplant with an additional 140 kg N ha^{-1} applied topdress; while 168 kg N ha^{-1} all preplant applied yielded only 2758 kg ha^{-1}, the opposite of what was found at Lake Carl Blackwell. In this a split application yielded more than a single preplant application.

Nitrogen Use Efficiency

As was the case at Hennessey, a preplant application of 28 kg N ha^{-1}, yielded the highest NUE. The highest NUE was 53%. A split application of 56 kg N ha^{-1} and 56 kg N ha^{-1} and the highest N rate (168 kg N ha^{-1}) yielded the lowest NUE of 14% at Hennessey. Notable was the fact that when NUE was averaged over total N rates, NUE values decreased with increasing N rate.

Grain Protein Content

A protein content as low as 9.2 % was observed in the control treatment (0N). The highest protein content of 13.4 % was obtained with a preplant N rate of 168 kg ha^{-1} without additional topdress N (Table 7). On average the highest N rate (168 kg ha^{-1}) yielded the highest grain protein content. As was observed at Lahoma and Lake Carl Blackwell, grain protein levels kept increasing with increasing N rate even when grain yield stopped increasing.

Feekes 4 and Feekes 5 NDVI

Feekes 4 NDVI values were not significantly different between treatments. Values ranged from 0.60, for the control treatment, to 0.68 for the treatment with168 kg N ha^{-1} all preplant applied. The average NDVI measured at F5 was 0.71, with values ranging from 0.65 to 0.78. Again as expected, the lowest NDVI value corresponded with 0 N applied and the highest NDVI value corresponded with the highest N rate applied.

Cropping Season 2010-2011

Climatic conditions during the 2010-2011 differed from the 2009-2010 season. Rainfall data retrieved from the Mesonet (Oklahoma mesonet) show that during the 2010-2011 there was less rainfall than during the previous season (Table 4). During early February, when the crop was tillering, a temperature as low as -31 ºC was recorded at the

Lake Carl Blackwell station. The Lahoma station recorded freezing temperatures ranging from -24 ºC to 0 ºC for 11 consecutive days during early February. These low temperatures combined with the low precipitation affected the growth and consequently the yield of the crop. When compared to the previous year yields in this cropping year were lower at all three experiment sites.

Lahoma

Grain Yield

Results showed significant differences in yield between treatments. Grain yield levels ranged from 1212 kg ha^{-1}, for the control treatment, to 2399 kg ha^{-1}, obtained with 224 kg N ha^{-1}(Table 9). Trend analysis showed a significant linear and quadratic relationship between grain yield and preplant N rate (Table 13), indicating a curvilinear relationship between preplant N rates and grain yield.

Nitrogen Use Efficiency

The highest NUE value at Lahoma, 28%, was observed with a split application of 56 kg N ha^{-1} preplant and 56 kg N ha^{-1} topdress (Table 9). The lowest NUE values were recorded with the highest N rates, 140, 168 and 224 kg N ha^{-1}. A split application of 28 kg N ha^{-1}preplant and 28 kg N ha^{-1} had a NUE of 25%. Single degree of freedom contrasts showed that there were significant differences in NUE between split- and single application (Table 13), with highest NUE values for split applications and the lowest values for single applications

Grain Protein Content

Grain protein percentages at this site for the 2010-2011 cropping season ranged from 9.6 to 14.7 %. A protein content of 9.9% was achieved without the addition of any fertilizer (control treatment) (Table 9). A protein content of 14.7% was obtained with a split application of 28 kg N ha^{-1} preplant and 56 kg N ha^{-1} topdress. Trend analysis showed that there was a significant linear relationship between preplant N rate and protein (Table 13). The results also show that there was a significant difference in grain protein content between split and single application.

Feekes 3, Feekes 5, and Feekes 7 NDVI

Feekes 3 NDVI values ranged from 0.38 to 0.56, with an average of 0.48, while F5 NDVI ranged from 0.39 to 0.58, with an average NDVI value of 0.48. In addition, NDVI collected at F7 had an average value of 0.43, with values between 0.39 and 0.47. This decrease in NDVI over time was likely due to environmental conditions (cold) that actually decreased biomass. On average, NDVI values at this site were lower than NDVI values at Lake Carl Blackwell and Hennessey.

Lake Carl Blackwell

Grain Yield

No significant difference was found in yield levels between treatments. The highest grain yield, 2554 kg ha^{-1}, was observed at a preplant N rate of 168 kg N ha^{-1} without additional topdress application (Table 10). Treatment 12 with a fertilizer N rate of 84 kg ha^{-1} all preplant applied resulted in the lowest yield of 1961 kg ha^{-1}. The control treatment did not always produce the lowest yields, as was observed at Lahoma and Hennessey.

Nitrogen Use Efficiency

A split application of 28 kg N ha^{-1} and 56 kg N ha^{-1} yielded the highest NUE of 25% at Lake Carl Blackwell (Table 10). The lowest NUE value was attained with a preplant N rate of 84 kg N ha^{-1}. Nitrogen use efficiency decreased from 17 to 3% when total N rate increased from 56 kg N to 224 kg N ha^{-1} (Table 12).

Grain Protein Content

Grain protein percentages ranged from 14.3% to 16.8%. The control treatment yielded the lowest protein content (Table 10). Grain protein levels increased with increasing total N rate between 0 and 140 kg N ha^{-1} (Table 12). There was significant difference in grain protein content when 112 kg N ha^{-1} was split or singly applied (Table 13).

Feekes 3, Feekes 5 and Feekes 7 NDVI

GreenSeeker NDVI values at F3 ranged from 0.57 to 0.67, with an average of 0.62. The average NDVI value at F5 growth stage was 0.76, while the average at F7 growth stage was 0.76. High NDVI did not always correspond with the highest N rate, neither did low values always correspond with the lowest N rates (Table 10). It needs to be noted however, that there was no significant difference between NDVI values as a function of the different N rates. This can be explained by the fact that the drought during this season affected the entire experiment and thus all of the treatments.

Hennessey

Grain Yield

Yield levels ranged from 1130 to 2130 kg $ha^{-1}$and were significantly different between treatments at the 5% level (Table 11). Grain yields increased linearly between the control treatment and a treatment of 28 kg N ha^{-1} with an additional 112 kg N ha^{-1}topdress. Increased N for either the topdress or preplant rate did not further increase yield levels, but rather caused a decrease in yield. Noticeable is that a preplant application of 224 kg N ha^{-1}gave the second lowest yield and the lowest NUE. This indicates that the application of one high N rate, all preplant applied, is inefficient; because as noted by Sowers et al. (1994), a one-time fall application of fertilizer prior to planting is more susceptible to losses such as denitrification and immobilization.

Nitrogen Use Efficiency

A NUE value as high as 37% was observed at Hennessey with an application of 28 kg N ha^{-1} and no additional sidedress application (Table 11). NUE decreased with increasing levels of total N (Table 12).

Grain Protein Content

As was observed at Lake Carl Blackwell, the lowest protein content corresponded with the control treatment. A grain protein content of 16.9% was obtained with a split application of 28 kg N ha^{-1} and an additional 140 kg N ha^{-1}topdress (Table 11). Grain protein levels increased with increasing N rates (Table 12). The 224 kg N ha^{-1} rate had a protein content of 18.4%.

Feekes 3, Feekes 5 and Feekes 7 NDVI

Early season NDVI readings (Feekes 3) at Hennessey were higher than Feekes 3 NDVI measurements at the other locations. These high NDVI readings are indicative of an optimal early season crop or biomass establishment; this could be attributed to the high initial soil NO_3^- levels found at Hennessey compared to the other sites (Table 3). Feekes 3 NDVI values ranged from 0.60 to 0.75; the lowest NDVI value corresponding with the control treatment (0 N) and the highest NDVI value corresponding with the highest N rate (224 kg N ha^{-1}). The average NDVI value at F5 was 0.68, while average NDVI at F7 was 0.70. At all three growth stages there was a significant difference in NDVI between treatments.

CHAPTER V

DISCUSSION

NDVI and Grain Yield

Data for the 2009-2010 cropping season, showed no significant relationship between NDVI at F3 growth stage, and grain yield for Lahoma and Lake Carl Blackwell (Figure 1). This was expected since early season cold temperatures limited N uptake. No F3 NDVI data was acquired at Hennessey in the 2009-2010 season. Feekes 4 NDVI for Lahoma showed a positive relationship with grain yield (Figure 2) with an r^2 of 0.15, while there was no significant relationship between F4 NDVI and grain yield at Hennessey. The subsequent growth stage showed an increased positive relationship with grain yield at all three sites when compared to earlier growth stages (Figure 3). The strongest correlation with NDVI at the F5 growth stage and grain yield was found at Lahoma with an r^2 of 0.36. Feekes 7 NDVI collected at Lake Carl Blackwell was positively correlated with grain yield while no relationship was found between F7 NDVI and grain yield at Lahoma (Figure 4).

In general grain yields in the cropping season 2010-2011 were lower than in the 2009-2010 season. This was due to the drought and the high temperatures during 2011, because as Johnson and Raun (2003) noted, temporal yield variability is greatly affected by differences in temperature and cumulative precipitation. With an r^2 of 0.30, F3 NDVI at Lahoma, showed the strongest relationship with grain yield in the 2010-2011 season, while no significant relationship was found between F3 NDVI and grain yield at Lake Carl Blackwell and Hennessey (Figure 5). Feekes 4 NDVI for Lahoma showed an even stronger relationship with grain yield with an r^2 of 0.39, while little correlation was found between NDVI at F4 and grain yield at LCB (Figure 6). The subsequent NDVI readings at Lahoma showed a strong relationship with grain yield (r^2=0.41), while again no significant relationship was found between NDVI and grain yield for Hennessey.

A strong relationship between NDVI and yield was expected because earlier work by Raun et al. (2001) showed that NDVI between F4 and F6 can be an excellent predictor of grain yield because at around F5 growth stage the majority of N has been taken up by the crop, 61 % as reported by Girma et al. (2011). An even further improvement was observed in the relationship between NDVI and grain yield at F7 for Lahoma.

It is notable, that in 2010-2011 at Lahoma there is a clear decrease in NDVI between growth stages, i.e. Δ NDVI is negative. This decrease in NDVI is indicative of a decrease in biomass due to drought conditions and this subsequently caused low yields. Delta NDVI at Lahoma was highly correlated with grain yield (r^2=0.93). When NDVI was normalized with growing degree days (GDD) there was no significant improvement in the relationship with grain yield.

When the relationship between grain yield and grain protein was evaluated, only at Hennessey for the 2010-2011 season was a negative relationship observed.

NDVI and Grain Protein

Feekes 3, NDVI data regressed against grain protein showed no significant relationship at Lahoma and Lake Carl Blackwell (Figure 9) for the 2009-2010 cropping season. A positive relationship (r^2=0.32) was found between F4 NDVI and grain protein for Hennessey, while F4 NDVI and grain protein showed no significant relationship at Lahoma (Figure 10). Feekes 4 NDVI data were not acquired at Lake Carl Blackwell during the 2009-2010 growing season. At the F5 growth stage an even stronger relationship was found between NDVI and grain protein at Hennessey (r^2 =0.47), while at Lahoma and Lake Carl Blackwell little correlation was found between F5 NDVI and grain protein (Figure 11).

The positive relationship between NDVI and grain protein found at Hennessey is somewhat surprising; keeping the inverse relationship between grain yield and grain protein in mind, it is expected that as NDVI increases, yield increases and protein decreases. Feekes 7 NDVI showed no significant relationship with grain protein at Lahoma and Lake Carl Blackwell for the 2009-2010 season (Figure 12).

Data for 2010- 2011 showed a negative relationship between F3 NDVI and grain protein for Lahoma, while Hennessey showed a positive relationship with an r^2 of 0.31 (Figure 13). No significant relationship was found between NDVI at F3 for Lake Carl Blackwell and grain protein. Feekes 4 NDVI collected at Lahoma was negatively correlated with grain protein, while these two parameters showed no significant relationship at Lake Carl Blackwell. No F4 NDVI data was acquired at Hennessey. Feekes 5 NDVI at Lahoma showed a negative relationship with grain protein (Figure 15), while no correlation was found between these two parameters at Lake Carl Blackwell. As was the case in the 2009-2010 growing season, NDVI data collected at Hennessey showed an increasing positive relationship with grain protein at subsequent growth stages (Figures 15 and 16). These results indicate that environmental and physiological factors need to be taken into consideration to improve the relationship between NDVI and grain protein; because as Freeman et al. (2003) notes, NDVI by itself cannot detect the translocation of N from the vegetative parts to the grain.

Grain Yield and Nitrogen Rate

The response to added fertilizer differed between sites and years. There was no consistent increase in grain yield with increased N rate. The results over the cropping season 2009-2010 showed that Lake Carl Blackwell had the highest average yield of 3479 kg ha^{-1}, while Lahoma had the lowest average yield (2387 kg ha^{-1}). At Lahoma and Hennessey the highest grain yield corresponded with a split application of 28 kg N ha^{-1} preplant and 140 kg N ha^{-1} topdress, while the highest grain yield at Lake Carl Blackwell was obtained with a single application of 168 kg N ha^{-1} preplant. For the 2010-2011 season Lake Carl Blackwell also produced the highest average yield; the highest yield at this location corresponded with a single preplant application of 168 kg ha^{-1}.

