EFFECT OF PREPLANT/EARLY IRRIGATION, NITROGEN AND SEEDING RATE ON WINTER WHEAT GRAIN YIELD

By

SULOCHANA DHITAL

Bachelor of Agricultural Science
Institute of Agriculture and Animal Science
Rampur, Chitwan
2007

Master of Plant and Soil Science
Oklahoma State University
Stillwater, Oklahoma
2013

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

EFFECT OF PREPLANT/EARLY IRRIGATION,

NITROGEN AND SEEDING RATE ON WINTER

WHEAT GRAIN YIELD

Dissertation Approved:

Dr. William R. Raun

Dissertation Adviser

Dr. Brian Arnall

Dr. Hailin Zhang

Dr. Randy Taylor

ACKNOWLEDGEMENTS

This dissertation is dedicated to my mother. She has been an inspiration for achieving this degree.

I would like to extend my sincere appreciation to my committee chair, Professor Dr. William Raun whose mentoring and encouragement I had through the entire study years. I want to thank my other committee members Dr. Arnall, Dr. Zhang and Dr.Taylor for their valuable time and continuous support.

I take this opportunity to thank my fellow soil fertility graduate students. The team effort they have shown in my research work is commendable.

I want to thank my parents and my family for supporting me and believing in me. I would like to thank all who directly and indirectly helped me.

Name: SULOCHANA DHITAL

Date of Degree: DECEMBER, 2016

Title of Study: EFFECT OF PREPLANT/EARLY IRRIGATION, NITROGEN AND SEEDING RATE ON WINTER WHEAT GRAIN YIELD

Major Field: SOIL SCIENCE

Abstract: Preplant or early irrigation in winter wheat (Triticum aestivum L.) can improve plant stands and lead to higher grain yields. Optimum seeding density more efficiently utilizes resources and optimizes yield. In lieu of groundwater storage continuing to decline, more precise and efficient utilization of water is needed. Wheat experiments were conducted to evaluate nitrogen (N) rate, seeding rate and early irrigation over three growing seasons near Stillwater, Oklahoma. Experimental design was a split-split plot with 3 replications and nine treatments, with irrigation as the main plot. Seeding rates of 45, 67 and 112 kg ha^{-1} were sub plots and that included three N rates (0, 67, 134 kg ha^{-1}) as sub-sub plots. Tiller count, head count and grain yields were collected. Mid-season biomass and harvest index were recorded. Results showed that, for different cropping seasons, grain yield, biomass, tillers, heads, grain N and harvest index depended either on the interaction effect or main effect or both. Early irrigation did not affect grain yield. Seeding rate and N rate were significant for number of heads. Midseason biomass weight was significant with irrigation. Harvest index was not significant for irrigation, seed rate and N rate or interaction effects. Grain yield response to irrigation varied considerably due to differences in rainfall received during the cropping season. This study showed for the given environmental conditions, early irrigation has no effect on winter wheat grain yields.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER I

CHAPTER II

Table Page

LIST OF FIGURES

CHAPTER I

Figure Page

CHAPTER II

Figure Page

.

CHAPTER I

VARIABILITY IN OPTIMUM NITROGEN RATES FOR MAIZE

ABSTRACT

Maize (Zea mays L.) grain yield levels and the response to fertilizer nitrogen (N) are expected to change from year to year and from location to location. Because yield level and N response have been documented to be independent and are known to influence N demand, optimum N rates at the same location vary each year due to unpredictable changes in the environment. The objective of this study was to further analyze maize grain yield levels and optimum fertilizer N rates from published data in maize growing regions of the United States. Optimum N rates were determined by calculating the difference in N uptake between the highest-yielding plot and the check plot (no N applied [0-N]). The difference in grain N uptake between the fertilized plot and the 0-N check plot was then divided by 0.33 (the assumed average N use efficiency) to estimate optimum N rate by site and year. For the 213 site-years of data included in this study, grain yields in both the high N rate and check (0-N) plots were highly variable. Optimum N rates fluctuated from year to year at all locations. Optimum N rates were not highly correlated with the high–N rate yield (R^2 = 0.20) or 0-N check yield (R^2 = 0.16).

The wide range in optimum N rates observed in all maize experiments suggests the need to adjust N rates by year and location. A potential solution is to use midseason sensor-based technologies that can accurately predict yield potential and simultaneously encumber N responsiveness known to be independent of yield.

INTRODUCTION

Nitrogen (N) fertilizer is an expensive input and is often needed to maximize grain crop yields. The increased area under maize production has led to increased prices and accelerated use of N fertilizer. Bundy et al. (1999) reported that 3.6 million t of N fertilizer were applied annually for maize production in 12 states within the northcentral United States, at a cost of 600 to 800 million USD. This estimate excluded N from manure and legumes used in crop rotations. The total N fertilizer used by 15 US States for maize in 2014 rose to 5 million t of fertilizer at an estimated cost of \$500 Mg^{-1} or 2.5 billion USD for 36.6 million ha (USDA–NASS, 2015a). Snyder (2012) documented that US maize consumes 37 to 51% of the total annual fertilizer N. Over the last 100 yrs, maize yield levels have increased nearly eightfold in the United States (Kraatz et al., 2008); this increase is attributed in part to increased fertilizer N use. In 2012, US farmers planted 39.3 million ha of maize (USDA– NASS, 2015b) and produced almost 273 million t of maize grain. Maize production increased to 361 million t in 2014 on a total of 36.6 million ha (USDA–NASS, 2015b). Iowa is the leading US state for maize production, with a total of 5.5 million ha in 2013. In 2010, Iowa accounted for almost 14% of the total maize planted in the United States (Dale et al., 2010).

Keeney and Muller (2000) reported that the US Grain Belt have a large amount of artificially drained soils, a high percentage of total land in agriculture, and the highest

N fertilizer rates. More than 30% of the cropland in the Midwest is in need of subsurface drainage to maintain the productivity of poorly drained soils (Kanwar et al., 2005). However, drainage systems serve as a pathway through which nitrate nitrogen (NO_3–N) can be transported to streams and rivers (Cooper, 1993). Nitrate-contaminated drainage water from artificial subsurface drainage systems (tiles) is a primary source of NO_3–N loading to surface water within the Midwestern United States grain belt (David et al., 1997). In research conducted near central Iowa, Jaynes et al. (2001) documented NO_3–N loss in tile drainage water totaling 48, 35, and 29 kg N ha^{-1} for high (172–202 kg ha^{-1}), medium (114–135 kg ha^{-1}), and low (57–67 kg ha^{-1}) N fertilizer rates, respectively. Rabalais et al. (1999) suggested that excessive nutrient runoff derived mainly from agricultural land had increased the spread and severity of the hypoxic zone within the Gulf of Mexico. Dale et al. (2010) noted that Illinois, Iowa, and Indiana alone produce 15% of the world's maize and soybeans, and these regions have the highest N and P loading, which has led to the hypoxic or "dead zone" in the Gulf of Mexico. Nutrient flow from the Mississippi-Atchafalaya river basin into the Gulf of Mexico determines the size of the seasonal hypoxia zone (Alexander et al., 2008). Further, David et al. (2010) reported the highly productive, tile-drained maize belt from southwestern Minnesota, Indiana, Iowa, Illinois, and Ohio is the greatest contributor of nitrate yield to the Mississippi river. Application of N in excess of that taken up by maize also leads to potential NO_3–N loss to ground water through leaching. Over fertilization may not always result in additional grain yield; instead, it can increase N losses (Raun and Johnson, 1995). Alternatively, lower N rates can lead to decreased economic returns (Scharf and Lory, 2000). Accumulation of residual N occurs as a result of applying a greater rate than necessary to maximize yields (Herron et al., 1971). Over time, soils can become oversupplied with nutrient inputs, especially when nutrient supply exceeds crop removal, resulting in nutrient leaching and runoff (Daniel et al., 1998; Sims, 1998). Several studies have shown that NO_3–N losses continue even with typical N rates (Baker and Johnson, 1981; Kanwar et al., 1988).

Efficient use of N fertilizer has raised concerns in modern crop production systems. Environmental concerns continue to be intertwined with the growing costs of N fertilizer production and use. Accurate N fertilizer rates, along with higher N use efficiency (NUE), remain important for maximizing returns while simultaneously protecting the environment and water quality. Nitrogen use efficiency for maize in the United States has increased more than 30% over the last 20 yr (Fixen and West, 2002). Early ^{15}N work with maize showed that 24.1 and 26.4% of the applied N was accounted for in the grain at N rates of 50 and 150 kg N ha^{-1}, respectively (Olson, 1980). Similar studies by Wienhold et al. (1995) reported that maize grain use of N applied averaged 35%. Cassman et al. (2002) noted that N recovery efficiency (REN) described N use and reported this value at 37% for the northcentral United States for maize grown in different rotations. Using global statistics from the Food and Agriculture Organization, Raun and Johnson (1999) found average NUE for worldwide cereal production to be 33%. An increase of 1% in global NUE for cereal production could save 234 million USD worldwide (Raun and Johnson, 1999). Added work from this group found that NUE could be improved by 15% when N fertilization was based on optically sensed in-season estimated grain yield (Raun et al., 2002). Related research from Dobermann (2005) calculated average partial factor productivity for NUE in cereal production to be 44%.

Ideal nutrient management would provide a balance between nutrient input and output over longer periods of time (Bacon et al., 1990). Several factors affect grain yield, such as growing season, soil fertility, soil moisture, and environmental changes year to year. This implies that accurate N rate recommendations should have a reliable estimate of those parameters that affect maize grain yield and/or that have a negative environmental and economic impact.

Determining optimum time, rate, and method of N fertilizer application for maize is crucial to minimize N losses. The synchronization of time of fertilizer application with plant N demand is also important. Fall N application creates a substantial risk of N loss and lower yield. Excess residual NO_3–N in the soil profile in the fall can end up in ground water, especially in humid regions of the United States (Lory et al., 1995). Keeney (1982) recommended the use of ammonium fertilizers and delaying time of application until soil temperatures are 10°C for fall application. Spring-applied N versus fall N can minimize the risk of N loss from the soils and optimize the profitability irrespective of the tillage system (Vetsch and Randall, 2004). Randall et al. (2003) found that on poorly drained Mollisols, the best application time strategies for anhydrous ammonia were fall N with nitrapyrin, spring preplant, and split application.

Nitrogen fertilizer needs for maize vary between fields (Bundy and Andraski, 1995) and within fields (Malzer et al., 1996). Fiez et al. (1995) suggested that the different N response between and within fields was due to spatial and temporal variations in crop demand. The optimum N fertilizer rate changes dramatically from one maize field to the next because it is affected by the complex interactions of spring precipitation, temperature patterns, soil organic matter, and crop development (Scharf, 2001; Scharf et al., 2005).

Research performed over the last few decades has focused on improving N fertilizer rate recommendations (Andraski and Bundy, 2002; Hanway and Dumenil, 1955; Schmitt and Randall, 1994; Vanotti and Bundy, 1994; Varvel et al., 2007). Before 1957, most N rate recommendations were based on soil criteria and crop management. Since 1970, the yield goal approach has been a popular method for maize in the Midwest; it converts the expected yield to N rate recommendations using fixed factors (Fernández et al., 2009). Yield goals are determined from a recent 5-yr crop yield average, increased typically by 10 to 30%, assuring adequate N for above-average growing conditions (Johnson, 1991). Maximum return to N is a procedure for estimating economically optimum N rates. It has been used in the Midwest across the Corn Belt and determines preplant N rates by estimating the yield increase to applied N using current grain and fertilizer prices (Sawyer et al., 2006). This approach provides generalized N rate recommendations over large areas and years. However, it fails to address the issue of year-to-year variability in temperature and rainfall (Shanahan, 2011; Van Es et al., 2006) and does not provide site-year recommendations.

Although optimal N rates can vary substantially within and between fields, most US maize producers apply the same rates to entire farms (Scharf et al., 2005). Limiting application rates is the most important factor in reducing environmental impacts; nonetheless, inappropriate methods and poor timing continue to pose the risk of N loss to the environment (Ribaudo et al., 2012). Additionally, the inability to accurately estimate optimum N rates results in over fertilization for some years and fields and under fertilization in others and a lower NUE (Shanahan, 2011). Consequently, there is a clear need to improve N fertilizer management. Early work from Van Es et al. (2006) noted that accurate estimation of optimum N rates year-to-year and field-to-field remains elusive. Nonetheless, in more recent work, Franzen et al. (2016) report that viable midseason sensor-based options are available for maize and wheat producers in many regions of the world.

In recent years, the use of normalized difference vegetation index (NDVI) crop sensors, such as Greenseeker (Trimble Navigation Ltd., Sunnyvale, CA) and Crop Circle (Holland Scientific, Lincoln, NE), have taken precision agriculture to a different level via the ability to detect N deficiencies and to prescribe environment-specific, mid-season N rates. Sensor-based N rate recommendations can vary spatially and temporally, have been further refined by location and crop (Oklahoma State University, 2016), and are currently available to producers (Franzen et al., 2016). Researchers have studied and validated in-season yield potential prediction using NDVI sensors (Crain et al., 2012; Teal et al., 2006). A very similar approach in Missouri was found to outperform the producer rate for maize (Scharf et al., 2011).

It is critical to understand that yield level and N response are unrelated (Arnall et al., 2013; Raun et al., 2011). Several researchers from the Midwest have substantiated that optimum N demand changes radically year to year and over locations, which is why applying the optimum N rates at the peak crop demand remains challenging. Furthermore, current N management decisions overlook year-to-year weather variations, thus failing to account for soil N mineralized in warm, wet years and ignoring indigenous N supply (Shanahan et al., 2008). Although optimum N rates vary widely, insufficient work is being done to encourage maize growers to apply different N fertilizer rates from one year to the next.

The Gulf of Mexico hypoxic zone reached 15,126 km^2 in 2013 (USEPA, 2014) and is expected to grow with continued nutrient loading rates coming from exceedingly high N fertilization rates in maize. Therefore, it is important to reconsider the common practice of applying the same N rate year after year. Rates of N tailored to temporal and spatial variability would deliver higher economic returns to maize farmers and a sound, sustainable environment. The objective of this work was to document the relationship between maize grain yield levels and optimum N rates over a wide range of locations and years from published literature.