Grain Protein and Nitrogen Rate

In general, grain protein concentrations increased with increasing N rates. These results were expected, because as Goos et al. (1982) noted, under severe N deficient conditions, added increments of N would only increase crop yield and not grain N content, but as N fertility increased added increments of fertilizer N increased both yield and grain N content. The results show that the optimum total N rate to obtain the highest yield and highest grain protein content were different. In general the maximum yield would be obtained with a total N rate of 84, 112, 140 or 168 kg N ha^{-1}, while grain protein would keep increasing. Trend analysis showed a significant linear relationship between preplant N rates and protein content for all three sites (Table 13). In general, the increase in protein content corresponded with an increase in total N uptake. The results show that preplant N rates did have a significant effect on protein content contradicting findings by Strong (1982) who found that preplant N rates up to 200 kg ha^{-1} did not significantly increase grain protein. It needs to be noted that in the 2010-2011 season only at Lahoma did we find grain protein levels under 11%, the minimum level not penalized, a quality standard set by the Kansas City Board of Trade (www.kcbt.com). Over the two cropping seasons protein levels ranged from 9-19%.

NUE and Nitrogen Rate

When NDVI readings collected at F3, F4, F5, and F7 were regressed against NUE, no significant relationship was found (Tables 14a and 14b). It needs to be noted however that in 2010-2011 some correlation was found between NDVI and NUE at Hennessey (r^2= 0.19, 0.18, 0.30; F3, F5, F7, respectively). When evaluated as a function of N rate, NUE consistently decreased with increasing N rates at Hennessey. These results were expected since according to the law of diminishing returns yield response to additional nitrogen decreases as N rates increase. Nitrogen use efficiency computes the N removal as a function of N applied. The lower the yield response the lower the N removal i.e. the higher the N rate the lower the yield response and thus the lower the NUE. These findings are consistent with findings by Gauer et al. (1992) who found that NUE increased as N rates decreased. There were few instances where NUE, rose above the world cereal NUE of 33%. The inverse relationship between N uptake and NUE indicates that the crop takes up more nitrogen with increasing N rates but also loses more of this nitrogen. At Lahoma and Lake Carl Blackwell there was no consistent decrease with increasing N rates.

The results of this study indicate a difference in the relationship of NDVI and grain yield and NDVI and grain protein between sites. This difference validates the independent analysis of data across sites and years.

CHAPTER VI

CONCLUSIONS

The objectives of this study were to improve the estimation of NUE using mid-season NDVI readings and to evaluate the use of mid-season NDVI readings to predict grain protein levels. Mid-season NDVI readings collected at Feekes 3 (F3), F4, F5, and F7 were evaluated as predictors of grain protein and NUE at different N rates. In-season NUE is currently estimated at 0.5. Over two cropping seasons it was observed that NDVI readings collected at F3, F4, F5, and F7 did not reliably predict NUE. INSEY, which includes GDD and thus changes in growing conditions during the season, did not improve this relationship. Also, the relationship between NDVI and grain protein was not significant at every site; over two cropping season a significant relationship was only found at Hennessey.

Delta NDVI or the change in NDVI between F3 and F7 did show a relationship with grain yield, the trend however differed greatly between sites. This parameter however seems to be a promising parameter for future studies as changes in biomass will ultimately affect final grain yield.

Nitrogen fertility greatly affected nitrogen uptake and grain protein; they increased with increasing N rates. These increases corresponded with a decrease in NUE, indicating that the highest N rates resulted in the lowest NUE values. Split- or single application made almost no difference for NUE. Except at Lahoma, the highest NUE value was obtained with a single application of 28 kg N ha^{-1} in 2009-2010. For the 2010-2011 season the highest NUE was found with a single application of 28 kg N ha^{-1}.The results of this study suggest that the environment has to be accounted for to improve the prediction of grain protein and NUE. These results also show that NUE decreases as grain protein increases.

TABLES

Table 1a. Treatment structure for experiments conducted at Lahoma, Lake Carl Blackwell, and Hennessey, OK, 2009-2010

Treatment	Preplant N rate* (kg ha^{-1})	Topdress N rate* (kg ha^{-1})
1	0	0
2	168	0
3	28	28
4	28	56
5	28	84
6	28	112
7	28	140
8	28	56
9	56	0
10	112	0

*Preplant and topdress N rates were applied as urea ammonium nitrate (28-0-0)

Table 1b. Treatment structure for experiments conducted at Lahoma, Lake Carl Blackwell, and Hennessey, OK, 2010-2011

Treatment	Preplant N rate* (kg ha^{-1})	Topdress N rate* (kg ha^{-1})
1	0	0
2	168	0
3	28	0
4	28	28
5	28	56
6	28	84
7	28	112
8	28	140
9	56	56
10	112	0
11	56	0
12	84	0
13	140	0
14	224	0

*Preplant and topdress N rates were applied as urea ammonium nitrate (28-0-0)

Table 2. Planting dates, seeding rates, variety, growth stages, and growing degree days (GDD) used for SPAD and GreenSeeker measurements at Lake Carl Blackwell, Lahoma and Hennessey, Oklahoma, 2009-2011.

Location	Planted	Variety	Seeding rate (kg ha^{-1})	Harvest	Sensing date	Growth-Stage†	Timing (GDD)
			Cropping year 2009				
LCB	7 Nov	Endurance	101	30 June 2010	18 March	Feekes 3	64
					6 April	Feekes 4	-
					15 April	Feekes 5	89
					-	Feekes 7	-
Lahoma	28 Oct	OK Bullet	101	11 June 2011	18 March	Feekes 3	67
					30 March	Feekes 4	77
					1 April	Feekes 5	79
					20 April	Feekes 7	98
Hennessey	6 Oct	Overley	101	9 June 2011	-	Feekes 3	73
					24 Feb	Feekes 4	70
					15 March	Feekes 5	85
					31 March	Feekes 7	98
			Cropping year 2010				
LCB	29 Sept	Centerfield	101	8 June 2011	17 Feb	Feekes 3	77
					23 Feb	Feekes 4	82
					16 March	Feekes 5	98
					31 March	Feekes 7	110
Lahoma	6 Oct	OK Bullet	101	6 June 2011	23 Feb	Feekes 3	74
					3 March	Feekes 4	81
					15 March	Feekes 5	88
					29 March	Feekes 7	100
Hennessey	1 Oct	Centerfield	101	3 June 2011	15 Feb	Feekes 3	73
					-	Feekes 4	-
					23 Feb	Feekes 5	79
					22 March	Feekes 7	100

* Feekes 3 – tillers formed

** Feekes 4 – beginning of erect growth

± Feekes 5- strong erection of leaf sheaths

† Feekes 7 –second node visible

Table 3. Initial surface (0-15cm) soil chemical properties and classification for Lahoma, Lake Carl Blackwell, and Hennessey, Oklahoma, 2010.

Location	NO_3-N[a]	NH_4-N[a]	K[b]	P[b]	pH[c]	Total N[d]	C[d]
	mg kg^{-1}					g kg^{-1}	
Lahoma	14.3	5.7	20.2	3.6	6.33	0.72	5.43
Classification: Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustolls)							
Lake Carl Blackwell	10.7	3.6	101.5	55.2	6.67	0.49	5.29
Classification: Port silt loam (fine-silty, mixed, thermic Cumulic Haplustolls)							
Hennessey	21.8	4.2	558.5	135.5	5.35	1.02	5.43
Classification: Bethany silt loam (fine, mixed, superactive, thermic, Paleustolls)							

[a] NO_3-N and NH4-N: KCl extraction
[b] K and P: Mehlich III extraction
[c] pH: 1:1 Soil: Water
[d] Total N and Organic C: LECO Truspec CN dry combustion analyzer

Table 4: Total monthly rainfall during winter wheat growing months at Lahoma, Lake Carl Blackwell and Hennessey, Oklahoma.

	Lahoma		LCB	
Month‡	Rainfall, mm†			
	2009-10	2010-11	2009-10	2010-11
October	126.5	36.8	92.7	56.6
November	6.4	52.8	0.3	52.3
December	5.1	4.1	8.6	12.2
January	8.9	3.6	13.0	7.4
February	33.8	4.3	81.0	41.7
March	45.5	40.0	45.2	203
April	82.8	17.5	108.5	43.4
May	124.5	138.4	156.2	115.1
Total	433.3	288.3	505.5	349.0

† Monthly averages obtained from the Oklahoma Mesonet © 1994-2012.

‡ Winter wheat growing season begins in the fall and end in the summer of the following year

^ For Hennessey weather data from the Lahoma station was utilized

Table 5. Analysis of variance and treatment means for NDVI at Feekes (F)3, F5 and F7, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Lahoma, Oklahoma 2009-2010.

			F3 NDVI	F5 NDVI	F7 NDVI	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level						
Replication		3	0.0160*	<0.0001**	0.1720	<0.0001**	<0.0001**	0.0013**	0.0002**
Treatment		9	0.0228*	<0.0001**	0.2324	<0.0001**	<0.0001**	0.3562	<0.0001**
Treatments	Preplant	Topdress	Treatment means						
1	0	0	0.39	0.37	0.65	1724	38	-	12.5
2	168	0	0.49	0.55	0.72	2543	65	15	14.6
3	28	0	0.45	0.43	0.70	1889	39	4	11.9
4	28	28	0.46	0.44	0.60	2235	52	24	13.1
5	28	56	0.41	0.45	0.54	2612	66	33	14.3
6	28	84	0.40	0.45	0.64	2498	64	23	14.7
7	28	112	0.42	0.43	0.65	2537	65	19	14.6
8	28	140	0.42	0.45	0.73	2674	73	21	15.7
9	56	56	0.44	0.49	0.66	2653	69	27	14.7
10	112	0	0.46	0.52	0.70	2507	61	20	13.9
SED			0.03	0.02	0.07	135	4	10	1.4
C.V. (%)			9	7	15	8	8	71	4

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ʌ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 6. Analysis of variance and treatment means for NDVI at Feekes (F)3, F5 and F7, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Lake Carl Blackwell, Oklahoma 2009-2010.

			F3 NDVI	F5 NDVI	F7 NDVI	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level						
Replication		3	0.0075**	0.0262*	0.0037**	0.8511	0.8759	0.0016**	0.8456
Treatment		9	0.7238	0.0099**	0.0003**	0.5286	$0.0855^{\wedge}$	0.0055**	<0.0001**
	Preplant	Topdress	Treatment means						
1	0	0	0.35	0.64	0.67	2698	45	-	9.8
2	168	0	0.39	0.79	0.86	4007	93	29	13.3
3	28	0	0.35	0.72	0.77	3723	69	86	10.6
4	28	28	0.39	0.72	0.76	3353	64	32	10.8
5	28	56	0.40	0.73	0.75	3604	74	34	11.8
6	28	84	0.37	0.69	0.75	3870	82	33	12.1
7	28	112	0.38	0.70	0.75	3339	74	20	12.6
8	28	140	0.35	0.69	0.72	3190	75	17	13.5
9	56	56	0.38	0.74	0.79	3161	68	21	12.2
10	112	0	0.40	0.78	0.84	3844	85	36	12.7
SED			0.03	0.03	0.03	598	13	15	0.5
C.V. (%)			13	7	6	24	26	62	6

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ∧ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 7. Analysis of variance and treatment means for NDVI at Feekes (F)4, and F5, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Hennessey, Oklahoma 2009-2010.

			F4 NDVI	F5 NDVI	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level					
Replication		3	0.5014	0.3973	0.0450*	0.0651$^{\wedge}$	0.1150	0.6976
Treatment		9	0.3724	0.0462*	0.0191*	0.0134*	0.8853	0.0198*
	Preplant	Topdress	Treatment means					
1	0	0	0.60	0.65	2581	42	-	9.2
2	168	0	0.68	0.78	2758	65	14	13.4
3	28	0	0.60	0.67	3049	57	53	10.4
4	28	28	0.65	0.71	3220	64	39	11.3
5	28	56	0.64	0.69	3585	69	32	10.9
6	28	84	0.64	0.70	3788	80	34	11.9
7	28	112	0.66	0.72	3712	76	24	11.7
8	28	140	0.63	0.70	4131	86	26	11.9
9	56	56	0.63	0.69	3176	58	14	10.3
10	112	0	0.67	0.77	3532	73	28	12.0
SED			0.04	0.04	410	10	26	1.0
C.V. (%)			8	7	17	22	126	12

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ʌ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 8. Effects of N rates on N uptake, grain yield, grain protein and NUE at Lahoma, Lake Carl Blackwell and Hennessey, Oklahoma 2009-2010.

N applied ($kg\ ha^{-1}$)	N uptake	Grain yield	Grain protein	NUE
	$kg\ ha^{-1}$		%	
Lahoma				
0	38.3	1724	12.5	-
28	39.4	1889	11.9	4
56	51.7	2235	13.1	24
84	65.6	2612	14.3	33
112	64.7	2553	14.4	24
140	64.9	2537	14.6	19
168	69.2	2609	15.1	18
SED	6	228	0.6	13
CV (%)	15	13	6	89
Lake Carl Blackwell				
0	45.3	2698	9.8	-
28	69.5	3723	10.6	86
56	63.6	3353	10.8	33
84	74.3	3604	11.8	34
112	78.8	3625	12.3	30
140	74.0	3339	12.6	20
168	84.0	3598	13.4	23
SED	13	572	1.6	19
CV (%)	25	23	5	77
Hennessey				
0	42.2	2581	9.2	-
28	69.5	3049	10.4	53
56	64.0	3220	11.3	39
84	68.6	3585	10.9	31
112	70.5	3499	11.4	25
140	75.9	3712	11.7	24
168	75.6	3445	12.7	20
SED	12	488	1.0	27
CV (%)	24	21	12	129

SED – standard error of the difference between two equally replicated means;
CV- Coefficient of Variation

Table 9. Analysis of variance and treatment means for NDVI at Feekes (F)3, F5 and F7, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Lahoma, Oklahoma 2010-2011.

			F3 NDVI	F5 NDVI	F7 NDVI	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level						
Replication		3	0.1719	0.0652*	0.0002	0.5594	<0.0001**	0.0094**	0.1142
Treatment		13	0.0702^	0.0010**	0.2327	0.0002**	0.9348	0.56738	<0.0001**
	Preplant	Topdress	Treatment means						
1	0	0	0.44	0.41	0.39	1212	21	-	9.9
2	168	0	0.44	0.47	0.40	1814	42	12	13.1
3	28	0	0.50	0.48	0.41	1423	24	12	9.6
4	28	28	0.51	0.47	0.39	1865	35	25	10.7
5	28	56	0.38	0.39	0.41	1526	39	22	14.7
6	28	84	0.49	0.46	0.43	2020	47	23	13.3
7	28	112	0.49	0.46	0.45	2039	51	21	14.2
8	28	140	0.49	0.47	0.46	2152	52	18	13.8
9	56	56	0.46	0.48	0.41	2152	52	28	13.9
10	112	0	0.49	0.50	0.42	1906	39	17	11.9
11	56	0	0.46	0.48	0.44	1572	32	19	11.6
12	84	0	0.56	0.54	0.47	2045	37	19	10.2
13	140	0	0.49	0.50	0.42	1929	41	14	12.3
14	224	0	0.52	0.58	0.45	2399	51	14	12.4
SED			0.04	0.04	0.03	220	4	7	0.9
C.V. (%)			13	10	10	17	16	56	10

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ʌ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 10. Analysis of variance and treatment means for NDVI at Feekes (F)3, F5 and F7, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Lake Carl Blackwell, Oklahoma 2010-2011.

			F3 NDVI	F5 NDVI	F7 NDVI	Grain yield (kg ha^{-1})	N uptake	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level						
Replication		3	0.3160	0.7671	0.5147	0.0344	0.0395	0.1292	0.1967
Treatment		13	0.4907	0.1573	0.1399	0.3834	0.0524^	<0.0001**	0.0038**
	Preplant	Topdress	Treatment means						
1	0	0	0.63	0.73	0.73	2020	51	-	14.3
2	168	0	0.64	0.79	0.73	2554	72	13	16.1
3	28	0	0.60	0.76	0.76	2108	54	13	14.7
4	28	28	0.61	0.75	0.76	2142	59	15	15.6
5	28	56	0.58	0.74	0.75	2355	69	25	16.6
6	28	84	0.67	0.79	0.79	2421	69	16	16.1
7	28	112	0.66	0.75	0.80	2123	63	9	16.8
8	28	140	0.63	0.74	0.79	1981	56	3	16.1
9	56	56	0.57	0.74	0.77	2317	62	10	15.2
10	112	0	0.61	0.75	0.75	2119	59	7	16.0
11	56	0	0.61	0.78	0.76	2292	61	19	15.2
12	84	0	0.64	0.77	0.74	1961	51	1	14.9
13	140	0	0.62	0.76	0.75	2057	55	3	15.5
14	224	0	0.63	0.76	0.79	1991	57	3	16.4
SED			0.04	0.02	0.03	246	7	8	0.6
C.V. (%)			9	4	6	16	16	108	5

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ^ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 11. Analysis of variance and treatment means for NDVI at Feekes (F)3, F5 and F7, N uptake, grain yield, NUE and grain protein for winter wheat grown with various nitrogen rates at Hennessey, Oklahoma 2010-2011.

			F3 NDVI	F5 NDVI	F7 NDVI	Grain yield (kg ha^{-1})	N uptake	NUE (%)	Grain protein (%)
Source of variation		df	Sig. level						
Replication		3	<0.0001**	<0.0001**	$0.0662^{\wedge}$	0.0215*	<0.0001**	$0.6544^{\P}$	0.0411*
Treatment		13	<0.0001**	<0.0001**	<0.0001**	0.0419*	0.9348	0.0008**	<0.0001**
	Preplant	Topdress	Treatment means						
1	0	0	0.60	0.62	0.54	1130	21	-	11.9
2	168	0	0.73	0.74	0.80	1480	42	13	17.3
3	28	0	0.65	0.67	0.62	1450	24	37	13.4
4	28	28	0.64	0.66	0.66	1678	35	28	13.6
5	28	56	0.62	0.65	0.69	1728	39	24	14.6
6	28	84	0.64	0.66	0.71	2076	47	24	13.8
7	28	112	0.63	0.66	0.76	2130	51	23	15.0
8	28	140	0.64	0.67	0.78	1738	52	15	16.9
9	56	56	0.66	0.68	0.74	1701	52	20	15.7
10	112	0	0.70	0.72	0.72	1420	39	13	15.4
11	56	0	0.66	0.69	0.64	1519	32	23	13.7
12	84	0	0.67	0.70	0.67	1563	37	17	13.9
13	140	0	0.68	0.70	0.69	1468	41	11	15.2
14	224	0	0.75	0.77	0.83	1299	51	8	18.4
SED			0.01	0.01	0.01	269	4	6	0.8
C.V. (%)			2	2	3	24	16	41	8

SED – standard error of the difference between two equally replicated means;

CV- Coefficient of Variation

*, **, ʌ significant at 0.05, 0.01 and 0.1 probability levels, respectively

¶ ns

Preplant- Nitrogen rate applied before planting in kg ha^{-1}

Topdress- Nitrogen rate applied during the season in kg ha^{-1}

Table 12. Effects of N rates on N uptake, grain yield, grain protein and NUE at Lahoma, Lake Carl Blackwell and Hennessey, Oklahoma 2010-2011.

N applied ($kg\ ha^{-1}$)	N uptake	Grain yield	Grain protein	NUE
	$kg\ ha^{-1}$		%	
Lahoma				
0	20.9	1212	9.9	
28	24.3	1423	9.6	12
56	33.4	1718	11.1	22
84	37.8	1786	12.4	20
112	46.1	2026	13.0	23
140	45.7	1984	13.2	18
168	46.8	1983	13.5	15
224	51.0	2399	12.4	14
SED	5	229	1.2	8
CV (%)	17	17	13	62
Lake Carl Blackwell				
0	50.6	2020	14.3	-
28	54.3	2108	14.7	13
56	60.0	2217	15.4	17
84	59.8	2158	15.7	13
112	63.0	2286	15.8	11
140	59.1	2090	16.1	6
168	63.7	2267	16.1	8
224	56.8	1991	16.4	3
SED	8	272	1.8	11
CV (%)	18	18	6	151
Hennessey				
0	23.5	1130	11.9	
28	33.9	1450	13.4	37
56	37.6	1590	13.7	25
84	40.8	1646	14.3	21
112	44.8	1733	14.9	19
140	47.2	1790	15.1	17
168	46.9	1609	17.1	14
224	41.4	1299	18.4	8
SED	7	310	0.9	6
CV (%)	24	27	9	43

SED – standard error of the difference between two equally replicated means;
CV- Coefficient of Variation

Table 13. Results of linear, quadratic and orthogonal contrasts for grain yield, protein content and NUE at Lahoma, Lake Carl Blackwell, and Hennessey, Oklahoma, 2010-2011.

Contrasts	Grain yield	Protein	NUE
Lahoma			
Linear: preplant	***	***	NS
Quadratic: preplant	**	NS	NS
Split versus single application	*	***	**
split versus single application 56 kg N ha	*	NS	*
split versus single application 84 kg N ha	**	NS	NS
split versus single application 112 kg N ha	NS	NS	NS
split versus single application 140 kg N ha	NS	NS	NS
split versus single application 168 kg N ha	NS	**	NS
Lake Carl Blackwell			
Linear: preplant	NS	***	NS
Quadratic: preplant	NS	NS	NS
Split versus single application	NS	***	NS
split versus single application 56 kg N ha	NS	NS	NS
split versus single application 84 kg N ha	NS	NS	NS
split versus single application 112 kg N ha	NS	**	NS
split versus single application 140 kg N ha	NS	NS	NS
split versus single application 168 kg N ha	NS	NS	NS
Hennessey			
Linear: preplant	NS	***	***
Quadratic: preplant	NS	NS	**
Split versus single application	***	NS	NS
split versus single application 56 kg N ha	NS	NS	NS
split versus single application 84 kg N ha	NS	NS	NS
split versus single application 112 kg N ha	NS	NS	NS
split versus single application 140 kg N ha	NS	*	NS
split versus single application 168 kg N ha	NS	NS	NS

***, **, * significant at 0.01, 0.05 and 0.1 probability levels, respectively
NS- Statistically not significant

Table 14a. Relationship of NDVI, INSEY and SPAD at growth stages Feekes (F)3, F4, F5, and F7 to NUE at Lahoma, LCB, and Hennessey, Oklahoma 2009-2010.

Cropping season 2009- 2010				
Location		Growth stage	r^2	Linear regression
Lahoma	NDVI†	F3	0.011	Y = -39.13x + 37.8
		F4	0.001	Y = 6.60x + 18.0
		F5	0.010	Y = 29.69x + 6.8
		F7	0.015	Y = -20.40x + 34.2
	INSEY‡	F3	0.015	Y= -3038.2x + 40.6
		F4	0.001	Y= 613.13x+ 17.4
		F5	0.010	Y= 2348.30x+ 6.8
		F7	0.016	Y= -2085.9x + 34.7
	SPAD±	F3	0.017	Y= -0.86x + 62.9
		F4	0.011	Y= 1.00x - 20.7
		F5	0.003	Y= -0.41x + 38.6
		F7	0.021	Y= 1.05x - 27.4
Lake Carl Blackwell	NDVI	F3	0.002	Y = 25.90x + 24.6
		F5	0.031	Y = 89.52x – 30.8
		F7	0.050	Y = 101.13x – 44.2
	INSEY	F3	0.002	Y= 1492.30x + 25.6
		F5	0.032	Y=7289.50x – 32.0
		F7	0.049	Y= 9004.40x – 44.2
	SPAD	F3	0.028	Y= -1.96x + 113.7
		F5	0.035	Y= 2.09x – 54.8
		F7	0.020	Y= 1.55x – 35.2
Hennessey	NDVI	F4	0.008	Y = 70.64x - 16.82
		F5	0.016	Y = 83.92x - 30.7
	INSEY	F4	0.009	Y= 5004 x - 16.8
		F5	0.014	Y= 6749.90x - 27.5
	SPAD	F4	0.001	Y=-0.15x + 22.2
		F5	0.011	Y= 0.81x - 8.9

† NDVI= normalized difference vegetative index

‡ INSEY= $\frac{NDVI}{GDD}$, where GDD > 0

±SPAD= Chlorophyll content of leaves measured with the Konica Minolta SPAD 502 chlorophyll meter

Table 14b. Relationship of NDVI, INSEY and SPAD at growth stages Feekes (F)3, F4, F5, and F7 to NUE at Lahoma, LCB, and Hennessey, Oklahoma 2010-2011.

Cropping season 2010- 2011				
Location		Growth stage	r^2	Linear regression
Lahoma	NDVI†	F3	0.009	Y = -15.50x + 26.3
		F4	0.015	Y = -21.99x + 29.4
		F5	0.011	Y = -19.82x + 28.4
		F7	0.001	Y = -7.20x + 21.9
	INSEY‡	F3	0.010	Y= -1199.9x + 26.6
		F4	0.014	Y= -1702.40x+ 29.0
		F5	0.010	Y= -1672.20x+ 28.0
		F7	0.001	Y= -559.42x + 21.2
	SPAD±	F3	0.000	Y= -0.01x + 19.3
		F4	0.001	Y= -0.13x + 24.8
		F5	0.031	Y= -0.67x + 48.1
		F7	0.000	Y= -0.04x + 20.6
Lake Carl Blackwell	NDVI	F3	0.008	Y = 25.31x - 5.2
		F4	0.007	Y = 21.77x - 3.3
		F5	0.043	Y = 89.66x – 64.4
		F7	0.036	Y = 71.38x – 44.3
	INSEY	F3	0.009	Y= -2007.60x - 5.7
		F4	0.007	Y= 1655x - 2.9
		F5	0.037	Y= 8945.20x – 58.9
		F7	0.037	Y= 7931.90x – 44.9
	SPAD	F3	0.009	Y= -0.30x + 25.4
		F4	0.024	Y= -0.52x + 37.5
		F5	0.053	Y= 1.44x – 61.6
		F7	0.006	Y= 0.42x – 10.2
Hennessey	NDVI	F3	0.186	Y = -108.25x + 91.8
		F5	0.176	Y = -115.16x + 98.9
		F7	0.298	Y = -89.46x + 83.7
	INSEY	F3	0.181	Y= -7740.10x + 90.3
		F5	0.177	Y= -9125.40x + 99.2
		F7	0.296	Y=-8926.30x + 83.6
	SPAD	F3	0.009	Y= -0.77x + 54.0
		F5	0.028	Y= -0.32x + 35.5
		F7	0.092	Y= -0.90x + 64.5

† NDVI= normalized difference vegetative index

‡ INSEY= $\frac{NDVI}{GDD}$, where GDD > 0

±SPAD= Chlorophyll content of leaves measured with the Konica Minolta SPAD 502 chlorophyll meter

FIGURES

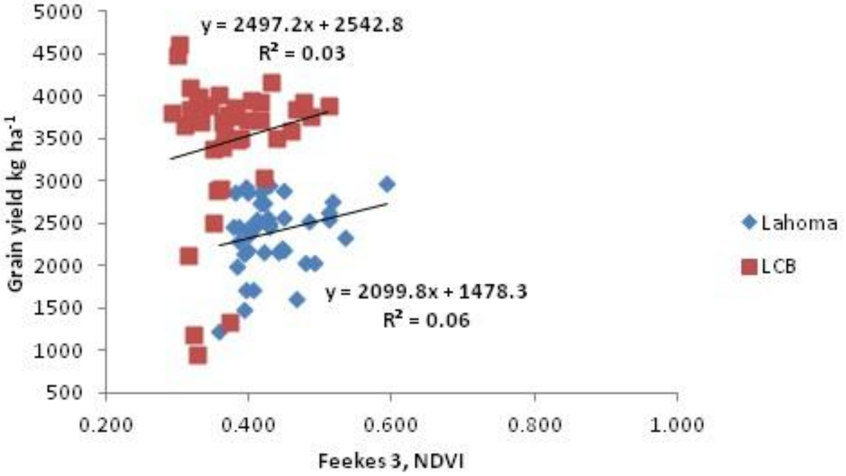

Figure 1. Relationship between NDVI and grain yield for growth stage Feekes 3, Lahoma, and Lake Carl Blackwell, 2009-2010.