MATERIALS AND METHODS

Grain yield and N fertilizer rate data from five different long-term (>15 yr) and nine short-term (2–7 yr) experiments in maize-growing regions of the United States were analyzed. This information was compiled from published papers and included added analysis. If the percent N in maize grain was reported in the paper, that value was used; if not, the percent maize N grain value was set at 1.2 (Shapiro et al., 2008). The difference in N uptake between the highest-yielding plots and check plots was calculated, and the optimum N rates were computed as:

$$\text{Optimum N rate} = \frac{(\text{Yield, (high N rate)} - \text{Yield, (check 0}-\text{N)}) * \%\mathit{grain\ N}}{\text{NUE Average}(0.33)}$$

Yield is expressed as kg ha^{-1} and grain N as a decimal (0.01 = 1%). A fixed NUE value of 33% (0.33) was used to reflect shared findings in cereals and with a derivation coming from a wide range of locations and years (Olson and Swallow, 1984; Raun and Johnson, 1999). Changing this value either higher or lower will result in a predictable bias. For example, an effective NUE of 0.40 would reduce the predicted N rate when compared with 0.33. Using a fixed NUE for these trials when combining over locations and years would likely compress the variability in optimum N rates reported. Other estimates of NUE exist and are in the 30 to 40% range (Cassman et al., 2002; Olson, 1980; Olson and Swallow, 1984). Also, computing NUE by individual site was no possible because grain N concentrations were only reported in a few of the papers included in this work. Optimum N fertilizer rates using 0.33 NUE over the 213 site-years ranged from 0 to 458 kg N ha^{-1}. All primary sources of data, years, range in observed yields, and the predicted optimum N rate for all locations are reported in Table 1. Substantive published research has shown dramatic changes in optimum N rates varying from year to year at the same location (Al-Kaisi and Yin, 2003; Bundy et al., 2011; Eck, 1984; Fenster et al., 1978; Gehl et al., 2005; Ismail et al., 1994; Jokela and Randall, 1989; Mallarino and Ortiz-Torres, 2006; Meisinger et al., 1985; Olson et al., 1986; Peterson and Varvel, 1989; Randall et al., 2003; Rice et al., 1986; Shapiro and Wortmann, 2006; Stecker et al., 1993; Varvel et al., 2007; Vetsch and Randall, 2004; Woodruff et al., 1984). Nonetheless, given the importance of N for both crop production and the environment, no single document addresses the comprehensive nature of the problem or provides realistic and accurate estimates of the present variability in N rate recommendations. Optimum N rates were calculated for each site-year using the difference in N uptake between the maximum yielding plot and the check plot and assuming a fixed level of fertilizer use efficiency. This permitted including the entire range of experiments, locations, and years. This work further concedes that NUEs are expected to change for all sites and years; even so, it was essential for by-location and over-site analysis to use an average. Also, the high–N-rate yield and 0-N check yields were plotted against the calculated optimum N rate. The relationship between optimum N rate and grain yield was established using simple linear regression analysis. Regression equations and R^2 values were identified for the high N yield and check plot yield using PROC GLM (SAS Institute, 2011).

Published maize grain yield data from long-term (>15 yrs) and short-term (2–7 yrs) experiments were used for the added analysis included in this study (Table 1). For each trial, the response index (RI) was computed using the high–N-rate yield as the numerator and 0-N check plot (RI 0-N) and medium– N-rate plot (RI Mid-N) as the denominator. The Medium-N rate was that rate used in each respective experiment that was at or near the middle of the range of N rates applied. This approach was also used by Arnall et al. (2013). Both RI 0-N and RI Mid-N were plotted as a function of time (Fig. 2–7). The relevance/use of RI and how it has been used over time has been described elsewhere (Arnall et al., 2013; Mullen et al., 2003; Raun et al., 2011). The computed RI, whether based on mid-season NDVI sensor readings (RI NDVI) or determined using harvest data (RI Harvest), indicates the actual crop response to additional N within a given year (Mullen et al., 2003). The work of Mullen et al. (2003) further showed that RI Harvest could be predicted using RI NDVI.

RESULTS

Results Yield levels for the check plots (0-N applied) and high–N-rate plots were highly variable at all sites (Table 1). By-site yield ranges in the 0-N check treatment and the high-N treatment were extreme. For one of the long-term trials, yields from the 0-N check ranged from 1.6 to 7.6 Mg ha^{-1}, and yields from the high-N treatment ranged from 4.3 to 8.8 Mg ha^{-1} (Bundy et al. (2011). For the 26 short- and long-term trials, comprising a total of 213 sites years of data, wide yield ranges were common (Table 1). The combined data reported in Table 1 reveal that these maize trials encompassing a wide range of states and climates had highly variable optimum N rates, with an average low of 62 ± 44 kg N ha^{-1} and average high of 173 ± 55 kg N ha^{-1}. The overall average optimum N rate was 120 ± 43 kg N ha^{-1} (Table 1). Using 1 SD from the average optimum N rate computed in this work results in an expected range of 77 to 163 kg N ha-1 (the complete database for computed optimum N rates was 0–239 kg N ha^{-1}) (Table 1). Because only maize sites from the United States were included, this is troubling when considering regional publications that do not consider the potential for improved environment-specific recommendations and because they report that there was no clear indication of a change in N rates over time (Sawyer et al., 2006).

Including all site years, optimum N rates were not correlated with the high–N-rate yield and/or the check plot yield (Fig. 1). The calculated R^2 value for optimum N-rate versus high–N-rate yield and check plot yield was poor (0.20 and 0.16, respectively) (Fig. 1). This was also consistent with the accompanied research articles that document year-to-year variability in optimum N rate. Several optimum N rates in excess of 240 kg N ha^{-1} were treated as outliers and were not included in this analysis. These data, although favorable for a paper highlighting dramatic ranges in optimum N rates, were omitted. Slope and intercept components for high–N-rate yield and check plot yield on optimum N rate were statistically significant (Pr > |t|) at the 0.10% level (Fig. 1). As expected, for all long-term experiments, RI 0-N was higher and fluctuated over the years, whereas RI Mid-N was lower and less variable over time (Fig. 2–7).

DISCUSSION

The data included in this paper report year-to-year and by-site variation in grain yield for the high–N-rate and 0-N plots. Factors that affect variable N demand are indirectly linked to yield variability. At some sites, the check plot where no N had ever been applied yielded almost the same as the high–N-rate plot after years of maize production (Wisconsin, 1958, 1959, 1981, and 1982 [Bundy et al., 2011]; Nebraska, 1995 [Varvel et al., 2007]). In fact, some check plots surpassed the yield recorded for the high–N rate plot (Kentucky, 1970 and 1988 [Ismail et al., 1994]; Martin County, Minnesota, 1971–1976 [Fenster et al., 1978]). The study by Mamo et al. (2003) is one of several documenting temporal variability and resultant maize grain yields. Expected differences in by-site rainfall and temperature contributed to the reported differences in grain yields and by-year and by-site optimum N rates (Table 1). As noted by Leiros et al. (1999), environmental variability can result in higher and lower N mineralization from soil organic matter, which influences N demand. Other reasons for the differing estimates of N response include the actual yield level, which changes from year to year and affects final demand (Gehl et al., 2005). Highly variable levels of atmospheric N deposition from one year to the next (Huang et al., 2016) can also affect N need. Tremblay et al. (2012) suggested that abundant and well-distributed rainfall can increase the N response of corn in fine-textured soil in terms of yield.

. It is thus not surprising that optimum fertilizer N rates will change from year to year and site to site. By-year soil testing for inorganic soil N is encouraged due to the relationship with changing yield levels (Binford et al., 1992). As such, maize producers should consider the unpredictable weather patterns that affect N mineralization, inorganic N, and the resultant grain/plant N uptake. Fluctuating yields can also be the consequence of variable soil-supplied N across the field and/or spatial variability (Crain et al., 2013; Holland and Schepers, 2010). Several researchers have noted how current N recommendations provide an estimate of how much N to apply but fail to account for soil N and maize N uptake, which can be influenced by in-season weather changes (Scharf et al., 2006; Van Es et al., 2006; Vanotti and Bundy, 1994).

CONCLUSIONS

Yield level and N response contribute to the final optimum N rate. Nonetheless, yield level and N response need to be considered independent of one another before deciphering N rate recommendations for maize. If the same N rates are applied each year, they will not include accurate accounting for variability in soil N and maize N uptake, which are dramatically influenced by the changing growing conditions from one year to the next. Published results coming from an array of sources and from multiple sites and years have revealed extensive variability in optimum N rates for maize that should be reflected in current day N recommendations.

REFERENCES

Al-Kaisi, M.M., and X. Yin. 2003. Effects of nitrogen rate, irrigation rate, and plant population on maize yield and water use efficiency. Agron. J. 95(6):1475–1482. doi:10.2134/agronj2003.1475

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environ. Sci. Technol. 42(3):822–830. doi:10.1021/es0716103

Arnall, D.B., A.P. Mallarino, M.D. Ruark, G.E. Varvel, J.B. Solie, M.L. Stone, J.L. Mullock, R.K. Taylor, and W.R. Raun. 2013. Relationship between grain crop yield potential and nitrogen response. Agron. J. 105(5):1335–1344. doi:10.2134/agronj2013.0034

Andraski, T.W., and L.G. Bundy. 2002. Using the pre-sidedress soil nitrate test and organic nitrogen crediting to improve maize nitrogen recommendations. Agron. J. 94(6):1411–1418. doi:10.2134/agronj2002.1411

Bacon, S.C., L.E. Lanyon, and R.M. Jr. Schlander. 1990. Plant nutrient flow in the managed pathways of an intensive dairy farm. Agron. J. 82:755–761. doi:10.2134/agronj1990.00021962008200040021x

Baker, J.L., and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10(4):519–522. doi:10.2134/jeq1981.00472425001000040020x

Bundy, L.G., and T.W. Andraski. 1995. Soil yield potential effects on performance of soil nitrate tests. J. Prod. Agric. 8:561–568. doi:10.2134/jpa1995.0561

Bundy, L.G., D.T. Walters, and A.E. Olness. 1999. Evaluation of soil nitrate tests for predicting maize nitrogen response in the North Central Region. North Central Reg. Res. Publ. 342. Wisconsin Agriculture Experiment Station, Univ. of Wisconsin, Madison.

Bundy, L.G., T.W. Andraski, M.D. Ruark, and A.E. Peterson. 2011. Long term continuous maize and nitrogen fertilizer effects on productivity and soil properties. Agron. J. 103:1346–1351. doi:10.2134/agronj2011.0094 2172

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84:53–59. doi:10.2134/agronj1992.00021962008400010012x

Cooper, C.M. 1993. Biological effects of agriculturally derived surface water pollutants on aquatic systems: A review. J. Environ. Qual.22:402–408. doi:10.2134/jeq1993.00472425002200030003x

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31(2):132–140. doi:10.1579/0044-7447-31.2.132

Crain, J., I. Ortiz-Monasterio, and B. Raun. 2012. Evaluation of a reduced cost active NDVI sensor for crop nutrient management. J. Sens. 2012:582028.

Crain, J. L., K. M. Waldschmidt, and W. R. Raun. 2013. Small-scale spatial variability in winter wheat production. Comm. Soil Sci. Plant Anal. 44:2830–2838. doi:10.1080/00103624.2013.812735

Dale, V.H., C.L. Kling, J.L. Meyer, J. Sanders, H. Stallworth, T. Armitage, et al. 2010. Hypoxia in the northern Gulf of Mexico. Springer Series on Environmental Management. Springer, New York. doi:10.1007/978-0-387-89686-1

Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27:251–257. doi:10.2134/jeq1998.00472425002700020002x

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. J. Environ. Qual. 26:1038–1048. doi:10.2134/jeq1997.00472425002600040015x

David, M.B., L.E. Drinkwater, and G.F. McIsaac. 2010. Sources of nitrate yields in the Mississippi River Basin. J. Environ. Qual. 39(5):1657–1667. doi:10.2134/jeq2010.0115

Dobermann, A.R. 2005. Nitrogen use efficiency: State of the art. Agronomy & Horticulture–Faculty Publications. Agronomy and Horticulture Dep., Univ. of Nebraska, Lincoln. http://digitalcommons.unl.edu/agronomyfacpub/316 (accessed 5 Oct 2016).

Eck, H.V. 1984. Irrigated maize yield response to nitrogen and water. Agron. J. 76(3):421–428. doi:10.2134/agronj1984.00021962007600030014x

Fenster, W.E., C.J. Overdahl, G.W. Randall, and R.P. Schoper. 1978.Effect of nitrogen fertilizer on maize yield and soil nitrates. Agri. Exp. Station., Univ. of Minnesota, St. Paul.

Fernández, F.G., E.D. Nafziger, S.A. Ebelhar, and R.G. Hoeft. 2009. Managing nitrogen. In: Illinois agronomy handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign. p. 113–132.

Fiez, T.E., W.L. Pan, and B.C. Miller. 1995. Nitrogen efficiency analysis of winter wheat among landscape positions. Soil Sci. Soc. Am. J. 59:1666–1671. doi:10.2136/sssaj1995.03615995005900060023x

Fixen, P.E., and F.B.West. 2002. Nitrogen fertilizers: Meeting contemporary challenges. Ambio 31(2):169–176. doi:10.1579/0044-7447-31.2.169

Franzen, D., N. Kitchen, K. Holland, J. Schepers, and W. Raun. 2016. Algorithms for in-season nutrient management in cereals. Agron. J. 108:1775–1781. doi:10.2134/agronj2016.01.0041

Gehl, R.J., J.P. Schmidt, L.D. Maddux, and W.B. Gordon. 2005. Maize yield response to nitrogen rate and timing in sandy irrigated soils. Agron. J. 97:1230–1238. doi:10.2134/agronj2004.0303

Hanway, J., and L. Dumenil. 1955. Predicting nitrogen fertilizer needs of Iowa soils: III. Use of nitrate production together with other information as a basis for making nitrogen fertilizer recommendation for maize in Iowa. Soil Sci. Soc. Am. J. 19(1):77–80. doi:10.2136/sssaj1955.03615995001900010019x

Herron, G.M., A.F. Dreier, A.D. Flowerday, W.L. Colville, and R.A. Olson. 1971. Residual mineral N accumulation in soil and its utilization by irrigated maize (Zea mays L.). Agron. J. 63:322-327.doi:10.2134/agronj1971.00021962006300020037x

Holland, K.H., and J.S. Schepers. 2010. Derivation of a variable rate nitrogen application model for in-season fertilization of corn. Agron. J. 102:1415–1424. doi:10.2134/agronj2010.0015

Huang, P., J. Zhang, D. Ma, Z. Wen, S. Wu, G. Garland, E.I.P. Pereira, A. Zhu, X. Xin, and C. Zhang. 2016. Atmospheric deposition as an important nitrogen load to a typical agro-ecosystem in the Huang Huai-Hai Plain: 2. Seasonal and inter-annual variations and their implications (2008-2012). Atmos. Environ. 129:1–8. doi:10.1016/j. atmosenv.2016.01.015

Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous maize yields. Soil Sci. Soc. Am. J. 58(1):193–198. doi:10.2136/sssaj1994.03615995005800010028x

Jaynes, D.B., T.S.Colvin, D.L.Karlen, C.A.Cambardella, and D.W.Meek. 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30(4):1305–1314. doi:10.2134/jeq2001.3041305x

Johnson, G.V. 1991. General model for predicting crop response to fertilizer. Agron. J. 83:367–373. doi:10.2134/agronj1991.00021962008300020021x

Jokela, W.E., and G.W. Randall. 1989. Maize yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81(5):720–726. doi:10.2134/agronj1989.00021962008100050004x

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1988. Tillage and split N-fertilizer effects on subsurface drainage water quality and crop yields. Trans. ASABE 31(2):453–460. doi:10.13031/2013.30730

Kanwar, R.S., R.M. Cruse, M. Ghaffarzadeh, A. Bakhsh, D.L. Karlen, T.B. Bailey, et al. 2005. Maize–soybean and alternative cropping systems effects on NO3–N leaching losses in subsurface drainage water. Appl. Eng. Agric. 21(2):181–188. doi:10.13031/2013.18151

Keeney, D.R., and M. Muller. 2000. Nitrogen and the upper Mississippi River. Institute for Agriculture and Trade Policy, Minneapolis, MN.

Keeney, D. R. 1982. Nitrogen availability indices. In: A.L. Page, Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA, Madison, WI. p. 711–733.

Kraatz, S., D. J. Reinemann, and W. E. Berg. 2008. Energy inputs for maize production in Wisconsin and Germany. ASABE, St. Joseph, MI.

Leirós, M.C., C. Trasar-Cepeda, S. Seoane, and F. Gil-Sotres. 1999. Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biol. Biochem. 31(3):327–335. doi:10.1016/S0038-0717(98)00129-1

Lory, J.A., M.P. Russelle, and G.W. Randall. 1995. Crop sequence effects on response of maize and soil inorganic nitrogen to fertilizer and manure nitrogen. Agron. J. 87:876–883. doi:10.2134/agronj1995.00021962008700050016x

Mallarino, A.P., and E. Ortiz-Torres. 2006. A long-term look at crop rotation effects on maize yield and response to N fertilization. In: The Integrated Crop Management Conference Proceedings, Ames, IA. 29–30 Nov. 2006. Iowa State Univ. Ext., Ames. p. 209–213.

Malzer, G.L., P.J. Copeland, J.G. Davis, J.A. Lamb, P.C. Robert, T.W. Bruulsema, et al. 1996. Spatial variability of profitability in site specific N management. In: P.C. Robert, R.H. Rust, and W.H. Larson, editors, Proc. 3rd Intl. Conf. on Precision Agriculture. ASA-CSSA-SSSA, Madison, WI. p. 967–975.

Mamo, M., G.L. Malzer, D.J. Mulla, D.R. Huggins, and J. Strock. 2003. Spatial and temporal variation in economically optimum nitrogen rate for corn. Agron. J. 95:958–964. doi:10.2134/agronj2003.0958

Meisinger, J.J., V.A. Bandel, G. Stanford, and J.O. Legg. 1985. Nitrogen utilization of maize under minimal tillage and moldboard plow tillage: I. Four-year results using labeled N fertilizer on an Atlantic coastal plain soil. Agron. J. 77:602–611. doi:10.2134/agronj1985.0 00021962007700040022x

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347–351. doi:10.2134/agronj2003.0347

Oklahoma State University. 2016. Nitrogen use efficiency. Oklahoma State Univ., Stillwater. www.nue.okstate.edu (accessed 1 May 2016).

Olson, R.V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc. Am. J. 44:514–517. doi:10.2136/sssaj1980.03615995004400030015x

Olson, R.V., and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 48:583–586. doi:10.2136/sssaj1984.03615995004800030023x

Olson, R.A., W.R. Raun, S.C. Yang, and J. Skopp. 1986. Nitrogen management and inter seeding effects on irrigated corn and sorghum and on soil strength. Agron. J. 78:856–862. doi:10.2134/agronj198 6.00021962007800050023x

Peterson, T.A., and G.E. Varvel. 1989. Crop yield as affected by rotation and nitrogen rate: III. Maize. Agron. J. 81:735–738. doi:10.2134/agronj1989.00021962008100050007x

Rabalais, N.N., R.E. Turner, D. Justic, Q. Dortch, and W.J. Wiseman.1999. Characterization of hypoxia. Topic 1 Rep. for the integrated assessment of hypoxia in the northern Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Ser. No. 18. NOAA Coastal Ocean Program, Silver Spring, MD.

Randall, G.W., J.A. Vetsch, and J.R. Huffman. 2003. Maize production on a subsurface-drained mollisol as affected by time of nitrogen application and Nitra pyrin. Agron. J. 95:1213–1219. doi:10.2134/agronj2003.1213

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop nitrogen response. Precis. Agric. 12:508–518.doi:10.1007/s11119-010-9196-z

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820. doi:10.2134/agronj2002.8150

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357–363. doi:10.2134/agronj1999.00021962009100030001x

Raun, W.R., and G.V. Johnson. 1995. Soil-plant buffering of inorganic nitrogen in continuous winter wheat. Agron. J. 87:827–834.doi:10.2134/agronj1995.00021962008700050008x

Ribaudo, M., M. Livingston, and J. Williamson. 2012. Nitrogen management on US maize acres, 2001-10. Tech. Rep. EB-20. USDA–ARS, Washington, DC.

Rice, C.W., M.S. Smith, and R.L. Blevins. 1986. Soil nitrogen availability after long-term continuous no-tillage and conventional tillage maize production. Soil Sci. Soc. Am. J. 50:1206–1210. doi:10.2136/sssaj1986.03615995005000050023x

SAS Institute. 2011. SAS/STAT 9.3 user's guide. SAS Institute Inc., Cary, NC.

Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. Iowa State Univ. Extension, Ames.

Scharf, P.C.2001. Soil and plant tests to predict optimum nitrogen rates for corn. J. Plant Nutr. 24(6):805–826. doi:10.1081/PLN-100103775

Scharf, P., and J.A. Lory. 2000. Calibration of remotely sensed maize color to predict nitrogen need. In: 5th International Conf. on Precis. Agri. Proceedings. ASA-CSA-SSSA, Madison, WI.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, et al. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97:452–461.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, and J.G. Davis. 2006. Spatially variable maize yield is a weak predictor of optimal nitrogen rate. Soil Sci. Soc. Am. J. 70:2154–2160. doi:10.2136/sssaj2005.0244

Scharf, P.C., D.K. Shannon, H.L. Palm, K.A. Sudduth, S.T. Drummond, N.R. Kitchen, and L.F. Oliveira. 2011. Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103:1683–1691. doi:10.2134/agronj2011.0164

Schmitt, M.A., and G.W. Randall. 1994. Developing a soil nitrogen test for improved recommendations for maize. J. Prod. Agric. 7(3):328–334. doi:10.2134/jpa1994.0328

Shanahan, J. 2011. Determining optimum nitrogen rates for maize. Crop Insights 21(2):1–5.

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008.Responsive in-season nitrogen management for cereals. Comput. Electron. Agric. 61:51–62. doi: 10.1016/j.compag.2007.06.006

Shapiro, C.A., and C.S. Wortmann. 2006. Maize response to nitrogen rate, row spacing, and plant density in eastern Nebraska. Agron. J. 98:529–535. doi:10.2134/agronj2005.0137

Shapiro, C. A., R. B. Ferguson, and G. W. Hergert. 2008. Fertilizer suggestions for corn. NebGuide EC117. Univ. of Nebraska Ext., Lincoln.

Sims, J.T. 1998. Phosphorus soil testing: Innovations for water quality protection. Commun. Soil Sci. Plant Anal. 29:1471–1489.doi:10.1080/00103629809370044

Snyder, C.S. 2012. Are mid-west maize farmers over-applying fertilizer N? Better Crops Plant Food 96:3–4.

Stecker, J.A., D.D. Buchholz, R.G. Hanson, N.C.Wollenhaupt, and K.A. McVay. 1993. Broadcast nitrogen sources for no-till continuous maize and maize following soybean. Agron. J. 85:893–897.doi:10.2134/agronj1993.00021962008500040021x

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J.98:1488–1494. doi:10.2134/agronj2006.0103

Tremblay, N., Y.M. Bouroubi, C. Bélec, R.W. Mullen, N.R. Kitchen, W.E. Thomason, S. Ebelhar, D.B. Mengel, W.R. Raun, D.D. Francis, E.D. Vories, and I. Ortiz-Monasterio. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658–1671. doi:10.2134/agronj2012.0184

USDA–NASS. 2015a. 2014 Agricultural chemical use survey corn. NASS highlights No. 2015-1. USDA–NASS, Washington, DC. http://www.nass.usda.gov/Surveys/Guide to NASS Surveys/ Chemical_Use/2014_Corn_Highlights/ChemUseHighlights_Corn_2014.pdf (accessed 17 Sept. 2015).

USDA–NASS. 2015b. Crop production 2014 summary. USDA–NASS, Washington, DC.

USEPA. 2014. Mississippi River Gulf of Mexico Watershed Nutrient Taskforce. 2013 Hypoxic Zone. http://water.epa.gov/type/watersheds/named/msbasin/zone.cfm (accessed 14 July 2014).

Vanotti, M.B., and L.G. Bundy. 1994. An alternative rationale for maize nitrogen recommendations. J. Prod. Agric. 7:249–256. doi:10.2134/jpa1994.0249

Varvel, G.E., W.W. Wilhelm, J.F. Shanahan, and J.S. Schepers. 2007. An algorithm for maize nitrogen recommendations using a chlorophyll meter based sufficiency index. Agron. J. 99:701–706. doi:10.2134/agronj2006.0190

Van Es, H.M., B.D. Kay, J.J. Melkonian, and J.M. Sogbedji. 2006. Nitrogen management for maize in humid regions: Case for a dynamic modeling approach. In: T.W. Bruulsma, editor, managing crop nitrogen for weather: Proceedings of the Symposium “Integrating Weather Variability into Nitrogen Recommendations”, Indianapolis, IN. International Plant Nutrition Institute, Peachtree Corners, GA. p. 6-13.

Vetsch, J.A., and G.W. Randall. 2004. Maize production as affected by nitrogen application timing and tillage. Agron. J. 96(2):502–509. doi:10.2134/agronj2004.0502

Wienhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the Northern Great Plains. Agron. J. 87:842–846. doi:10.2134/agronj1995.00021962008700050010x

Woodruff, J.R., J.T. Ligon, and B.R. Smith. 1984. Water table depth interaction with nitrogen rates on sub-irrigated corn. Agron. J. 76(2):280–283. doi:10.2134/agronj1984.000219 62007600020025x

CHAPTER II

EFFECT OF PREPLANT/EARLY IRRIGATION, NITROGEN AND SEEDING RATE ON WINTER WHEAT GRAIN YIELD

ABSTRACT

Preplant or early irrigation in winter wheat (Triticum aestivum L.) can improve plant stands and lead to higher grain yields. Optimum seeding density more efficiently utilizes resources and optimizes yield. In lieu of groundwater storage continuing to decline, more precise and efficient utilization of water is needed. Wheat experiments were conducted to evaluate nitrogen (N) rate, seeding rate and early irrigation over three growing seasons near Stillwater, Oklahoma. Experimental design was a split-split plot with 3 replications and nine treatments, with irrigation as the main plot. Seeding rates of 45, 67 and 112 kg ha^{-1} were sub plots and that included three N rates (0, 67, 134 kg ha^{-1}) as sub-sub plots. Tiller count, head count and grain yields were collected. Mid-season biomass and harvest index were recorded. Results showed that, for different cropping seasons, grain yield, biomass, tillers, heads, grain N and harvest index depended either on the interaction effect or main effect or both. Early irrigation did not affect grain yield. Seeding rate and N rate were significant for number of heads. Midseason biomass weight was significant with irrigation. Harvest index was not significant for irrigation, seed rate and N rate or interaction effects. Grain yield response to irrigation varied considerably due to differences in rainfall received during the cropping season. This study showed for

the given environmental conditions, early irrigation has no effect on winter wheat grain yields.

INTRODUCTION

Climate in Oklahoma ranges from humid subtropical in the east to semi-arid in the west (Oklahoma Climatological survey, 2015). Water can be limiting for winter wheat production in arid and semi-arid regions. The year 2012 encountered a severe drought (Hoerling et al., 2014) and one of the most expensive natural disasters in U.S history. Crop indemnity payments exceeded $17 billion (USDA, 2013). As increasing drought duration and changing rainfall patterns continue, a growing challenge is to increase crop production with limited water supplies.

Winter wheat is the third largest crop in terms of production after corn and soybean in the US (USDA, 2016) and is a major dryland crop in Oklahoma. The Oklahoma had a total planted area of 2.2 and 2.1 million hectares (5.6 and 5.3 million acres) in 2013 and 2014 respectively (USDA-NASS, 2015). Wheat can be planted for forage only, grain only and dual purpose (forage and grain). Depending on the use, wheat farmers use different seeding rates, amount of N fertilizer and planting dates. Winter wheat in Oklahoma is either irrigated or rainfed. High Plains farmers apply water five times in a season: Before planting (usually in September or October), after planting, and with two to three irrigations between April and harvest (Peck and Kirkham, 1979). The Ogallala aquifer has been the source of irrigation in parts of this region.

However, in recent years, deficit irrigation is an alternative practice in winter wheat so as to compensate declining ground water resources and the high costs of pumping (Musick et al., 1994; Eck, 1988). Deficit irrigation allows conserving limited irrigation water by applying less water than required for potential evapotranspiration and maximum grain yield (Musick et al., 1994).

Soil water and wheat growth

The importance of available water for winter wheat yield and biomass can be explained in a number of ways. Winter wheat adapts well in drought or limited irrigation, attributed in part to deep roots that facilitate water and nutrient absorption in the soil profile (Aamodt and Johnston 1936). Understanding factors like soil characteristics and environmental conditions are crucial for water and nutrient uptake which further elucidate how plant roots respond to water limited conditions. Ray et al. (1974) suggested that small rooted plants can use limited water more efficiently. However, a large root system can increase grain yield by increasing water and N uptake under water limited conditions in Mediterranean type environments where crops depend largely on seasonal rainfall but increases the risk of depleting soil water in environments where crops are more reliant on stored soil water (Palta et al., 2011). Depending on the growing season rainfall, continuous cropping and elimination of fallow on dryland winter wheat can reduce soil water at planting as much as 11.8 cm and yield ranging from 450 to 1650 kg ha^{-1} (Nielsen et al., 2000). In a winter wheat experiment, N fertilizer treatments indicated soil water extraction occurred to a depth of 183 cm while control treatments were limited to the upper 91 cm (Brown, 1971). Grain yield was higher and a lesser amount of water was left in the N treated soils when measured at maturity.

All crop stages are not equally susceptible to soil moisture stress. Moisture stress at jointing, flowering and dough stages affect spring wheat yield in Arizona (Day et al., 1970). Wheat stressed at jointing is most critical and can decrease yield by reducing the total heads per unit area and reduce seeds per head. Stress at flowering and dough stage makes the seeds light in weight and also hastens maturity. Robins and Domingo (1962) studied limited irrigation of spring wheat at Prosser, Washington, and found that relatively high soil-moisture stress before the booting stage of plant development did not reduce yields. However, severe moisture stress from heading to grain maturation significantly decreased yields (10-35%). They further concluded that depletion of all available soil moisture prior to maturity should be completely avoided. Another study in Bushland, Texas suggested that adequate moisture from booting through grain filling could be an important factor influencing grain yield levels (Schneider et al., 1969). Similarly, Johnson and Kanemasu (1982) suggested with available irrigation option, pre-anthesis water application can give maximum positive effect on yield.