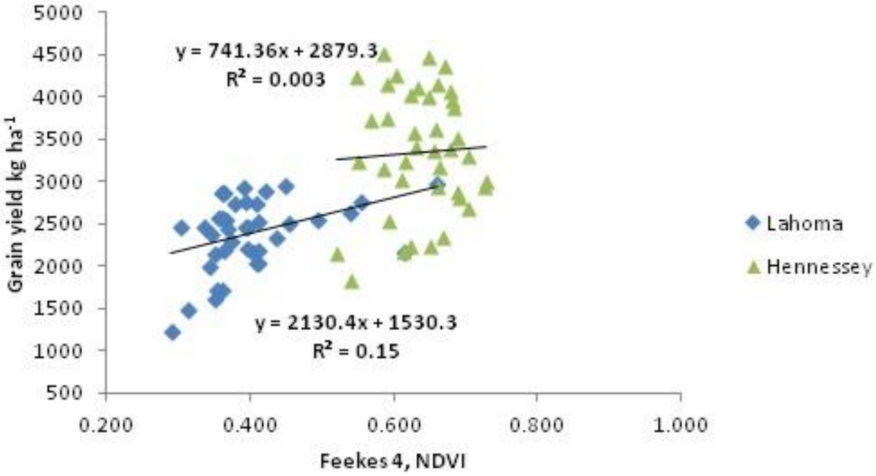

Figure 2. Relationship between NDVI and grain yield for growth stage Feekes 4, Lahoma, and Hennessey, 2009-2010.

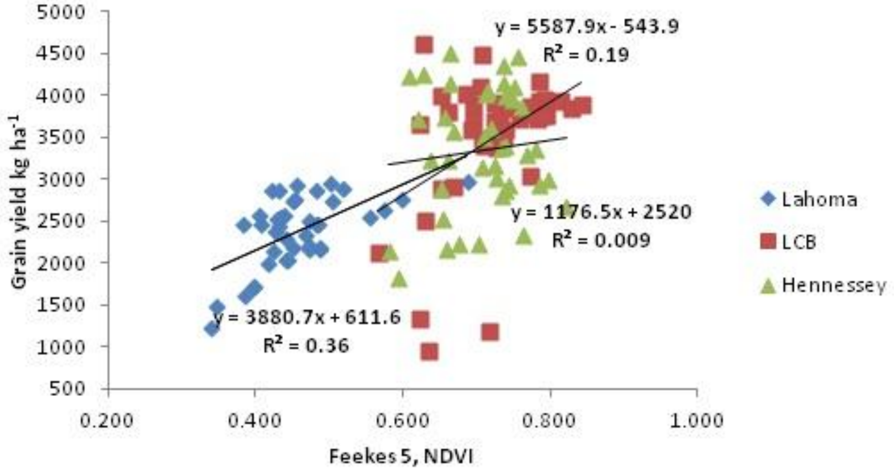

Figure 3. Relationship between NDVI and grain yield for growth stage Feekes 5, Lahoma, Lake Carl Blackwell, and Hennessey, 2009-2010.

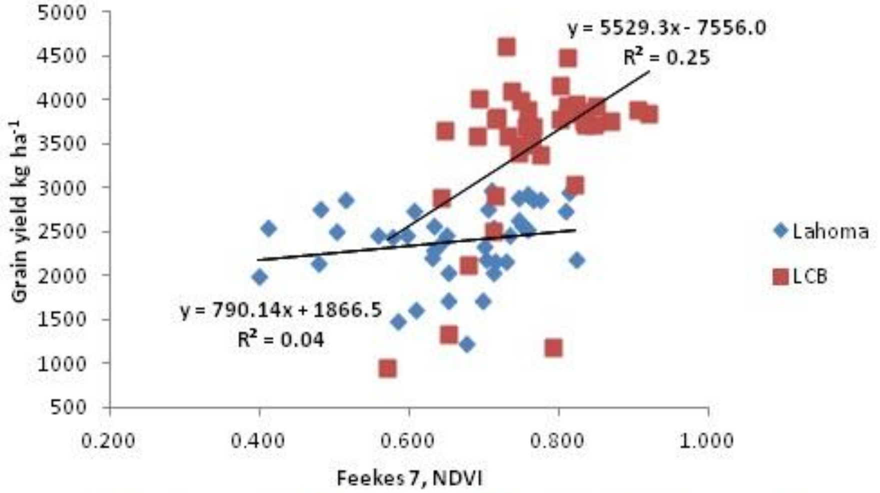

Figure 4. Relationship between NDVI and grain yield for growth stage Feekes 7, Lahoma and Lake Carl Blackwell, 2009-2010.

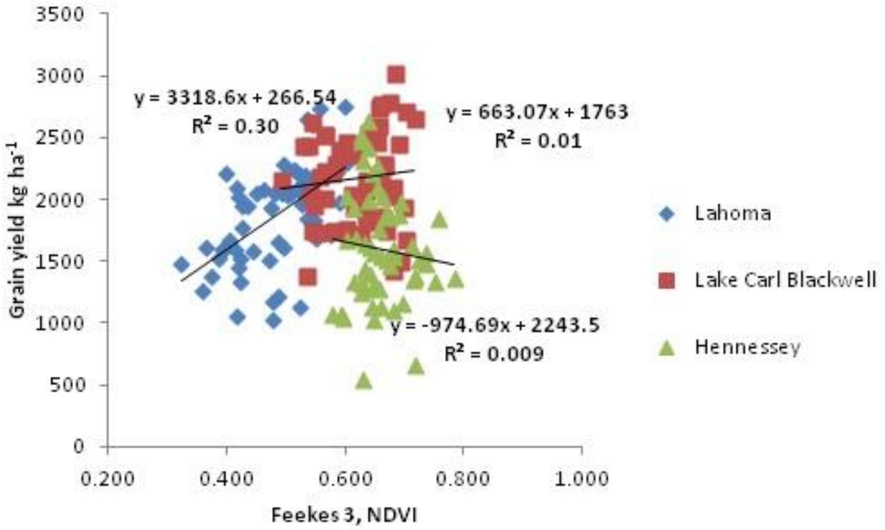

Figure 5. Relationship between NDVI and grain yield for growth stage Feekes 3, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

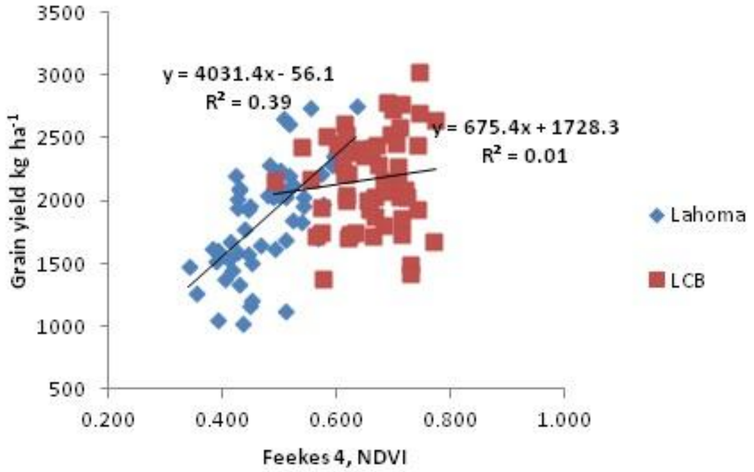

Figure 6. Relationship between NDVI and grain yield for growth stage Feekes 4, Lahoma, and Lake Carl Blackwell, 2010-2011.

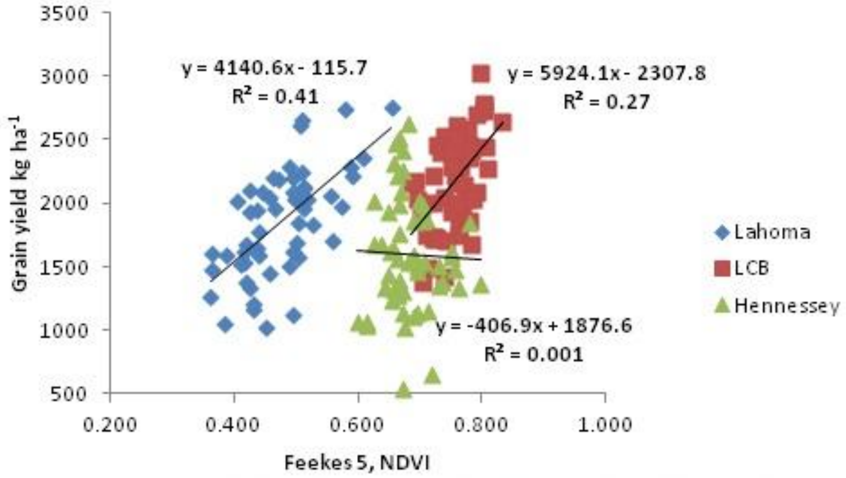

Figure 7. Relationship between NDVI and grain yield for growth stage Feekes 5, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

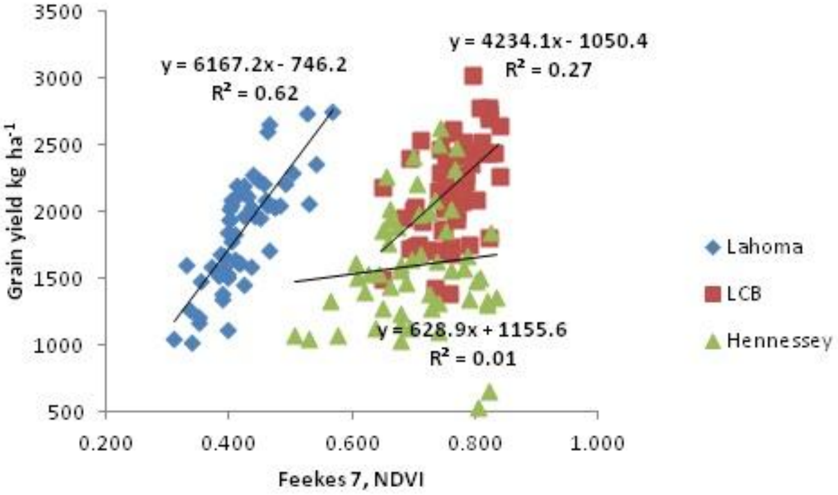

Figure 8. Relationship between NDVI and grain yield for growth stage Feekes 7, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

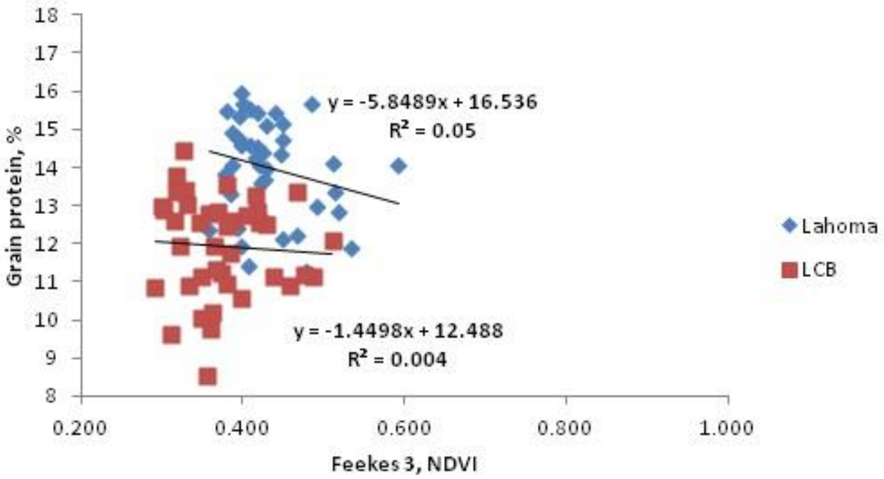

Figure 9. Relationship between NDVI and grain protein for growth stage Feekes 3, Lahoma and Lake Carl Blackwell, 2009-2010.

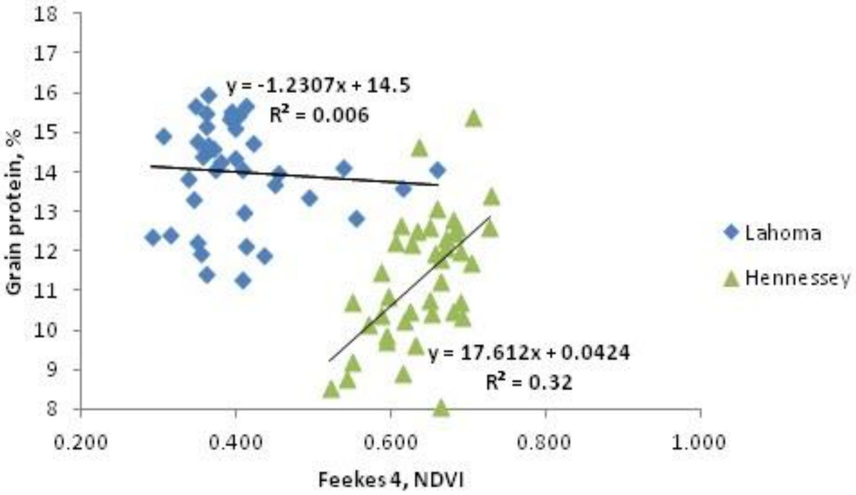

Figure 10. Relationship between NDVI and grain protein for growth stage Feekes 4, Lahoma and Hennessey, 2009-2010.

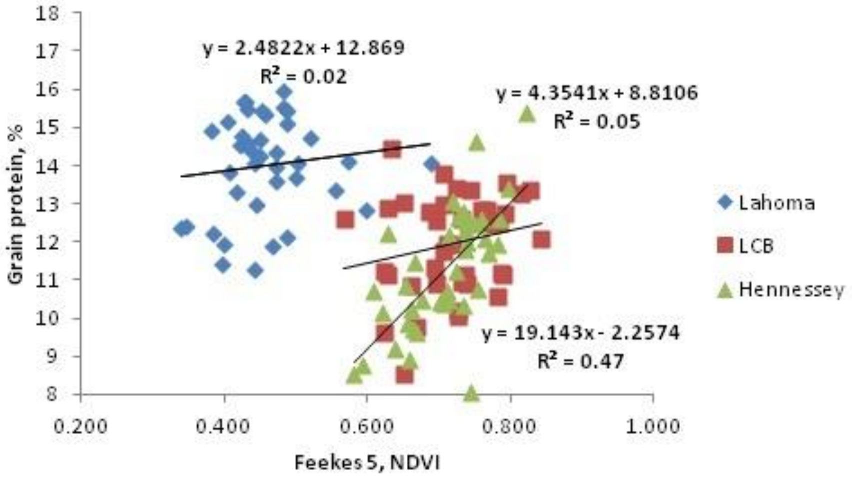

Figure 11. Relationship between NDVI and grain protein for growth stage Feekes 5, Lahoma, Lake Carl Blackwell, and Hennessey, 2009-2010.

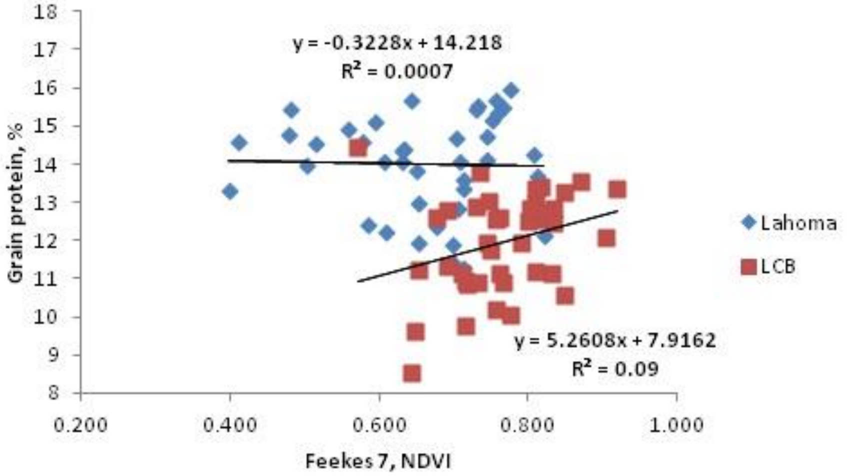

Figure 12. Relationship between NDVI and grain protein for growth stage Feekes 7, Lahoma and Lake Carl Blackwell, 2009-2010.

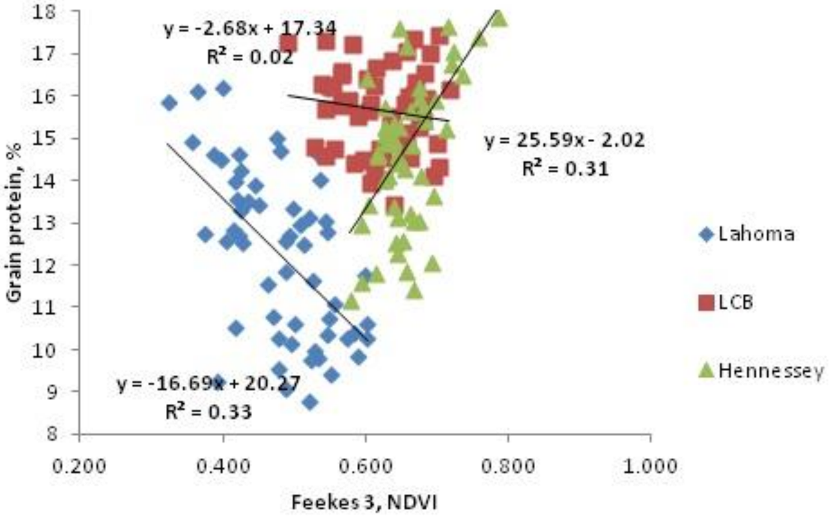

Figure 13. Relationship between NDVI and grain protein for growth stage Feekes 3, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

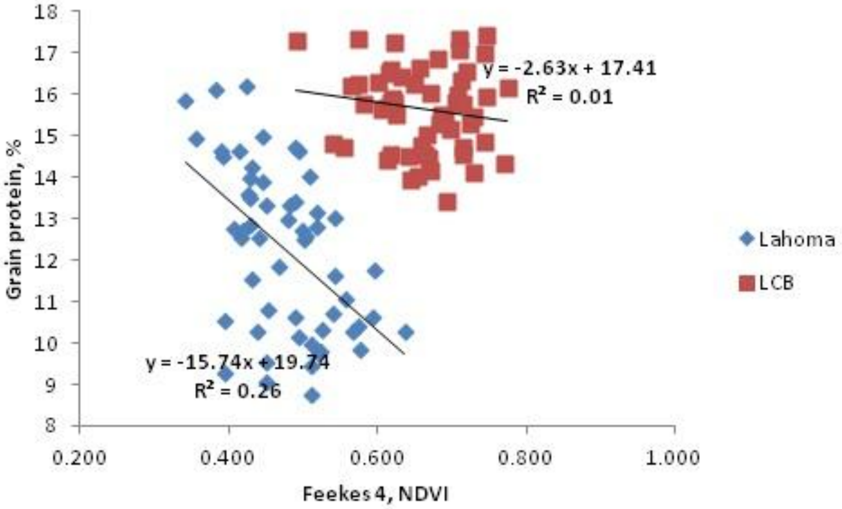

Figure 14. Relationship between NDVI and grain protein for growth stage Feekes 4, Lahoma and Lake Carl Blackwell, and Hennessey, 2010-2011.

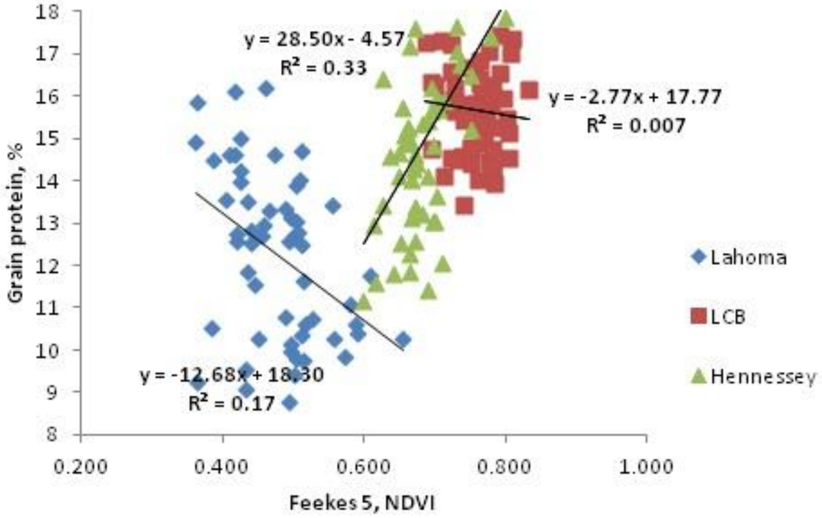

Figure 15. Relationship between NDVI and grain protein for growth stage Feekes 5, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

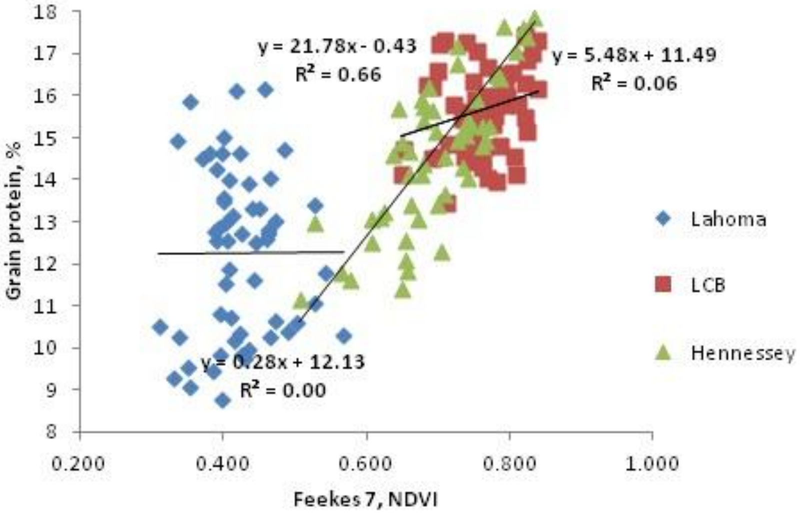

Figure 16. Relationship between NDVI and grain protein for growth stage Feekes 7, Lahoma, Lake Carl Blackwell, and Hennessey, 2010-2011.

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APPENDICES

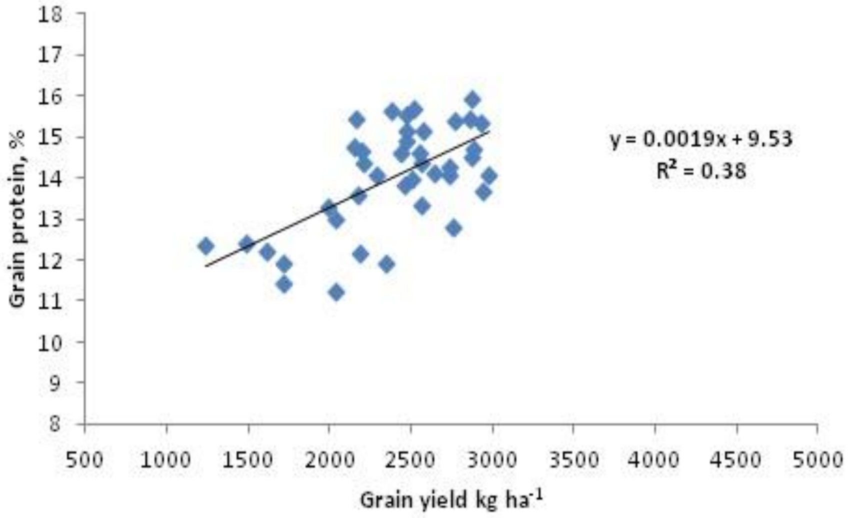


Figure A1: Relationship between grain yield and grain protein content at Lahoma, 2009-2010.

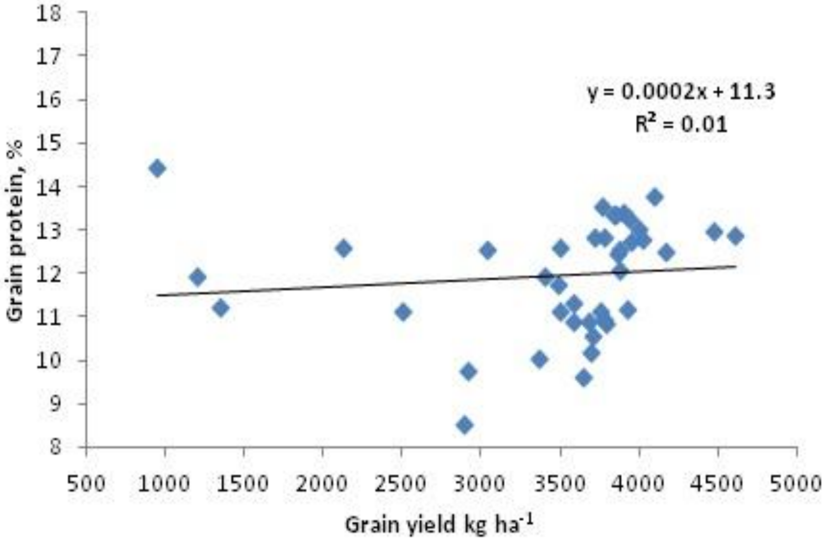
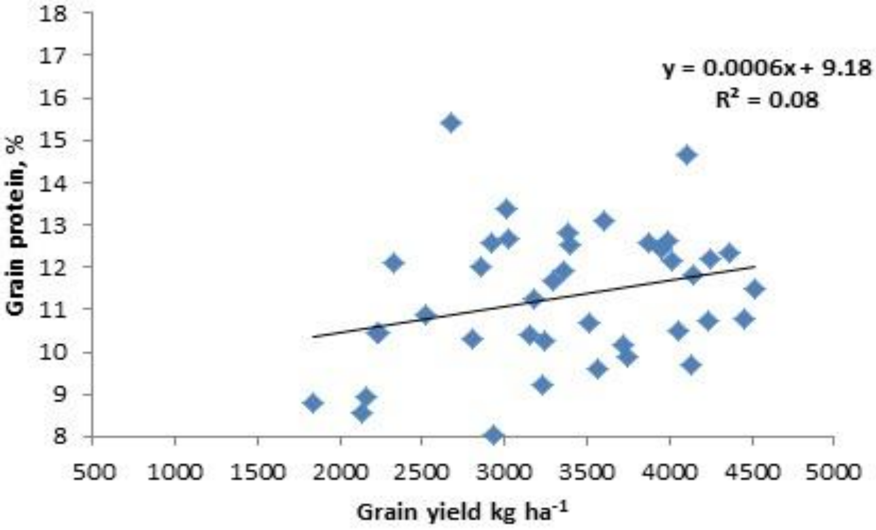


Figure A2: Relationship between grain yield and grain protein content at Lake Carl Blackwell, 2009-2010.