Soil moisture, N uptake, grain yield and water use efficiency

Several researchers in the 1990's showed that limited irrigation could maintain crop yield and improve product quality. Limited irrigation could also increase crop water use efficiency (WUE) (Zhang et al., 1998; Zhang et al., 2004). With early irrigation and N application, root growth was more extensive and rapid in a sandy loam soil and the increase in root growth was comparable with loamy sand soils. However, early irrigation had a much larger effect on the loamy sand (Gajri et al., 1989). Wheat grown in limited soil moisture at early growth stages yielded well on fine sandy loam, clay loam and heavy clay soils in a greenhouse experiment in Saskatchewan. Moisture stress late in the season yielded poor in loam soils however clay soil was able to better distribute moisture during critical periods (Lehane and Staple, 1959). Increasing available soil moisture at seeding from 0-8 inches could increase N recovery by 30-50 % in Wisconsin wheat (Ramig and Rhoades, 1963). Research under rainfall and available stored condition revealed N response to increased grain yields was positively correlated with increasing water storage but not affected by rainfall (Singh et al., 1975). When the initial water storage was higher, rainfed wheat roots depleted more water and stimulated deep rooting. Application of N increased soil water use and depth of soil water extraction at different moisture levels in winter wheat (Kmoch et al., 1957). Increasing N fertilizer rates can reduce winter wheat grain yield when water limiting conditions reduce the evapotranspiration rate to below 62% of the potential evapotranspiration (Nielsen and Halvorson, 1991).

Water stress during grain fill in wheat reduces photosynthesis and accelerates leaf senescence and thereby decreases grain yield (Kobata et al., 1992). Despite having a relatively deep root system in rainfed wheat, irrigated wheat yielded higher because of increased harvest index and higher water uptake during grain fill (Xue et al., 2003). Schillinger et al. (2008) conducted an experiment to compare wheat grain yield produced per unit of available soil water and spring rainfall for winter and spring wheat. The data showed winter wheat yield was higher than the spring wheat. They also found that modern semi-dwarf wheat cultivars use 4.2 cm less available water than taller cultivars.

Present literature has shown increased WUE with limited water supply during different growth stages of wheat. Experiments conducted by Bushong et al. (2014) near Altus, OK showed preplant irrigation could increase grain yield and WUE in winter wheat. Water use efficiency was maximized when evapotranspiration was around 35 % with an average 60-140 mm seasonal irrigation (Zhang et al., 2008). Furthermore, WUE for irrigated wheat doubled that of dryland wheat in the Southern Plains of the U.S (Musick et al., 1994).

Seeding rate and grain yield

Seeding rate is a major factor influencing nutrient uptake and grain yield. Seeding rate has long been studied as an integral part of wheat production and productivity (Geleta et al., 2002). Past research shows a variation in the response of winter wheat grain yield to seeding rate (Lloveras et al., 2004; Staggenborg et al., 2003). Optimum planting density can greatly vary depending on the climatic condition, soil, sowing time and varieties. Geleta et al. (2002) reported that grain protein concentration decreased with increased seeding rate. Grain volume weight was lowest at a seeding rate 16 kg ha^{-1} but increased when seeding rate was increased to 65 and 130 kg ha^{-1}. Kiesselbach and Sprague (1926) suggested that increasing the seed rate from 34 to 101 kg ha^{-1} resulted in a linear increase in grain yield and concluded that the seeding rates of 84 to 101 kg ha^{-1} were practical for eastern Nebraska. For Northern Great Plains spring wheat, Chen et al. (2007) recommended narrow row spacing for high grain yield. Olaru et al. (2008) suggested that seeding rates influenced quality indicators like wet gluten content. However, research conducted in North Dakota showed that seeding rate did not significantly affect grain quality, milling, and baking quality of winter wheat (Otteson et al., 2008). Staggenborg et al. (2003) showed that winter wheat requires different seeding and N rates when planted in no-till after grain sorghum and soybean. The research showed that seeding rates of 134 kg ha^{-1} or higher were able to produce maximum grain yields regardless of the previous crop which was 35 kg ha^{-1} higher than the recommended seeding rate for continuous winter wheat.

Nitrogen rate and grain yield

Proper N fertilizer management is necessary for winter wheat production in rainfed systems to optimize grain yield and protein. Terman et al. (1969) suggested that N applied with adequate water increases grain yield, and N with severe water deficit can increase grain protein whereas in intermediate situations, increase both grain yield and N. However, Halloran (1981) and Pearman et al. (1978) suggested that higher grain yields may not give higher protein as yield and protein are inversely related due to energy constraints and dilution effects within the plant. Nitrogen is mobile in the soil and plant and thus subject to loss through different processes. Nitrogen can be leached in the form of nitrates, volatilize from the soil surface and from the plant surface. The estimate of gaseous N loss from winter wheat plants ranged from 4 kg ha^{-1} to 27.9 kg ha^{-1} with preplant N rates ranging from 30 to 180 kg ha^{-1} and most of the loss observed between anthesis and 14 days post anthesis (Kanampiu et al., 1997). Sowers et al. (1994) recommended spring N application either top dress or injecting N over preplant application in dryland soft winter wheat to get higher N recovery and higher nitrogen use efficiency (NUE). Placement of N fertilizer is a critical part of N management and can influence both yield and NUE. Late season foliar N application can improve the grain yield and grain N content in winter wheat (Woolfolk et al., 2002).

Much of the research on irrigated winter wheat has shown higher yield ranging with seasonal and timely application of water. In Oklahoma, it would be interesting to see if the preplant/early irrigation application on winter wheat has some effect on the grain yield of dryland winter wheat that primarily depends on seasonal precipitation. The objectives of this research were to investigate the influence of (i) seeding rate (SR), (ii) N rate (NR), and (iii) early irrigation on biomass accumulation, grain yield, protein content, and harvest index (HI).

MATERIALS AND METHOD

Field trials for winter wheat were established at EFAW, southcentral Oklahoma for 3 years starting in the fall of 2013 in order to evaluate grain yield and biomass accumulation as a function of seeding rate, N rate and early irrigation. Central Oklahoma has a subtropical climate with long-term average annual precipitation of 86 cm (34 in) per year (Oklahoma Climatological survey, 2015). Based on the precipitation in Oklahoma, the year 2011 was the second driest since 1925 (Shivers and Andrews, 2013). Average length of growing season ranges from 170 to 230 days (Oklahoma Climatological survey, 2015). A brief summary of the soils utilized for each cropping season is reported in Table 3.

The experimental design was a split plot with irrigation as the main plot (Table 1 and 2). This design included 3 replications and 9 treatments in each main plot, with plot sizes of 3.05 m wide by 6.10 m long. There were 10 rows in each plot with a row spacing of 30.5 cm. Seeding rates 45, 67 and 112 kg ha^{-1} were randomized within N subplots (0, 67, 134 kg ha^{-1}). The seeding drill was calibrated for three seed rates. Irrigation was applied using mobile sprinkler units. The depth or thickness of water layer in the soil was calculated in cm using following formula.

$$\text{Water depth (cm)} = \frac{\text{Volume of water (cubic cm)}}{\text{Surface area of the field (squared cm)}}$$

The amount and time of irrigation is reported in Table 5. Plots not receiving irrigation were continuously tilled to expose the soil surface to deplete soil moisture while plots to receive irrigation were plowed once. Initial soil moisture content at surface was measured by using core method for 2013 and 2014. The gravimetric water content, bulk density, and volumetric water content calculated for 6 cm depth for the growing season 2014-15, and 2015-16 are reported in Table 2. The preplant soil chemical properties for (0-15 cm) and post-harvest soil chemical properties are represented in Table 4.

Green Seeker™ normalized difference vegetation index (NDVI) sensor readings were collected at Feekes growth stages 4, 5, 6 and 7. All NDVI readings were 30 cm above the canopy from the center of each plot. Green Seeker™ calculates NDVI with the formula:

NDVI = (NIRref – Redref)/ (NIRref + Redref)

Red reflectance (Redref) is calculated by dividing red reflected light by red incident light and similarly, NIR reflectance (NIRref) is calculated by dividing NIR reflected light by NIR incident light. Mid-season readings including tiller count/head-count was taken in 25 cm of each row, from five random rows in each plot. The total tiller count/head-count value for 1 m^2 was calculated using the formula:

$$\text{Tiller or head count} = \frac{100\ \text{cm} * \text{tillers or heads} * 3}{25\ \text{cm}}$$

The mid-season shoot biomass was taken at Feekes 5 growth stage of wheat.

Biomass was collected for 25 cm of two border rows in each plot. The biomass for 1 m^2 was calculated by using the formula:

$$\text{Biomass weight} = \frac{100\text{ cm } * \text{weight} * 3}{25\text{ cm}}$$

At maturity, wheat was harvested using a self-propelled combine in 2014 and manually for other years. Wheat above ground biomass at harvest was also collected using a 1m^2 frame from each plot. The initial weight of bundles and final weight after keeping them at room temperature for 2-3 days were collected. Grain was threshed and weighed separately. Harvest ratio was calculated using a wheat grain yield to biomass ratio. Samples collected from each plot were adjusted to 12.5% moisture. Grain samples were dried for 48 hours at 70°C, and then ground and rolled to pass a 100 µm sieve. Total grain N content was analyzed with a LECO TruSpec (LECO Corp., St. Joseph, MI) dry combustion analyzer (Schepers et al., 1989). Grain protein was calculated by multiplying total N by 5.7 (Mosse, 1990). Climatological data available online via Mesonet (mesonet.org) was used to understand the possible effects on the yield and biomass of winter wheat.

The dependent variables included grain yield, tiller count, head count, mid-season biomass, harvest index, NDVI, and grain N. Statistical analysis was performed to evaluate main and interaction effects of early irrigation, Seeding rate and N rate for each year and location. Analysis of variance (ANOVA) and means by year were performed for all the dependent variables using the GLM procedure from SAS software v.9.4 (SAS Inst., Cary NC).

RESULTS

Statistical analysis for all the dependent variables was performed by site and year. The treatment structure was same for all growing seasons and that is reported in Table 1. Field activities including preplant N application, planting wheat, irrigation, biomass collection, tiller count, head count, and harvest date for all growing seasons are reported in Table 5. Total rainfall and average air temperature data for all three growing seasons and the 19-year average from the nearest Mesonet© station, Stillwater are reported in Figures 1 and 2. In addition, the fractional water index (FWI) data for 5 and 25 cm depths are reported in Figures 3 and 4. Dependent variable results over three growing seasons are reported in Tables 6, 8, and 10. Main effects and interaction effects for all variables are reported in Tables 7, 9, and 11. Excel graphs are used to show the results for dependent variables with and without irrigation for each cropping season (Figure 5-22). The results are explained by each cropping season and include observations for all variables.

Cropping season 2013-14

Rainfall and temperature data by cropping season were compared to the 19-year average (Figure 1 and 2). The Mesonet© station, in Stillwater recorded the temperature range from 1ºC to 25 ºC. December through February was cool and a gradual increase in temperature afterward was favorable for wheat growth and development during the growing season. Although the rainfall was below average, 41 mm rain was received in November which was enough for initial wheat growth and development. Later in the growing season continuous rain was received and in June 126 mm was recorded. In addition, the fractional water index at 5 cm and 25 cm recorded a good soil moisture status for initial growth stages until March. The FWI at both depths was as low as 0.15 during mid-April to mid-May.

Grain yield

Grain yields for 2013-14 data ranged from 1682-1937 kg ha^{-1} and an average of 1845 kg ha^{-1} without early irrigation (Table 6). The check plot had highest yield above 1900 kg ha^{-1}. With early irrigation grain yields ranged from 1336-1512 kg ha^{-1} for which the highest seed rate with no N application (check plot) gave higher yield (Table 6). However, this was not even close to the minimum yield from the non-irrigated plot. Grain yields yielded higher and were above State average yields 1143 kg ha^{-1} (17 bu ac^{-1}) (USDA, 2016a). However, finding lower yields in the irrigated plots was not expected.

The main effect showed that grain yields were significantly different with irrigation treatment (Table 7). Grain yield level was highly significant for seeding rate, but not for N rate. A significant two-way interaction was observed between early irrigation and seed rate.

Tiller count and head count

Number of tillers ranged from 270-418 and 197-317 with an average of 357 and 261 for non-irrigated and irrigated plots respectively (Table 6). For the non-irrigated section, the tiller numbers were higher with highest seeding rate (112 kg ha^{-1}) .

However, there was not much difference between other seeding rates on tiller count. For the irrigated section, the number of tillers were lower even in the treatments with highest seeding rates. There were fewer heads compared to number of tillers in both irrigated and non-irrigated plots. The number of heads were not high at higher seed rates for non-irrigated sections. Number of heads ranged from 143-210 and 110-183 with an average of 164 and 138 for non-irrigated and irrigated sections respectively (Table 6).

Tiller number was highly significant for irrigation and seeding rate (Table 7). A significant two-way interaction between irrigation and seed rate and three-way interaction was observed between irrigation, seed rate and N. Number of heads were highly significant with irrigation and seed rate. Interactions were not observed (Table 7).

FK2/ FK3/ FK5/ FK7 NDVI

The NDVI values for FK2 ranged from 0.22-0.26 with an average of 0.24. Similarly, NDVI ranged from 0.22-0.30, 0.34-0.41, and 0.43-0.51 and averaged 0.25, 0.37 and 0.48 for FK3, FK5 and FK7 growth stages respectively (Table 3). The NDVI values increased with each growth stage. With irrigation the NDVI value ranged from 0.21-0.24, 0.21-0.27, 0.27-0.34 and 0.34-0.41 and averaged 0.23, 0.23, 0.3 and 0.37 for FK 2, FK3, FK5 and FK7 growth stages respectively (Table 6).

The NDVI values for FK2 were significant ($p \leq 0.01$) for irrigation and a significant interaction between irrigation and N rate was observed (alpha = 0.05) (Table 7). The FK3 NDVI values were significant for irrigation and seed rate. Both FK5 and FK7 NDVI were highly significant for irrigation (Figure 17, Table 7). Values for FK7 NDVI were highly significant for N application (Figure 18, Table 7).

Grain N

Grain N for non-irrigated and irrigated sections ranged from 21.3-25.3 g kg^{-1} and 22.3-25.7 g kg^{-1} with an average value of 23 g kg^{-1} and 25 g kg^{-1} respectively (Table 6). Clearly there was an inverse relationship between grain N and grain yield in irrigated and non-irrigated sections. Yields were higher for non-irrigated and while grain protein was lower and vice-versa for irrigated plots. Grain N was highly significant ($p \leq 0.001$) for irrigation and N rate. Similarly grain N was significant ($p \leq 0.05$) for seed rate (Table 7).

Cropping season 2014-15

Days were cooler from December to February and gradually got warmer in March when compared to the 19-year average. Although rainfall was below average from October to April, monthly rainfall distribution was uniform and enough rainfall was received during the wheat growing cycle. The soil had good amount of moisture for initial growth and development. The fractional water index for the 5cm depth was above 0.6 throughout the growing season (Figure 3). The fractional water index for the 25 cm depth ranged from 0.92-0.41 (Figure 4). Rainfall was highest (234 mm) in May (Figure 2). The soil was wetter late in the growing season.

Grain yield

Yield data from 2014-15 ranged from 1017-1767 kg ha^{-1} with an average of 1344 kg ha^{-1} for non-irrigated plots. This year yields for irrigated plots were higher and ranged from 1267-2017 kg ha^{-1} with an average of 1535 kg ha^{-1}. Overall yield for irrigated and non-irrigated plots were lower than the Oklahoma State average which was 1748 kg ha^{-1} (26 bu ac^{-1}) (USDA, 2016a) (Table 8).

Grain yield was significant for seed rate and N rate at the 5% probability levels (Table 9). No interactions were found to be significant.

Mid-season biomass

The biomass collected in the FK5 stage ranged from 31-65 g m^{-2} and 23.5-61 m^{-2} and averaged 52 g m^{-2} and 38 g m^{-2} for non-irrigated and irrigated plots (Table 8). Plots with no irrigation had higher biomass than irrigated plots. Treatments with higher seed rates had higher biomass weight. The biomass weight was significant ($p \leq 0.05$) for irrigation and seed rate. No other main effect and/or interaction effects were significant (Table 9).

Head count

Number of heads ranged from 171-245 m^{-2} with an average of 199 m^{-2} without irrigation and ranged from 172-307 m^{-2} with an average of 224 m^{-2} with irrigation (Table 8). Number of heads were significant for irrigation, seed rate, and N rate at 0.05, 0.01 and 0.05 probability levels respectively (Table 9).

FK3/ FK4/ FK6 NDVI

The NDVI values for FK3, FK4 and FK6 ranged from 0.24-0.29, 0.30-0.35, 0.56-0.75 with an average of 0.26, 0.32, and 0.68 respectively for non-irrigated plots (Table 8). For irrigated sections, the FK3 ranged from 0.23-0.30 with an average of 0.26, FK4 values ranged from 0.27-0.31 with an average of 0.29 and FK7 ranged from 0.57-0.75 with an average of 0.67 respectively. Values for FK3 NDVI were highly significant ($p \leq 0.001$) for seed rate (Table 9). A significant ($p \leq 0.05$) two-way interaction was observed between seed rate and N rate. At Feekes growth stages 4 NDVI value was significant for irrigation and seed rate at the 0.01probability level. Similarly, FK6 NDVI was significant for seed rate and N rate at the 0.01 probability level (Figure 19, 20). A significant ($p \leq 0.05$) two-way interaction was found between irrigation and seed rate (Table 9).

Harvest index

Harvest index ranged from 0.24-0.33 and 0.27-0.58 with an average of 0.29 and 0.46 for non-irrigated and irrigated sections, respectively (Table 8). The value was comparatively higher for irrigated plots. Harvest index was not significantly different for main effects and/or interactions effect (Table 9).

Grain N

Grain N ranged from 22-24 g kg^{-1} and 21-24 g kg^{-1} for non-irrigated and irrigated sections, respectively with an average of 23 g kg^{-1} for both of the sections (Table 8). Grain N was significant for seed rate and N rate at 0.05 and 0.01 probability levels, respectively (Table 9).

Cropping season 2015-16

January to March was cooler and got warmer in March (Figure 1). The total monthly rainfall data fluctuated when compared with the 19-year average. The year 2015-16 received higher rainfall over the growing season which was above 50 mm for all months except January and February. The highest was 141 mm in April. Fractional water index for the 5 cm depth recorded an average of 0.65 and this index was better at the 25 cm soil depth and documents adequate soil moisture conditions for proper growth and development of winter wheat.

Grain yield

Grain yield level for 2015-16 ranged from 1119-1799 kg ha^{-1} and 1043-1860 kg ha^{-1}, yielded an average of 1393 kg ha^{-1} and 1477 kg ha^{-1} without and with irrigation, respectively (Table 10). There was no significant difference between the irrigated and non-irrigated plots. Rainfall during the cropping season might have minimized the yield difference. Grain yield was not significantly different for either main effect or interaction effect (Table 11). Despite of the suitable environmental and rainfall conditions available for the winter wheat growth grain yields were much lower than the State average yield 2690 kg ha^{-1} (40 bu ac^{-1}) (USDA, 2016b).

Mid-season biomass

Mid-season biomass recorded ranged from 25.8-36.3 g m^{-2} and 29-33 g m^{-2} with an average value of 33 g m^{-2} and 19 g m^{-2} without and with irrigation, respectively. Biomass was higher for non-irrigated sections (Table 10). Biomass was significant for irrigation at the 0.05 probability level (Table 11).

Head Count

Head count number ranged from 204-319 m^{-2} and 183-289 m^{-2} and an average of 274 m^{-2} and 235 m^{-2}, respectively without and with irrigation (Table 10). Higher yields were expected with higher head counts for non-irrigated plots. Similarly, it was significantly different for seed rate and N rate at 0.01 and 0.05 probability levels, respectively (Table 11).

FK1/ FK2/ FK3/ FK4/ FK5/ FK6/ FK7 NDVI

The NDVI values recorded had a range of 0.17-0.18, 0.21-0.26, 0.23-0.31, 0.30-0.41, 0.49-0.77, 0.55-0.76, and 0.55-0.75 for FK, FK2, FK3, FK4, FK5, FK6, and FK7 growth stages with an average value of 0.18, 0.23, 0.27, 0.36, 0.66, 0.66, and 0.67 in respectively without irrigation (Table 10). Similarly, with irrigation NDVI values ranged from 0.17-0.18, 0.19-0.24, 0.19-0.27, 0.25-0.38, 0.45-0.64, 0.44-0.68 and 0.49-0.68 for FK1, FK2, FK3, FK4, FK5, FK6, and FK7 with an average value of 0.18, 0.22, 0.24, 0.32, 0.57, 0.57, and 0.59 respectively (Table 10). The average NDVI value increased as biomass increased at each growth stage.

The NDVI values for FK5, FK6, and FK7 were highly significant ($p \leq 0.001$) for irrigation and N rate. For FK5 and FK6 significant two way interactions were observed between irrigation and seed rate at the 0.05 probability level. The values of NDVI for FK1-FK4 were highly significant ($p \leq 0.001$) for seed rate (Table 11).

Harvest index

Harvest index ranged from 0.18-0.32 and 0.18-0.33 and averaged 0.23 and 0.26 without and with irrigation, respectively (Table 10). Harvest index was not significant for either main effect or interactions effect (Table 11).

Grain N

Grain N content with and without irrigation ranged from 18.7-20 g kg^{-1} and 17-21.3 g kg^{-1} respectively with an average of 19 g kg^{-1} for both (Table 10). Grain N was significant for N rate, seed rate and the interaction between irrigation and seed rate at 0.001, 0.01, and 0.01 respectively (Table 11).

DISCUSSION

Grain yield was higher without irrigation in 2013. Fractional water index was above 0.65, and 0.6 at 25 cm and 5 cm depth of soil throughout the growing season indicating no soil moisture constraint. Initial volumetric water content showed an average 15 % for the non-irrigated plots and average 19 % for irrigated plots (Table 2). Winter wheat in this year received enough rainfall for initial growth and development. Yield was significant for main effects: seeding rate, and irrigation, and interaction effects of irrigation and seed rate although highest yield was observed with no preplant N application in 2013. The tillers and heads were higher at higher seeding rates. Research suggested higher tillering at higher seed rates (Hameed et al., 2003, Khokar et al., 1985). Higher seed rate provides greater number of primary tillers per square meter, which causes the formation of grains with larger size and mass (Zecevic et al., 2013). The tillers and heads were higher for the non-irrigated plots and this might have contributed to higher yields (Figure 7). With lower seeding rates a greater number of secondary tillers were created which produce small grains with less weight and poor quality. In addition, the check plot yielded more than N treated plots and suggests the possibility of higher N mineralization that led to higher yields. Similar results were observed with other long-term experiments and that were reported by Dhital and Raun (2016).

In 2014-15 grain yield was not significant for irrigation. Puri et al. (1988) suggested one irrigation at tillering could significantly increase grain yield and grain yield components when compared to the only preplant irrigation. Grain yield was only significant for two main effects: seed rate and N rate. The overall grain yield was lower than the state average yield 1748 kg ha^{-1} (26 bu ac^{-1}). A possible reason for yield loss could be the late November planting. Zeb at al. (1987) suggested that grain yield decreased progressively with delayed planting. Winter and Musick (1993) found November planting reduced grain yield because of insufficient rooting to fully extracts soil water from below 1.2 m. In addition, initial soil N level was lower than expected.

Presence of weeds might also have impacted yields. Herbicides were sprayed for weed control but continuous rain later in the growing season promoted growth of wild buckwheat. Thus the presence of weeds might have contributed to the lower yields for 2014-2015. Similarly, Grain yields were not significant for irrigation for 2015-16. This might be possible because enough rainfall was received throughout the growing season.

Grain N was significant for main effects: seed rate, N rate and irrigation. Similarly, significant for interaction effects: irrigation and replication; and irrigation, and seed rate. In addition, grain N linearly increased with increased N rate for irrigated conditions for 2013-14. In 2014-15 grain N was significant for two main effects seed rate and N rate. Overall grain N was higher in the check plot than other preplant applied N plots (Figure 9). Similarly, for 2015-16 grain N was significant for two main effects: N rate, seed rate, and interaction of seed rate and irrigation. Also, preplant soil N level and midseason soil N level was lower (Table 2).

Mid-season biomass weight was significant for irrigation for both years. Biomass weight was significant for N rate for 2014-15. Harvest index was not significant for main effects and interaction effects for both years. Tiller and head counts were highly significant for irrigation, and seed rate. A significant two-way interaction was observed between irrigation and seed rate for year 2013-14. Similarly, a significant two-way interaction between irrigation and seed rate was found for tillers. Heads were significant for irrigation, seed rate and N rate.

CONCLUSIONS

The objective of this study was to investigate the influence of seeding rate, N rate and early irrigation on biomass accumulation, grain yield, protein content and harvest index.

Early irrigation did not affect grain yield. Grain yields were not significantly different for all years. Grain yield response to irrigation varied considerably due to differences in rainfall received during the cropping season. Nitrogen rate positively influenced N uptake and amount of grain N. Seeding rate and N rate were significant for number of heads. Midseason biomass weight was significant with irrigation. Harvest index was not significant for either main effects or interaction effects.

This study showed for the given environmental conditions, early irrigation has no effect on winter wheat grain yields. This observation needs to be tied to wheat production environments where enough rainfall was received over the growing season for adequate growth and development.

REFERENCES

Aamodt, O. S., and W. H. Johnston. 1936. Studies on drought resistance in spring wheat. Canadian Journal of Research, 14(3), 122-152.b

Akram, M., 2011. Growth and yield components of wheat under water stress of different growth stages. Bangladesh Journal of Agricultural Research, 36(3), 455-468.

Brown, P. L., 1971. Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. Agron. J. 63(1), 43-46.

Bauer, A., R. A.Young and J. L. Ozbun. 1965. Effects of moisture and fertilizer on yields of spring wheat and barley. Agron. J. 57(4), 354-356.

Bushong, J. T., D. B. Arnall and W. R. Raun. 2014. Effect of Preplant Irrigation, Nitrogen Fertilizer Application Timing, and Phosphorus and Potassium Fertilization on Winter Wheat Grain Yield and Water Use Efficiency. Int. J. Agron.

Chen, C., K. Neill, D. Wichman and M. Westcott. 2008. Hard red spring wheat response to row spacing, seeding rate, and nitrogen. Agron. J. 100(5), 1296-1302.

Crop Production 2014 Summary. 2015 United States Department of Agriculture National Agricultural Statistics Service. Accessed on March 26: http://www.usda.gov/nass/PUBS/TODAYRPT/cropan15.pdf

Day, A. D., and S. Intalap. 1970. Some effects of soil moisture stress on the growth of wheat (Triticum aestivum L. em Thell.). Agron. J. 62(1), 27-29.

Debaeke, P., and A. Aboudrare. 2004. Adaptation of crop management to water-limited environments. Euro. J. Agron. 21(4), 433-446.

Dhital, S., and W. R. Raun. 2016. Variability in Optimum Nitrogen Rates for Maize. Agron. J.

Eck, H. V., 1988. Winter wheat response to nitrogen and irrigation. Agron. J. 80(6), 902-908.

Engel, R. 1993. Winter wheat response to available nitrogen and water. Montana State University, Ext. Service.

Epplin, F. M., D. E. Beck, E. G. Krenzer, and W. F. Heer. 1993. Effects of planting dates and tillage systems on the economics of hard red winter wheat production. J. Prod. Ag. 6(1), 57-62.

Epplin, F. M., True, R. R., and E. G. Krenzer. 1998. Practices used by Oklahoma wheat growers by region. Okla. Curr. Farm Econ, 71, 14-23.

Fischer, R. A., and G. D. Kohn. 1966. The relationship of grain yield to vegetative growth and post-flowering leaf area in the wheat crop under conditions of limited soil moisture. Crop and Pasture Science, 17(3), 281-295.

Frederick, J. R., and J. J. Camberato. 1995. Water and Nitrogen Effects on Winter Wheat in the Southeastern Coastal Plain: II. Physiological Responses. Agron. J. 87(3), 527-533.

Gajri, P. R., S. S. Prihar and V. K. Arora. 1989. Effects of nitrogen and early irrigation on root development and water use by wheat on two soils. Field Crops Research, 21(2), 103-114.

Gajri, P. R., Prihar, S. S., and V. K. Arora. 1993. Interdependence of nitrogen and irrigation effects on growth and input-use efficiencies in wheat. Field Crops Research, 31(1), 71-86.

Geleta, B., M. Atak, P. S. Baenziger, L. A. Nelson, D. D. Baltenesperger, K. M. Eskridge, M. J. Shipman and D. R. Shelton. 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Crop Science, 42(3), 827-832.

Guru, M. V., and J. E. Horne. 2000. The Ogallala Aquifer. Kerr Center for Sustainable Agriculture.

Halloran, G.M., 1981. Cultivar differences in nitrogen translocation in wheat. Aust. J. Exp. Agric. 32:535-544.

Hameed, E., W. A. Shah, A. A. Shad, J. Bakht, and T. Muhammad. 2003. Effect of different planting dates, seed rate and nitrogen levels on wheat. Asian J. Plant Sci.