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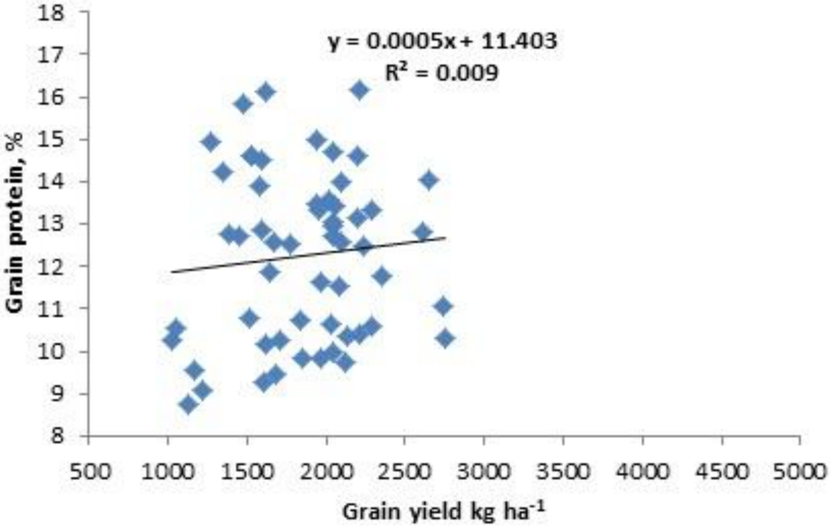

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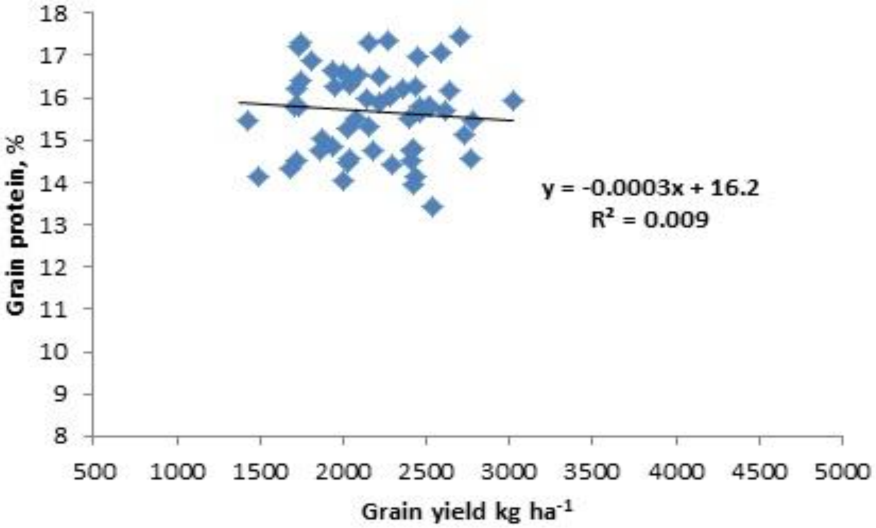

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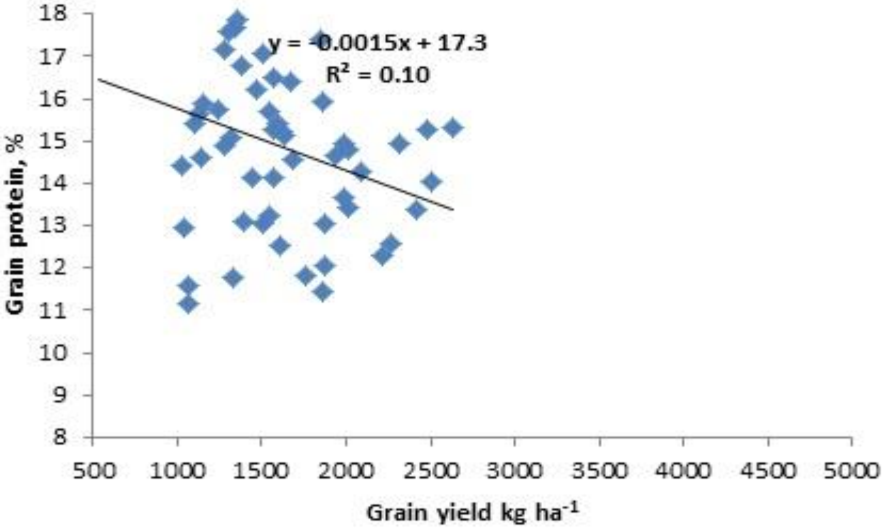

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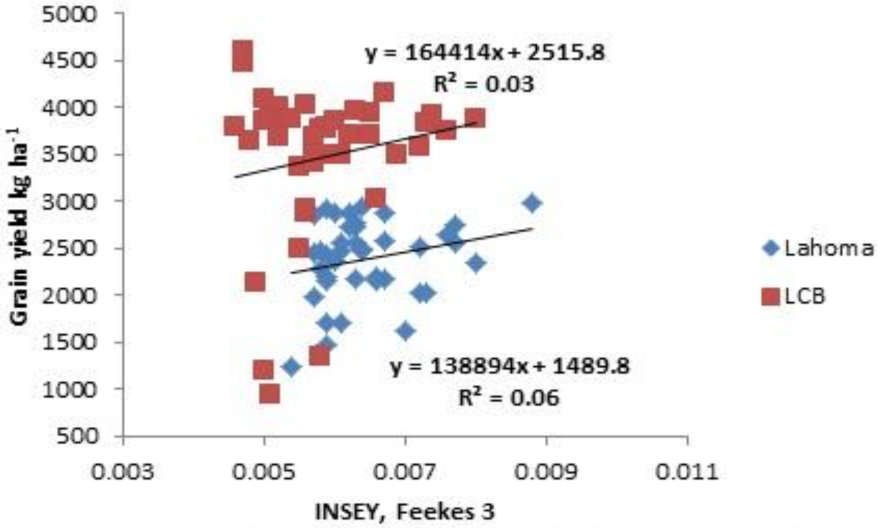

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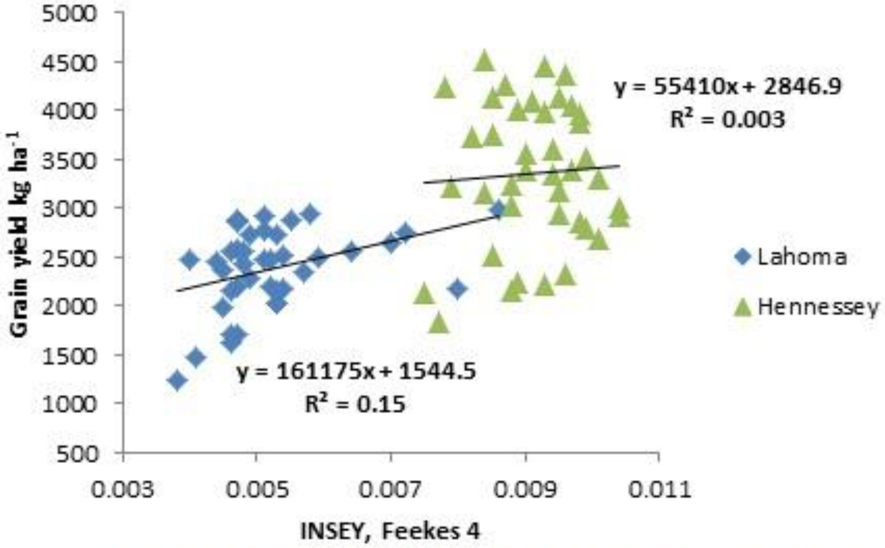

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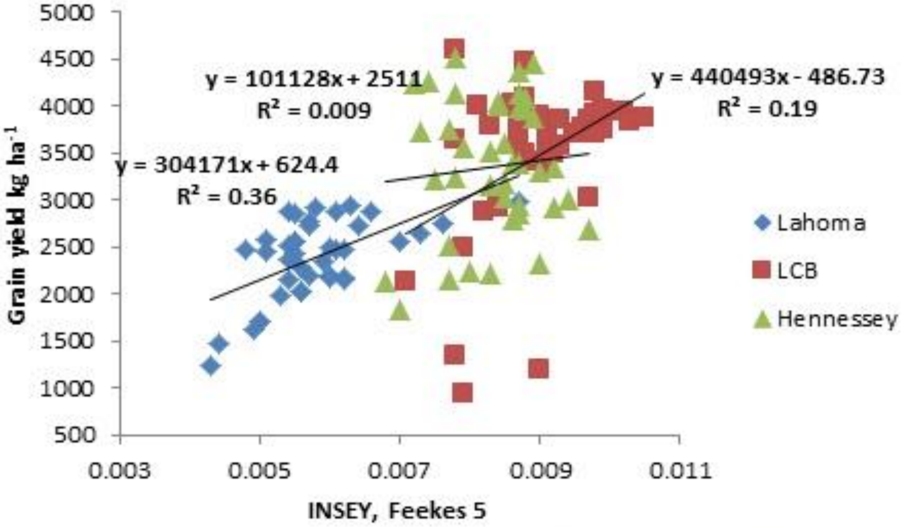

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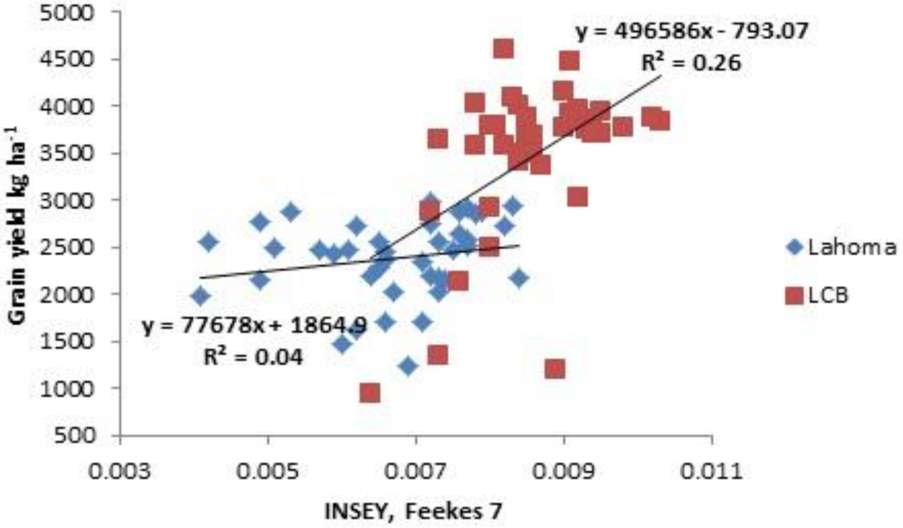

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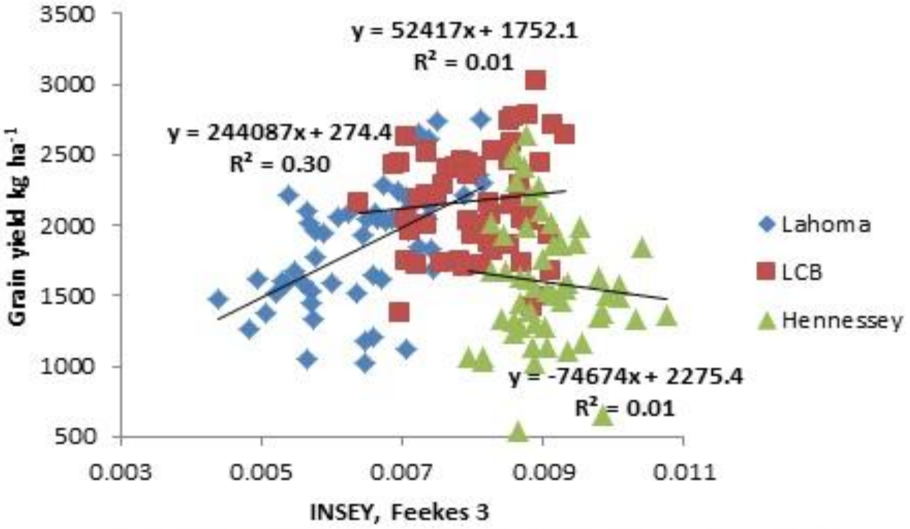