Hatfield, J. L., T. J. Sauer and J. H. Prueger. 2001. Managing soils to achieve greater water use efficiency. Agron. J. 93(2), 271-280.

Heer, W. F., and E. G. Krenzer. 1989. Soil water availability for spring growth of winter wheat (Triticum aestivum L.) as influenced by early growth and tillage. Soil and Tillage Research, 14(2), 185-196.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager. 2014. Causes and predictability of the 2012 Great Plains drought. Bulletin of the Ame. Mete. Soc., 95(2), 269-282.

Hossain, I., F. M. Epplin and E.G. Krenzer. 2004. Wheat Production and Management Practices used by Oklahoma Grain and Livestock Producers. Oklahoma State University Agricultural Experiment Station. Bulletin no. B-818.

Johnson, R. C., and E. T. Kanemasu. 1982. The influence of water availability on winter wheat yields. Canad. J. Plant Science, 62(4), 831-838.

Kanampiu, F. K., Raun, W. R., and G. V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. of Plant Nutr. 20 (2&3):389-404.

Kiesselbach, T. A., and H. B. Sprague. 1926. Relation of the development of the wheat spike to environmental factors. Agron. J., 18(1), 40-60.

Kmoch, H. G., R. E. Ramig, R. L. Fox, and F. E. Koehler. 1957. Root development of winter wheat as influenced by soil moisture and nitrogen fertilization. Agron. J. 49(1), 20-26.

Kobata T, J.A, Palta and N.C. Turner.1992. Rate of development of post-anthesis water deficits and grain filling of spring wheat. Crop Sci. 1992; 32:1238–42.

Lehane, J. J., and W. J. Staple. 1962. Effects of soil moisture tensions on growth of wheat. Can. J. Soil Sci. 42(1), 180-188.

Lloveras, J., J., Manent, J., Viudas, A., López and P. Santiveri. 2004. Seeding rate influence on yield and yield components of irrigated winter wheat in a Mediterranean climate. Agron. J. 96(5), 1258-1265.

Mosse, J., 1990. Nitrogen-to-protein conversion factor for ten cereals and six legumes or oilseeds. A reappraisal of its definition and determination. Variation according to species and to seed protein content. J. Agri. and Food Chem. 38(1), 18-24.

Musick, J. T., and S. R. Winter. 1994. Effect of wheat planting date on soil water extraction, growth, and yield. In Proc. Intens. Wheat Mgmt. Con. (pp. 144-157).

Musick, J. T., O. R. Jones, B. A. Stewart, and D. A. Dusek, 1994. Water-yield relationships for irrigated and dryland wheat in the US Southern Plains. Agron. J. 86(6), 980-986.

Musick, J. T., and F. R. Lamm. 1990. Preplant irrigation in the Central and Southern High Plains. A review. Trans. ASAE, 33(6), 1834-1842.

Nielsen, D. C., M. F. Vigil, R. L. Anderson, R. A. Bowman, J. G. Benjamin, and A. D. Halvorson. 2000. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94(5), 962-967.

Nielsen, D. C., and A. D. Halvorson. 1991. Nitrogen fertility influence on water stress and yield of winter wheat. Agron. J. 83(6), 1065-1070.

Oklahoma Climatological Survey. 2015. Climate of Oklahoma accessed on March, 2015: http://climate.ok.gov/index.php/site/page/climate_of_oklahoma.

Olaru, L., F. Oncică, and G. Matei. 2008. Responses of wheat grain yield and quality to seed rate in central part of Oltenia, Romania. In Proceedings of 43rd Croatian and 3rd International Symposium on Agriculture, Opatija, Croatia (pp. 588-590).

Otteson, B. N., M. Mergoum, and J. K. Ransom. 2008. Seeding rate and nitrogen management on milling and baking quality of hard red spring wheat genotypes. Crop Science, 48(2), 749-755.

Palta, J. A., X. Chen, S. P. Milroy, G. J. Rebetzke, M. F. Dreccer, and M. Watt. 2011. Large root systems: are they useful in adapting wheat to dry environments? Functional Plant Biology, 38(5), 347-354.

Pearman, I., S.M. Thomas, and G.N. Thorne. 1978. Effect of nitrogen fertilizer on growth and yield of semi-dwarf and tall varieties of winter wheat. Agron. J. 91:31-45.

Peck, R. A., and M. B. Kirkham. 1979. Water Relations and Yield of Winter Wheat Grown Under Three Water Regimes in the High Plains. In Proc. Okla. Acad. Sci (Vol. 59, pp. 53-59).

Puri, Y. P., M. F. Miller, R. N. Sah, K. G. Baghott, E. Fereres-Castel and R. D. Meyer. 1989. Response surface analysis of the effects of seeding rates, N-rates and irrigation on durum wheat. II. Protein yield and grain quality. Phyton.

Ramig, R. E., and H. F. Rhoades. 1963. Interrelationships of Soil Moisture Level at Planting Time and Nitrogen Fertilization on Winter Wheat Production. Agron. J. 55(2), 123-127.

Ray, L. L., C. W. Wendt, B. Roark, and J. E. Quisenberry. 1974. Genetic modification of cotton plants for more effective water use. In: J. F. Stone (Editor), Plant Modification for More Efficient Water. Agric. Meteorol. 14:31--38.

Robins, J. S., and C. E. Domingo. 1962. Moisture and nitrogen effects on irrigated spring wheat. Agron. J. 54(2), 135-138.

Schepers, J. S., D. D. Francis, and M. T. Thompson. 1989. Simultaneous determination of total C, total N, and 15N on soil and plant material 1. Commun. Soil Sci. and Plant Anal. 20(9-10), 949-959.

Schillinger, W. F., S. E. Schofstoll, and J. R. Alldredge. 2008. Available water and wheat grain yield relations in a Mediterranean climate. Field crops research, 109(1), 45-49.

Schneider, A. D., Musick, J. T., and Dusek, D. A. 1969. Efficient wheat irrigation with limited water. Transactions of the ASAE, 12(1), 23-0026.

Shivers, M. J., and W. J. Andrews. 2013. Hydrologic Drought of Water Year 2011 Compared to Four Major Drought Periods of the 20th Century in Oklahoma. US Department of the Interior, US Geological Survey.

Singh, R., Y. Singh, S. S. Prihar and P. Singh. 1975. Effect of N fertilization on yield and water use efficiency of dryland winter wheat as affected by stored water and rainfall. Agron. J. 67(5), 599-603.

Sowers, K. E., Miller, B. C., and W. L. Pan.1994. Optimizing yield and grain protein in soft white winter wheat with split nitrogen applications. Agron. J. 86(6), 1020-1025.

Staggenborg, S. A., D. A. Whitney, D. L. Fjell and J. P. Shroyer. 2003. Seeding and nitrogen rates required to optimize winter wheat yields following grain sorghum and soybean. Agron. J. 95(2), 253-259.

Terman, G. L., R. E. Ramig, A. F. Dreier, and Olson, R. A. 1969. Yield-protein relationships in wheat grain, as affected by nitrogen and water. Agron. J. 61(5), 755-759.

United States Department of Agriculture. 2013. Crop production 2012 summary USDA Doc. (2013) 95 pp. Available at: http://usda01.library. cornell.edu/usda/nass/CropProdSu/2010s/2013/CropProdSu-01-11-2013.pdf

United States Department of Agriculture, National Agricultural Statistics Service. 2016a. Crop production 2015 summary. National Agriculture Statistics Service. Accessed on: 5/25/2016. http://www.usda.gov/nass/PUBS/TODAYRPT/cropan16.pdf.

United States Department of Agriculture, National Agricultural Statistics Service. 2016b. Crop Production (August 2016) USDA, Accessed on: http://www.usda.gov/nass/PUBS/TODAYRPT/crop0816.pdf

Wajid, A. F. T. A. B., A. B. I. D. Hussain, A. S. H. F. A. Q. Ahmad, A. R. Goheer, M. U. H. A. M. M. A. D. Ibrahim and M. Mussaddique, 2004. Effect of sowing date and plant population on biomass, grain yield and yield components of wheat. Int. J. Ag. & Bio. 6, 1003-1005.

Winter, S. R., and J. T. Musick. 1993. Wheat planting date effects on soil water extraction and grain yield. Agron. J. 85(4), 912-916.

Woolfolk, C. W., W. R. Raun, G. V. Johnson, W. E. Thomason, R. W. Mullen, K. J. Wynn, and K. W. Freeman. 2002. Influence of late-season foliar nitrogen applications on yield and grain nitrogen in winter wheat. Agron. J. 94(3), 429-434. Xue, Q., Z. Zhu, J. T. Musick, B. A. Stewart and D. A. Dusek. 2003. Root growth and water uptake in winter wheat under deficit irrigation. Plant and Soil, 257(1), 151-161.

Zecevic, V., J. Boskovic, D. Knezevic, and D. Micanovic. 2014. Effect of seeding rate on grain quality of winter wheat. Chilean J. Agric. Res. 74(1), 23-28.

Zeb, A., A. Blodshah, M. Ahmad, T. Muhammad and I. Khan, 1987. Yield and yield quality response of different wheat cultivars to date of sowing. Sarhad J. Agric., 3: 431-440.

Zhang, J., X. Sui, B. Li, B. Su, J. Li, and D. Zhou. 1998. An improved water-use efficiency for winter wheat grown under reduced irrigation. Field Crops Research, 59(2), 91-98.

Zhang, Y., E. Kendy, Y. Qiang, L. Changming, S. Yanjun, and S. Hongyong. 2004. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. Agric. Water Mgmt. 64(2), 107-122.

APPENDICES

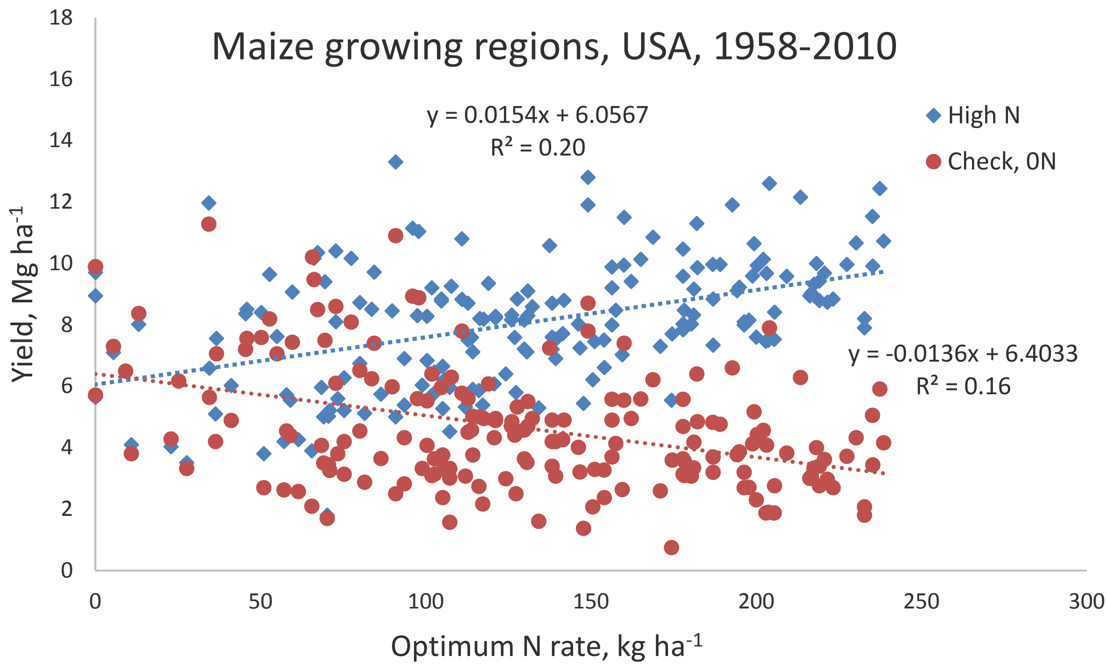

Figure 1. Relationship between maize grain yield and optimum N rate computed using the Zero-N check and the high N rate, maize growing regions of the United States, 1958-2010.

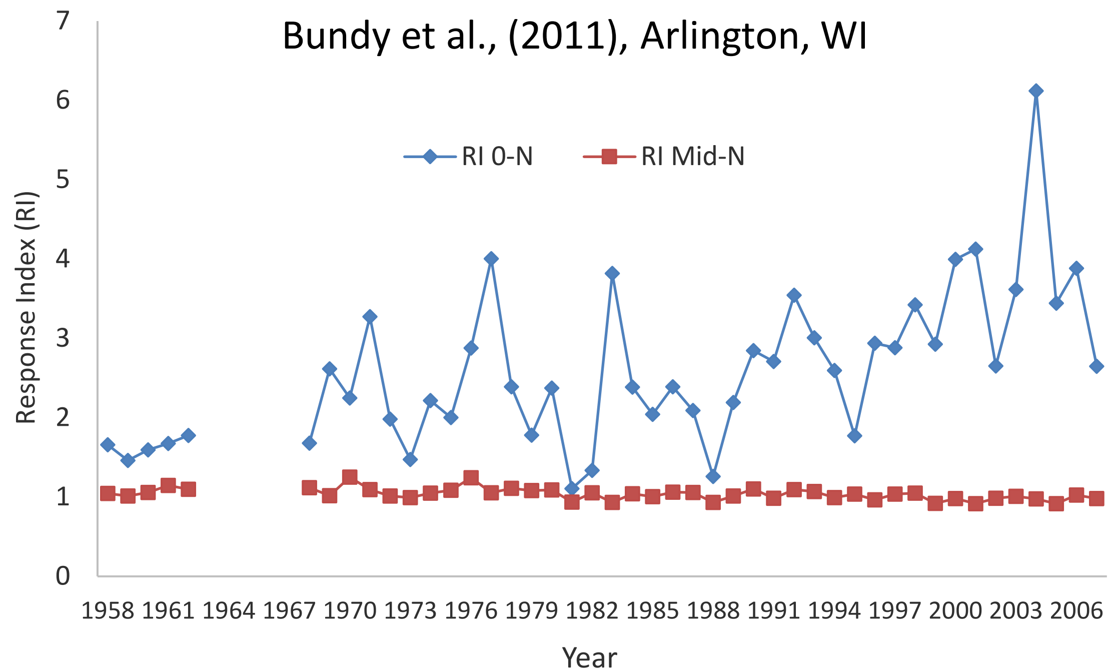

Figure 2. Nitrogen response Index (RI) in a conventional-till maize experiment over 49 years, Arlington, WI. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