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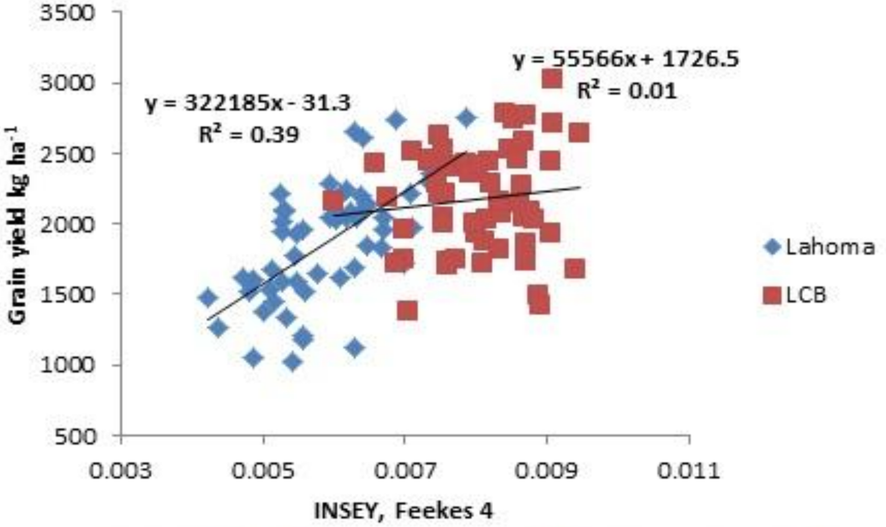

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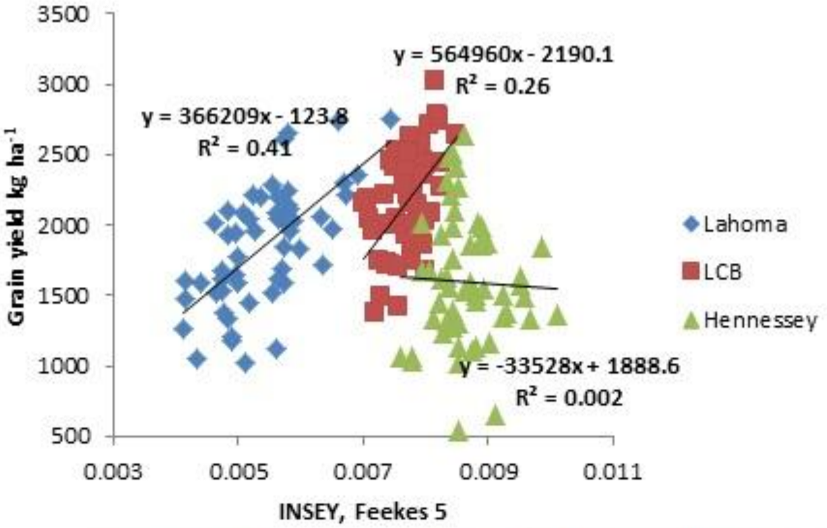

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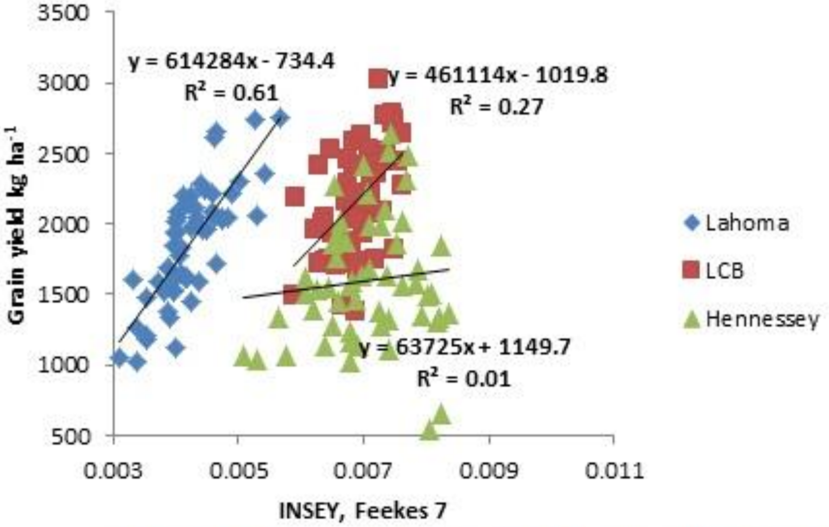

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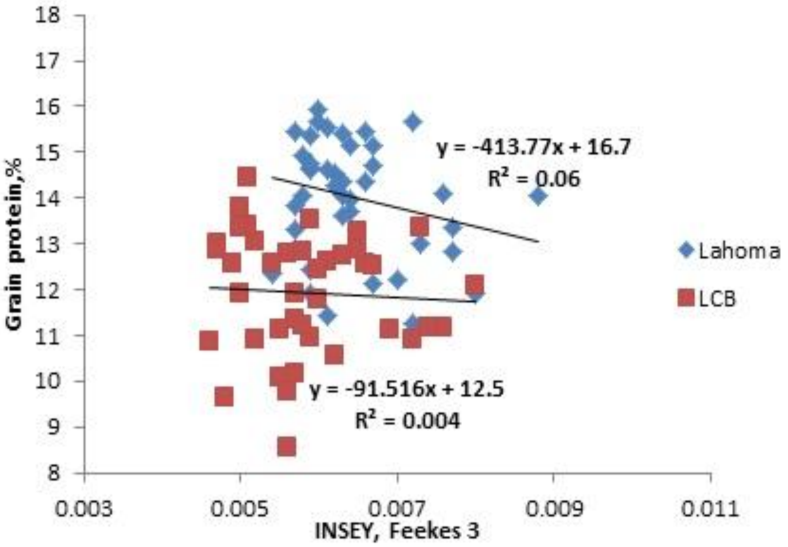
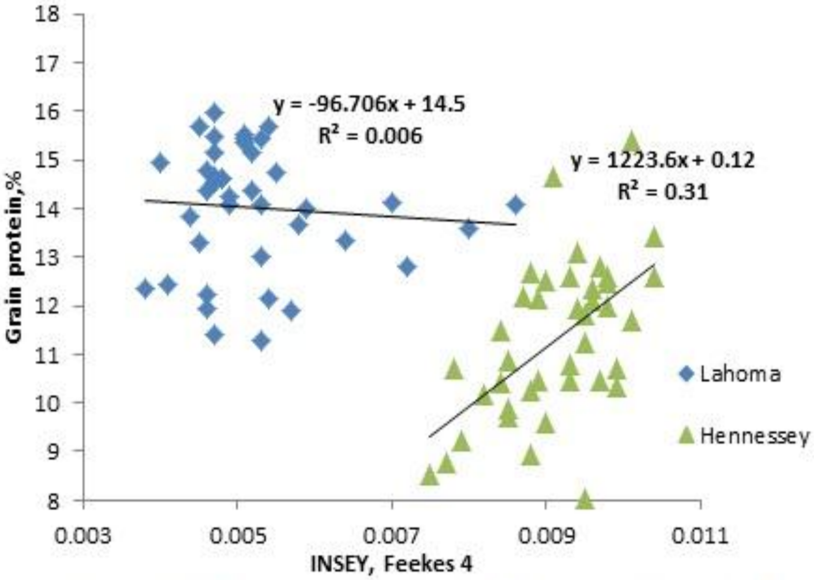


Figure A15. Relationship between INSEY and grain protein for growth stage Feekes 3, Lahoma, and Lake Carl Blackwell, 2009-2010.



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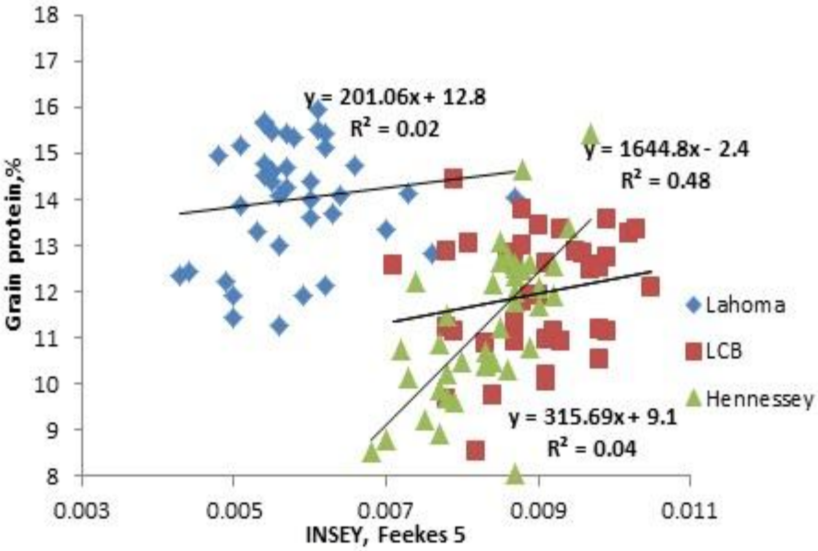

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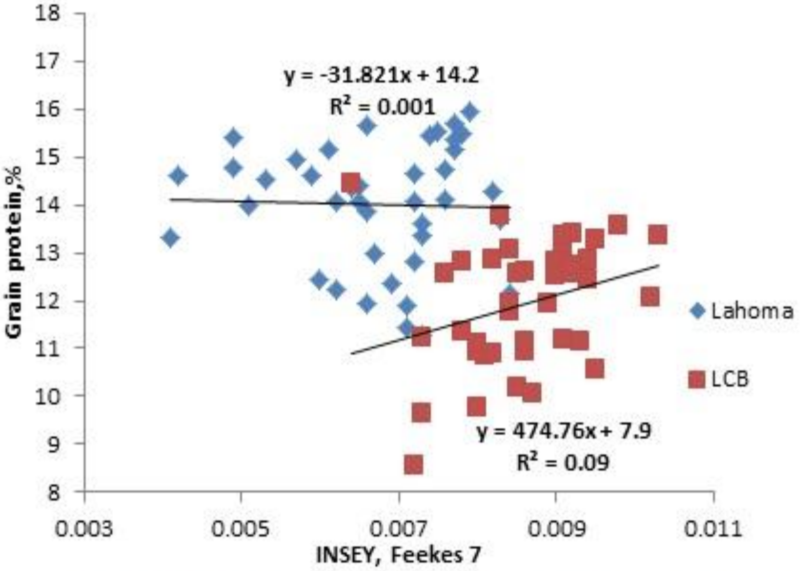

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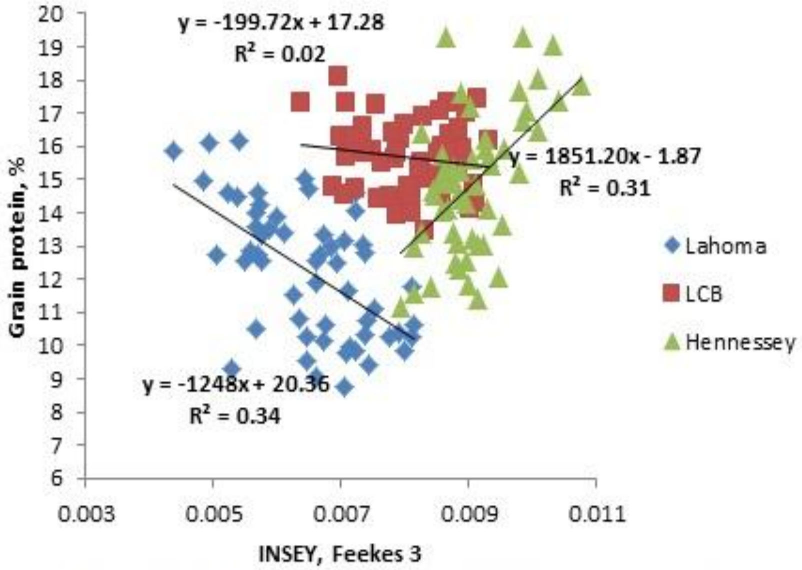

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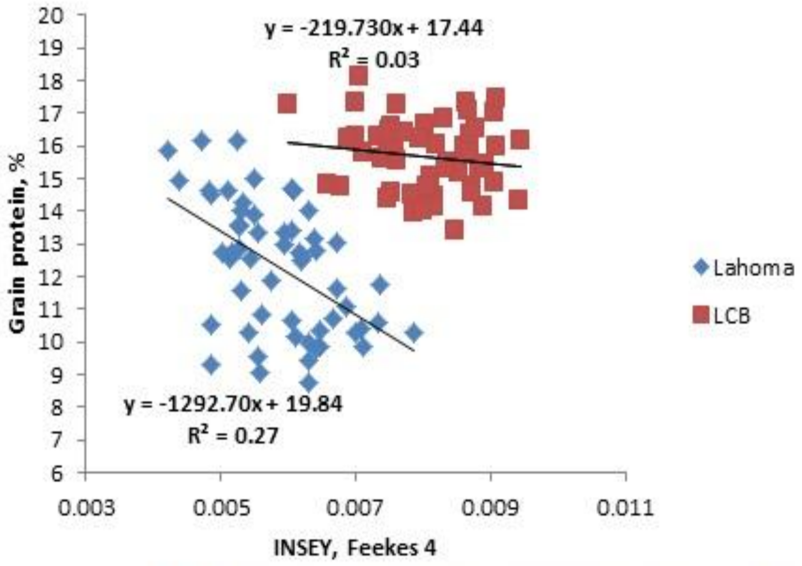