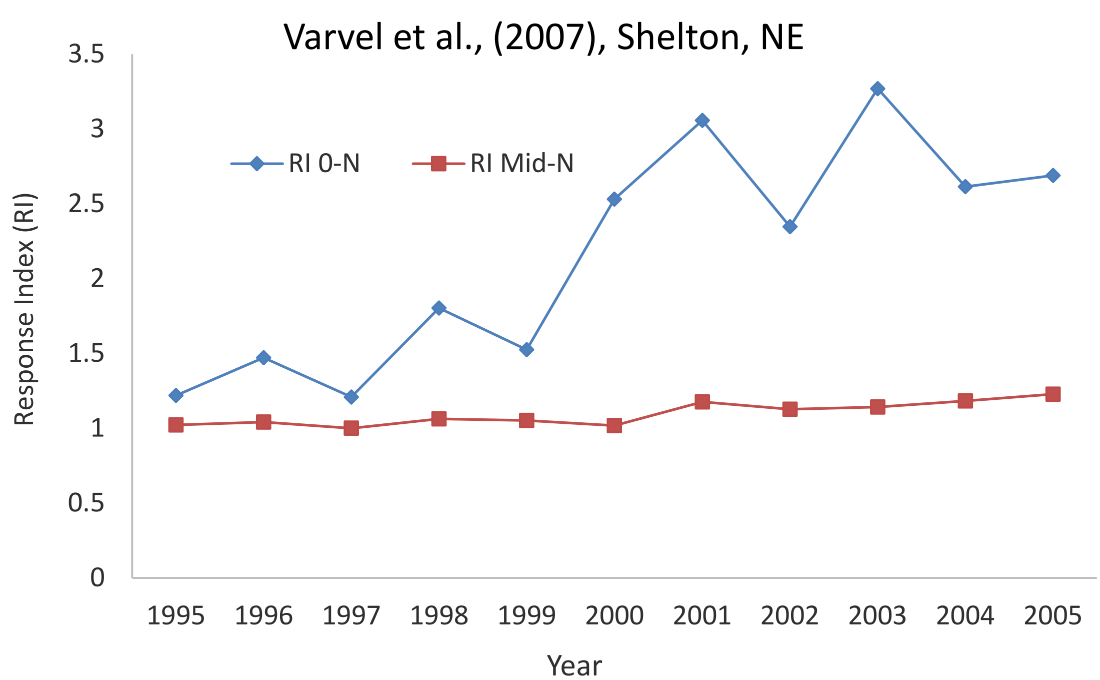

Figure 3. Nitrogen response Index (RI) in a conventional-till maize experiment over 11 years, Shelton, NE. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

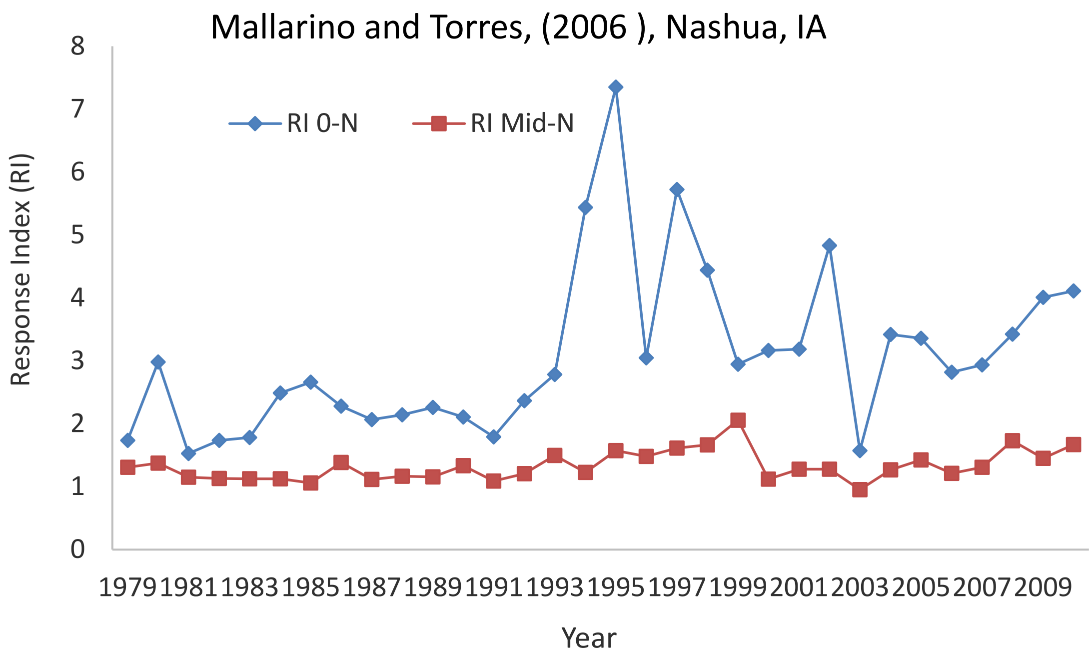

Figure 4. Nitrogen response Index (RI) in a conventional-till maize experiment over 32 years, Nashua, IA. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

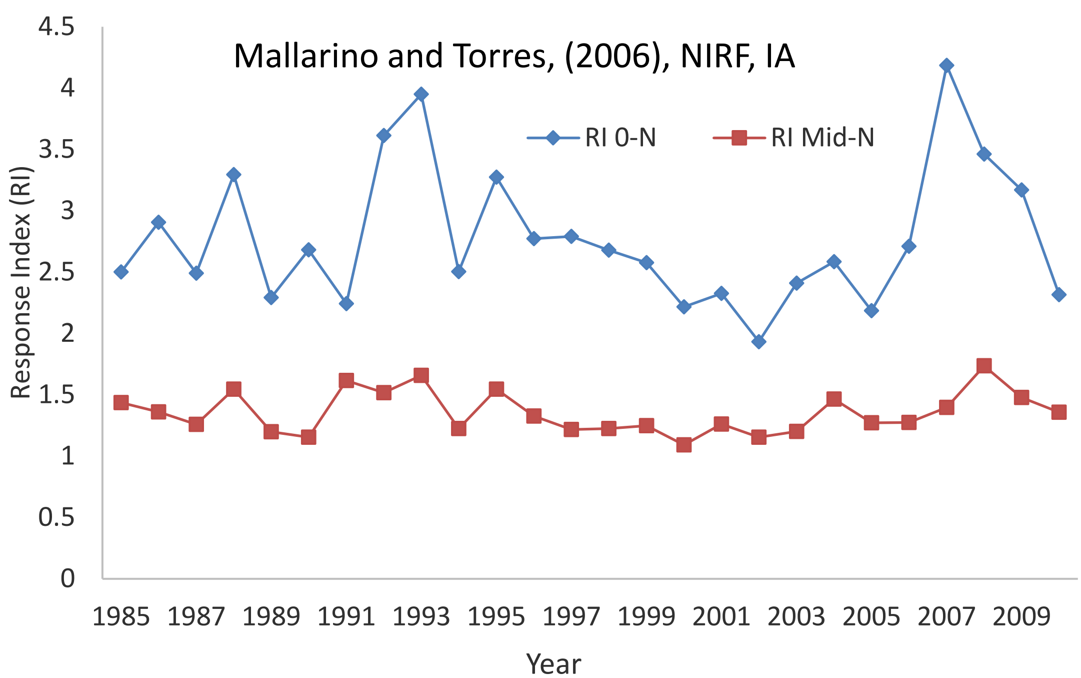

Figure 5. Nitrogen response Index (RI) in a conventional-till maize experiment over 25 years, NIRF, Kanawha, IA. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

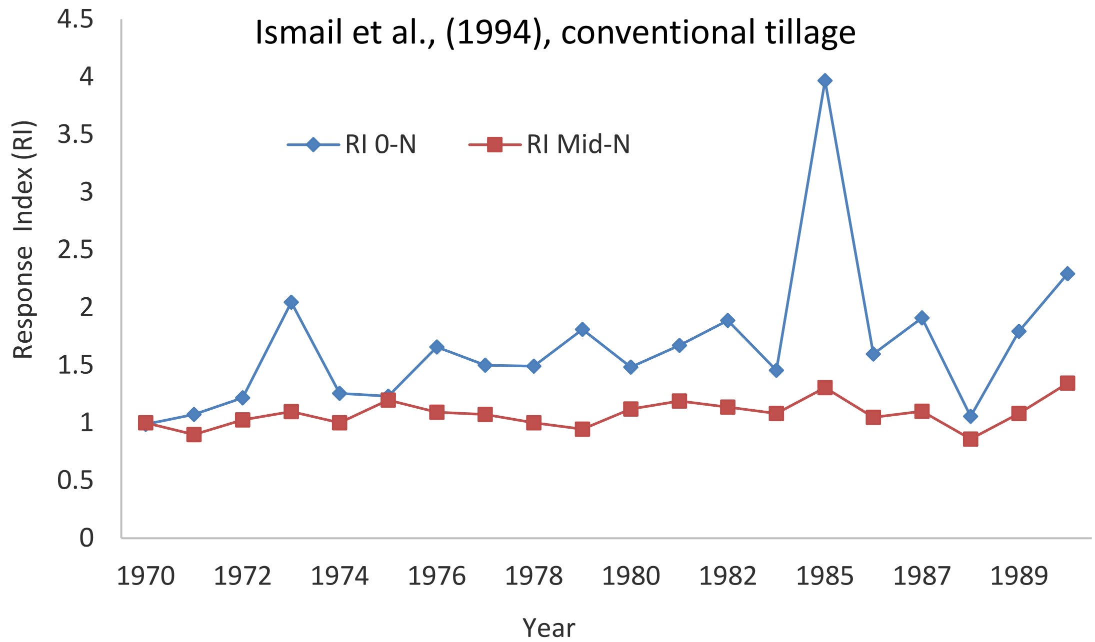

Figure 6. Nitrogen response Index (RI) in a conventional till maize experiment, over 20 years, Lexington, KY. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

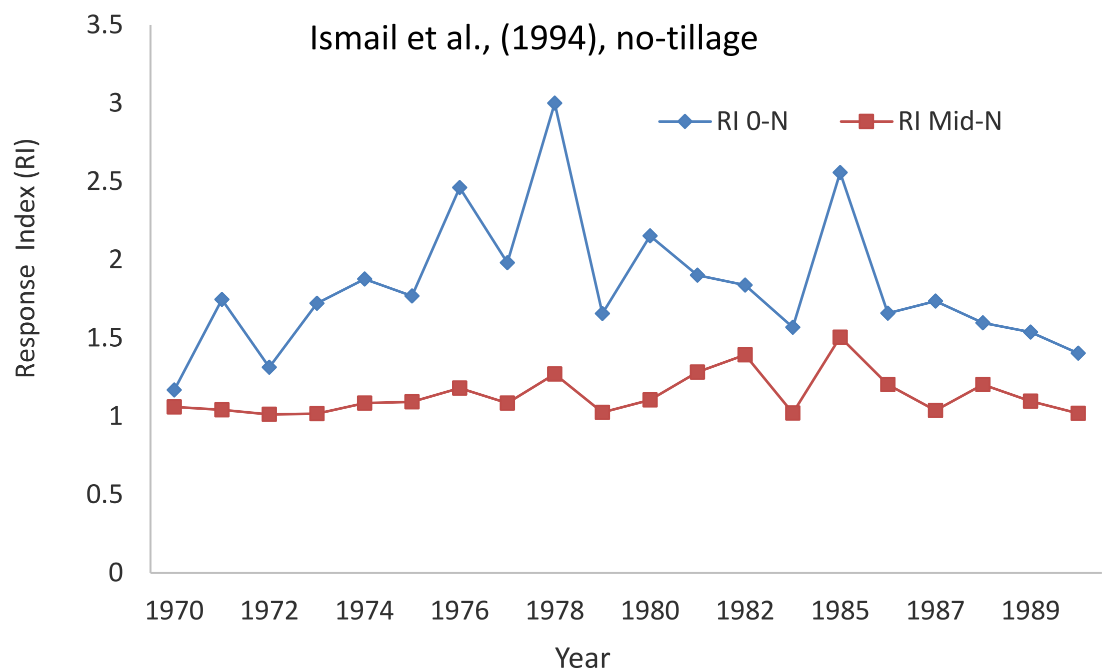

Figure 7. Nitrogen response Index (RI) in a no-tillage maize experiment, over 20 years, Lexington, KY. (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high N rate yield by mid N rate yield).

Table 1. Maize grain yield for the 0-N treatment (check plot), high-N treatment, and a computed optimum N rate in 26 field experiments that included 198 site years of published data in maize growing regions of the United States 1958–2010.

Source †	Location	Years	Time period	Yield Range		Optimum N rate¶			
				0-N ‡	High N ʛ	Min	Max	Avg.	SD
				-------- Mg ha-1 --------		--------- kg ha-1---------			
Bundy et al. (2011)	WI	21	1958-1983	1.6-7.6	4.3-8.8	50	233	130	53
Bundy et al. (2011)	WI	9	1984-1997	2.7-5.6	5.7-9.96	58	235	179	51
Mallarino and Torres (2006)	IA	20	1979-2003	0.8-5.9	5.1-12.4	81	237	165	49
Mallarino and Torres (2006)	IA	14	1985-2010	1.4-6.2	5.3-12.8	134	239	197	32
Varvel et al. (2007)	NE	5	1995-2005	6.6-10.9	10.4-13.3	73	193	131	49
Jokela et al. (1989) Carroll	MN	3	1982-1984	5.5-7.3	7.1-9.1	5	131	84	69
Jokela et al. (1989) Webster	MN	3	1982-1984	1.7-5.6	1.8-8.7	70	113	91	21
Fenster et al. (1976) Waseca	MN	5	1970-1975	3.2-7.4	7.1-10.6	60	199	135	50
Fenster et al. (1976) Martin A	MN	7	1970-1976	3.8-8.2	4.0-9.6	23	126	69	36
Fenster et al. (1976) Martin B	MN	6	1971-1976	6.2-11.3	6.2-12.0	0	37	18	15
Al Kaisi et al. (2003)	CO	3	1998-2000	5.6-10.2	8.3-10.8	66	111	91	23
Ismail et al. (1994) NT	KY	20	1998-2000	2.1-7.4	5.2-10.9	35	230	128	46
Ismail et al. (1994) CT	KY	20	1970-1990	1.9-9.5	3.5-10.4	0	203	98	52
Rice et al. (1986) NT	KY	15	1970-1985	3.1-4.9	5.7-9.2	102	178	144	30
Rice et al. (1986) CT	KY	15	1970-1985	1.9-6.1	5.0-8.8	69	204	124	47
Stecker et al. (1993) Columbia	MO	3	1988-1990	3.3-5.6	6.0-10.1	99	194	153	49
Stecker et al. (1993) Novelty	MO	3	1988-1990	4.5-7.2	6.7-9.9	45	182	103	71
Stecker et al. (1993) Corning	MO	2	1989-1990	5.0-6.0	8.2-8.5	90	117	104	20
Peterson et al. (1989)	NE	4	1983-1986	2.1-6.4	3.9-10.0	11	218	104	88
Eck (1982)	TX	2	1977-1978	2.7-4.4	5.6-5.9	59	116	88	40
Shapiro et al. (2006) RS 51cm	NE	3	1996-1998	6.2-8.9	9.4-11.1	69	96	83	13
Shapiro et al. (2006) RS 76cm	NE	3	1996-1998	5.0-8.9	7.1-11.0	13	114	75	54
Meisinger et al. (1985) MT	MD	4	1974-1977	1.8-2.6	5.8-8.2	127	233	183	45
Meisinger et al. (1985) PT	MD	4	1974-1977	2.7-4.2	5.1-8.1	36	196	142	75
Gehl et al. (2005) Rossville	KS	2	2001-2002	6.4-7.9	11.3-12.6	182	204	193	15
Gehl et al. (2005) Scandia	KS	2	2001-2002	2.7-7.4	3.8-11.5	51	160	105	77
Total		198			**Average**	62	173	120	45
					SD	44	55	43	20

† CT, conservation tillage; Martin A, yield data from continuous maize experiment; Martin B, yield data from virgin soil experiment; MT, minimal tillage; NT, no tillage; PT, moldboard plow tillage; RS, row spacing.