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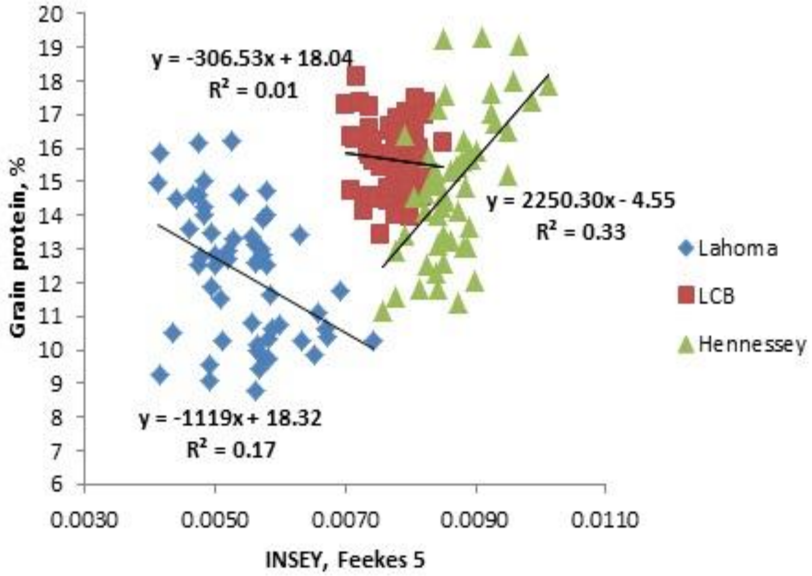

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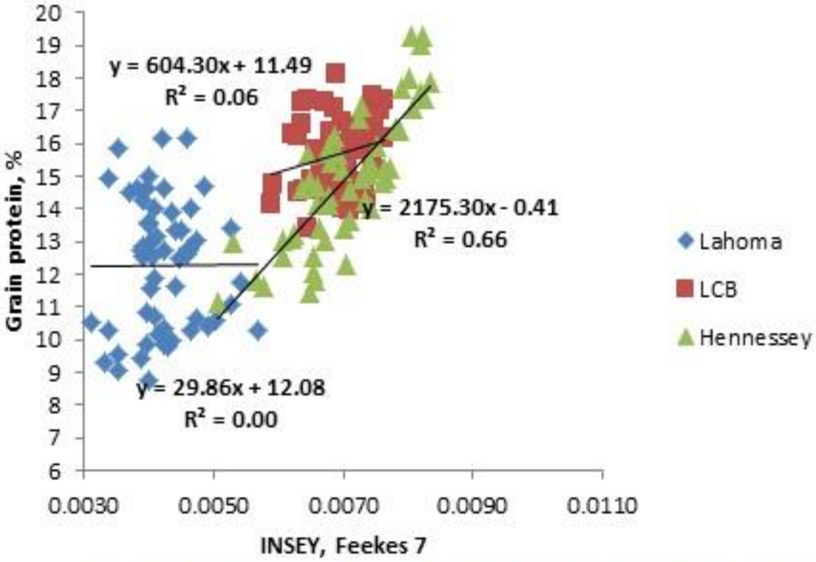

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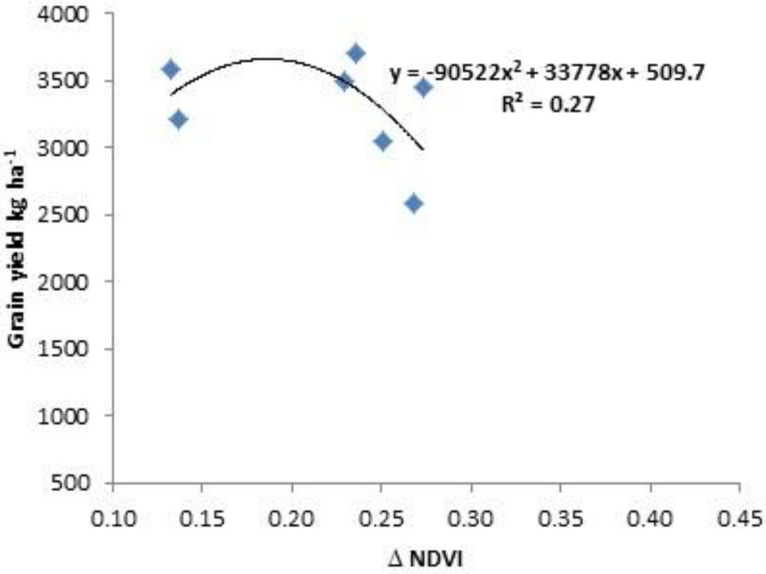

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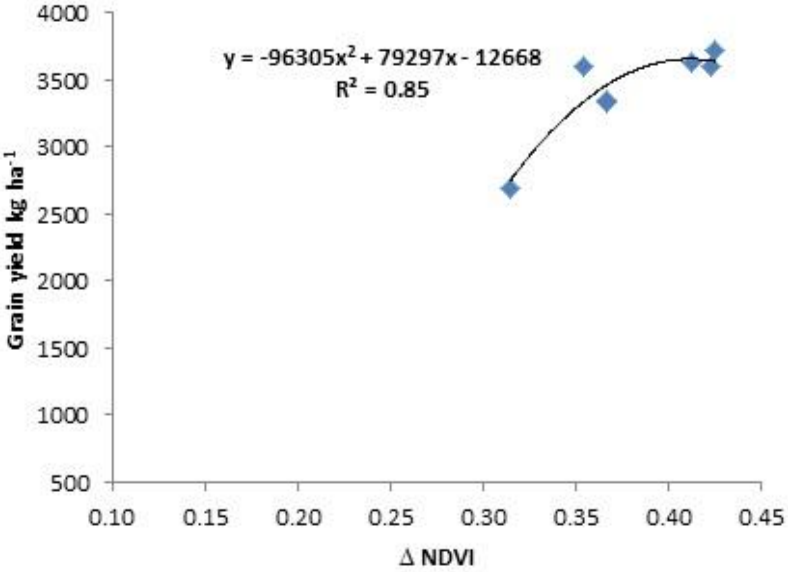
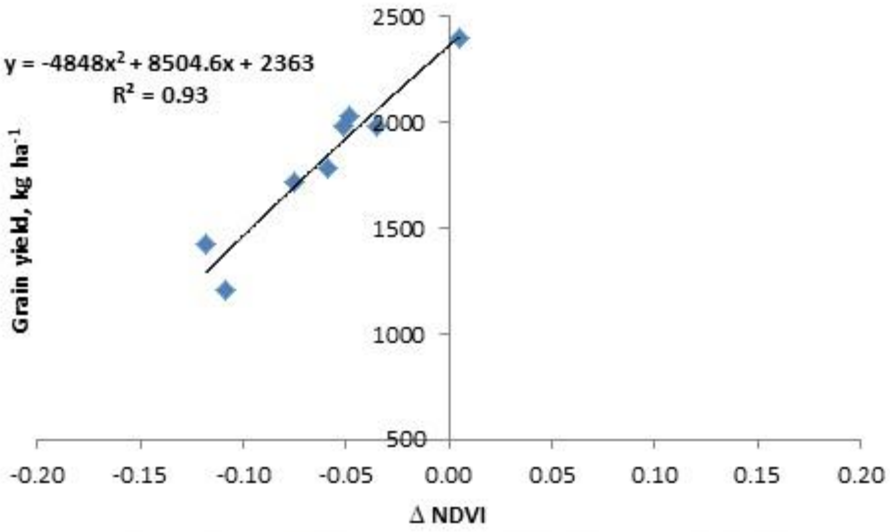


Figure A24. Relationship between delta NDVI and grain yield at Lake Carl Blackwell, 2009-2010.



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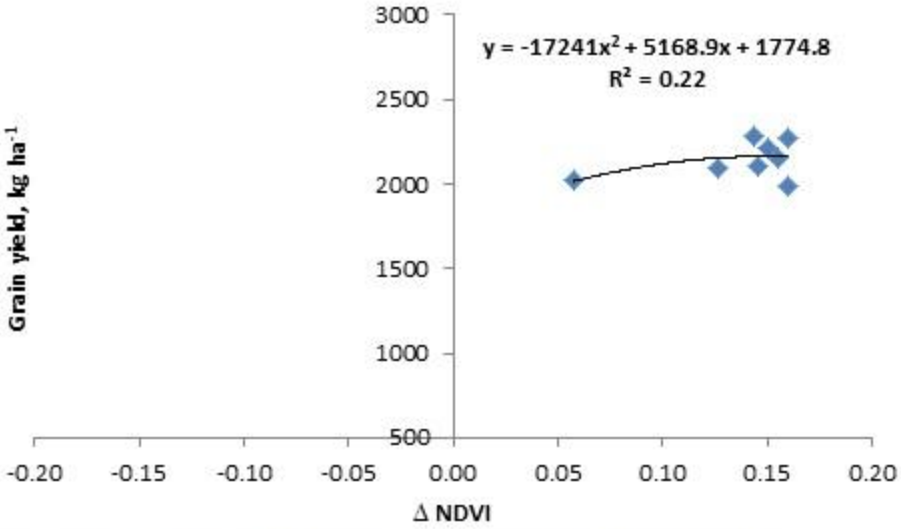

Figure A26. Relationship between delta NDVI and grain yield at Lake Carl Blackwell, 2010-2011.

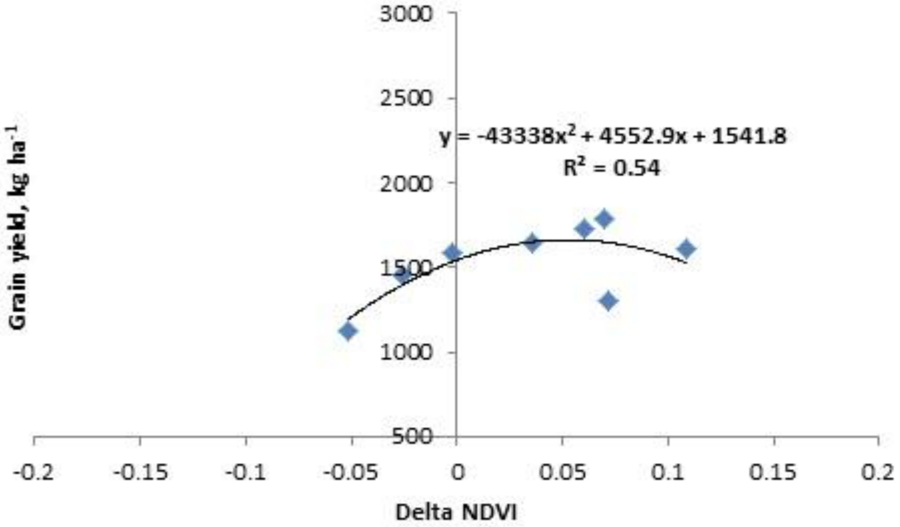

Figure A27. Relationship between delta NDVI and grain yield at Hennessey, 2010-2011.

VITA

Natasha Elizabeth Macnack

Candidate for the Degree of

Master of Science

Thesis: IN SEASON PREDICTION OF NITROGEN USE EFFICIENCY AND GRAIN PROTEIN IN WINTER WHEAT (*TRITICUM AESTIVUM L.*)

Major Field: Plant and Soil Sciences

Biographical:

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Name: Natasha Elizabeth Macnack Date of Degree: May, 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: IN SEASON PREDICTION OF NITROGEN USE EFFICIENCY AND GRAIN PROTEIN IN WINTER WHEAT (*TRITICUM AESTIVUM L.*)

Pages in Study: 84 Candidate for the Degree of Master of Science

Major Field: Plant and Soil Sciences

Scope and Method of Study: The algorithm currently used at Oklahoma State University for mid-season fertilizer nitrogen (N) recommendations utilizes an assumed nitrogen use efficiency (NUE) of 0.5. The recommended N rate is calculated by subtracting N uptake without additional N from N uptake with additional N and dividing the difference by the NUE. Refining the estimation of NUE would allow more precise N fertilizer recommendations. Also, many winter wheat producers in Oklahoma have at some point encountered protein related deductions at the elevator. Knowing protein levels mid-season would allow farmers to make fertilizer adjustments in time to achieve optimal yield and protein levels. The objective of this study was to evaluate the use of Normalized Difference Vegetation Index (NDVI) and SPAD chlorophyll meter readings to predict NUE and grain protein in winter wheat. In addition yield, NUE, grain protein, and N uptake were evaluated as a function of rate and timing of N application. Preplant treatments ranged from 28 kg ha^{-1} to 224 kg ha^{-1}. Selected treatments also included topdress rates of 28, 56, 84, 112, and 140 kg N ha^{-1}. GreenSeeker and SPAD readings were collected at Feekes (F) 3, 4, 5, and 7.

Findings and Conclusions: Over two cropping seasons it was noted that NDVI did not reliably predict NUE. GreenSeeker NDVI readings collected at Hennessey gave the best correlation with grain protein (in 2010, r^2= 0.32, 0.47; F4, F5, respectively and in 2011, r^2= 0.31, 0.33, 0.66; F3, F5, F7, respectively). In general grain yield and grain protein increased with increasing N rates, and NUE decreased with increasing N rates; a phenomenon most clearly observed at Hennessey. The results of this study suggest that the environment has to be accounted for to improve the prediction of grain protein and NUE.

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ADVISER'S APPROVAL: Dr. William Raun