‡ Range in the recorded maize grain yields for the check plot where no N was applied.

ʛ Range in the recorded maize grain yields for the high N rate treatment in each experiment. These high N rates ranged from 1.8 to13.3 Mg ha^{-1}.

¶ Optimum N rates determined by subtracting the yield the check (0N) treatment from the yield in the high N treatment, multiplying by a known N concentration, and dividing by a fixed nitrogen use efficiency (NUE), set at 0.33.

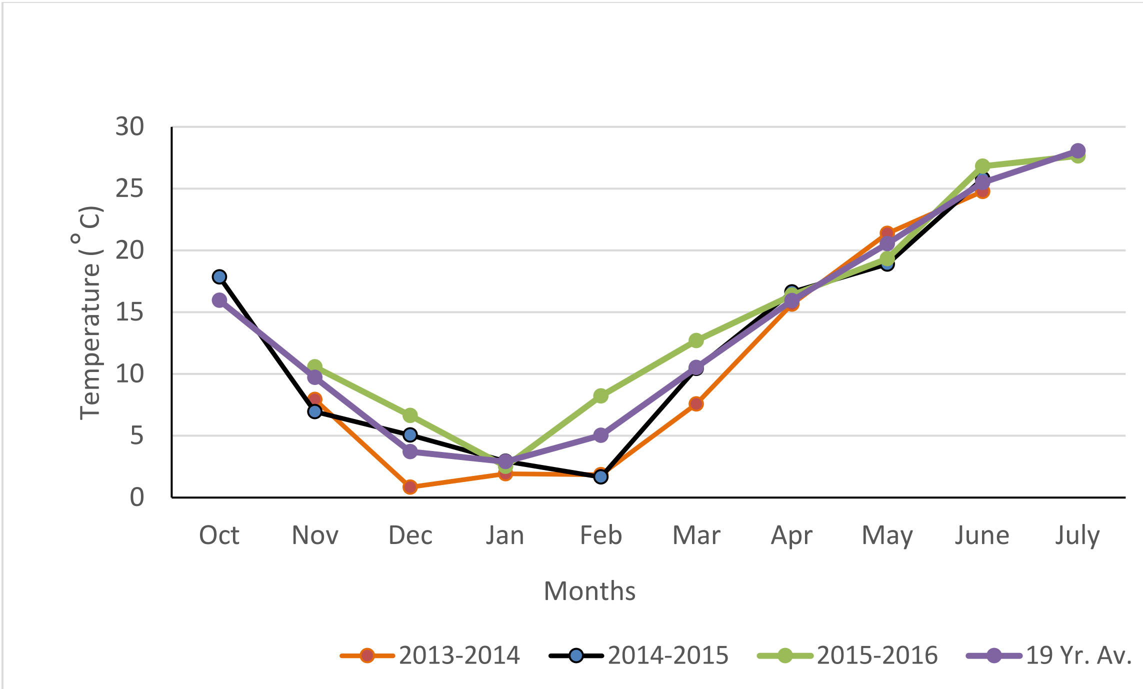

Figure 1. Average monthly air temperatures during 201-14, 2014-15, and 2015-16 winter wheat growing season at Stillwater (nearest Mesonet weather station to Efaw), OK.

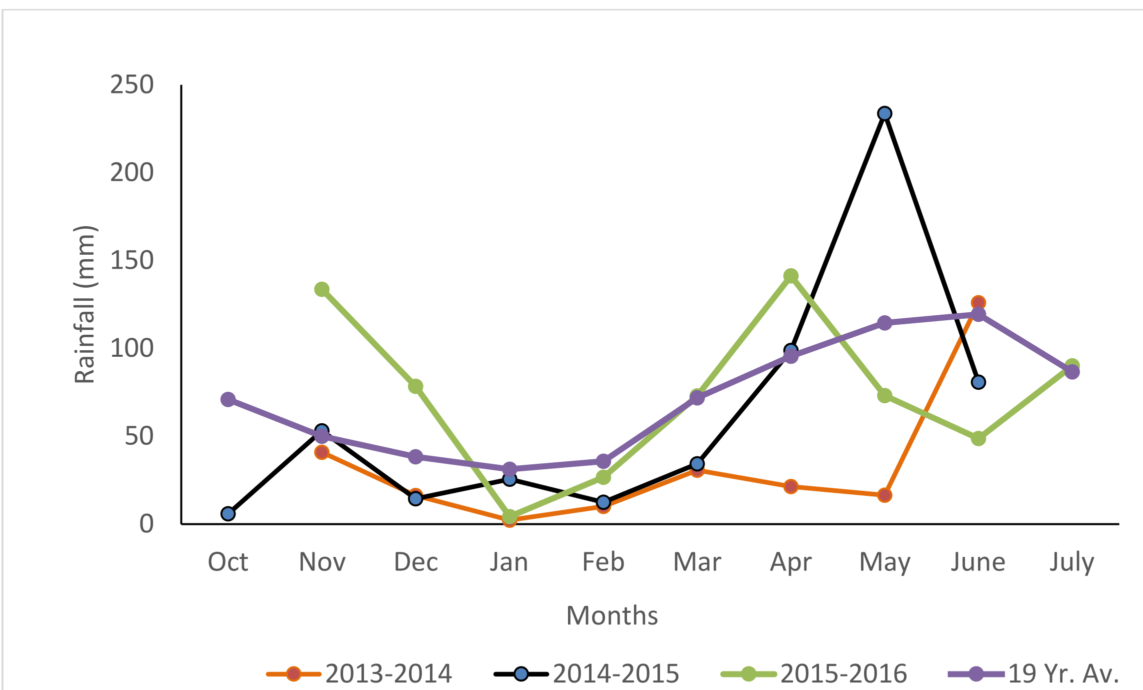

Figure 2. Total monthly rainfall during 2013-14, 2014-15, and 2015-16 winter wheat growing season at Stillwater (nearest Mesonet weather station to Efaw), OK.

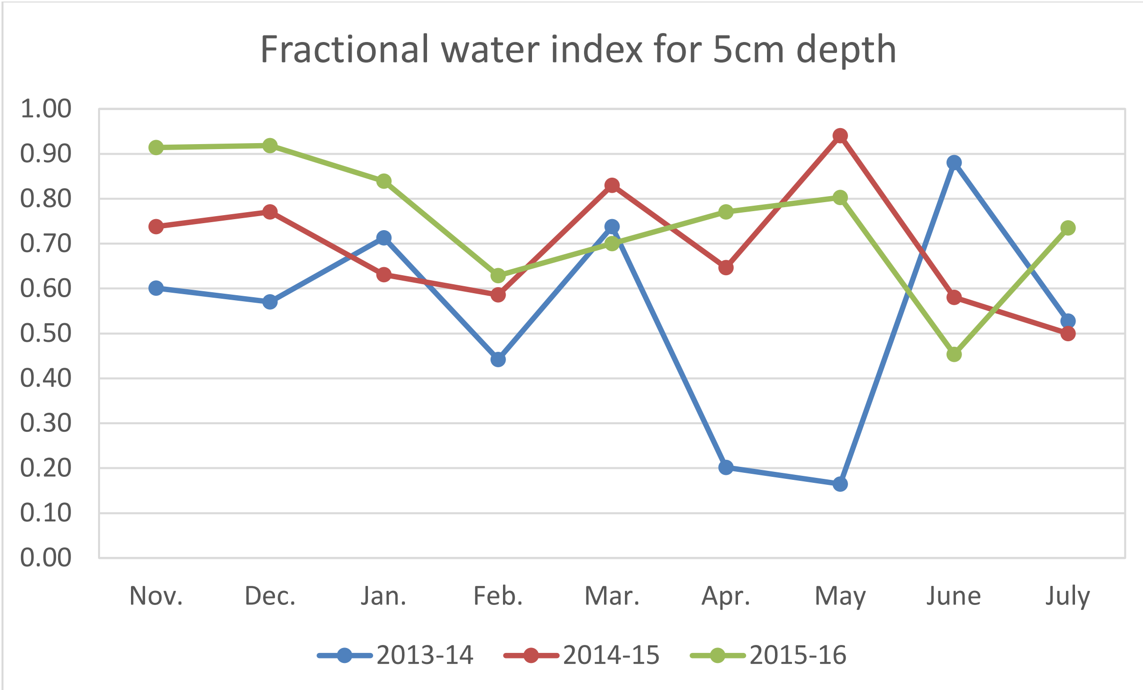

Figure 3. Average monthly fractional water index for average 5 cm depth during the 2013-2014, 2014-2015 and 2015-16 winter wheat growing season at Stillwater (nearest Mesonet weather station to Efaw), OK.

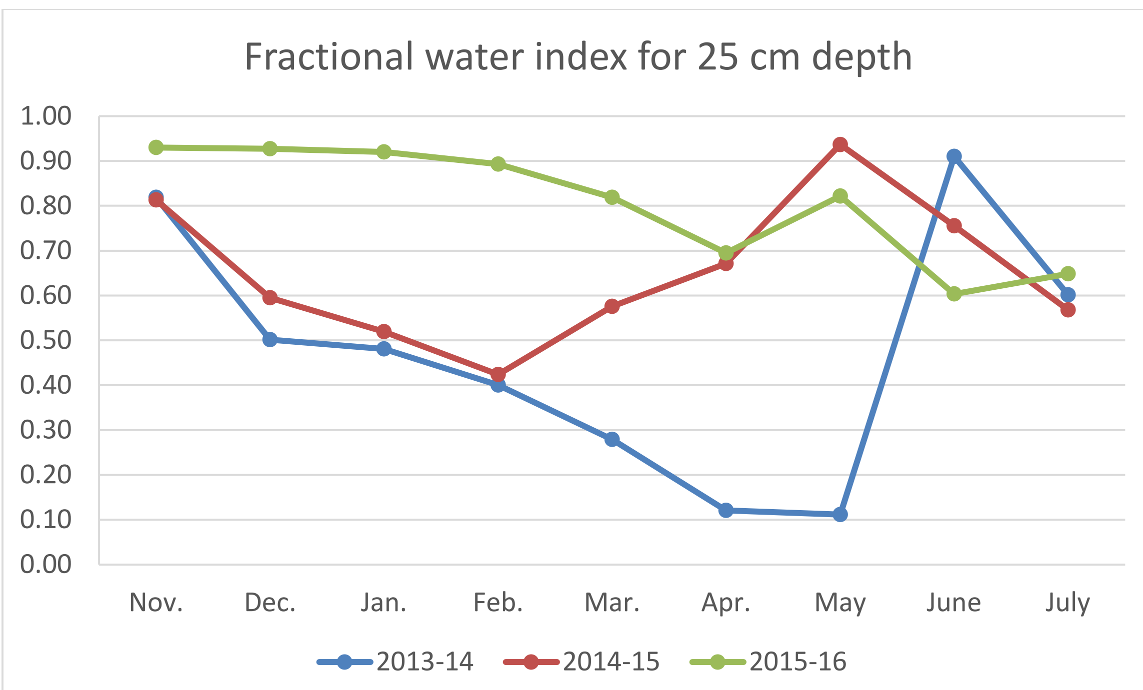

Figure 4. Average monthly fractional water index for average 25 cm depth during the 2013-2014, 2014-2015 and 2015-16 winter wheat growing season at Stillwater (nearest Mesonet weather station to Efaw), OK.

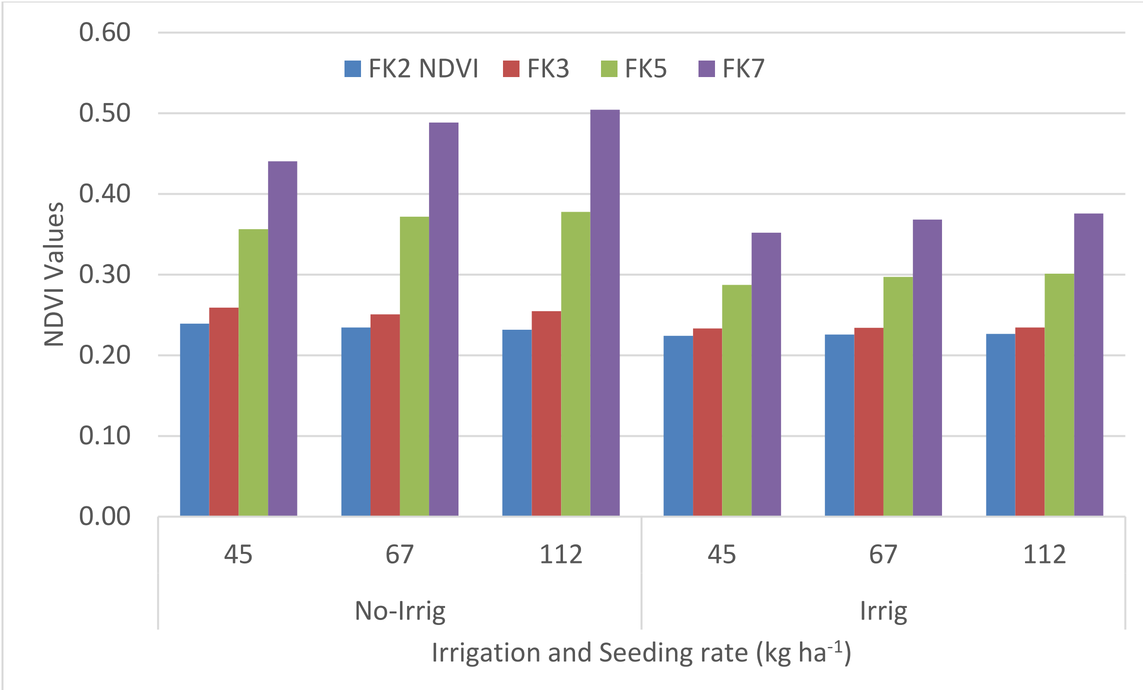

Figure 5. Average NDVI values collected at Feekes growth stages with seeding rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2013-14 at Stillwater, OK.

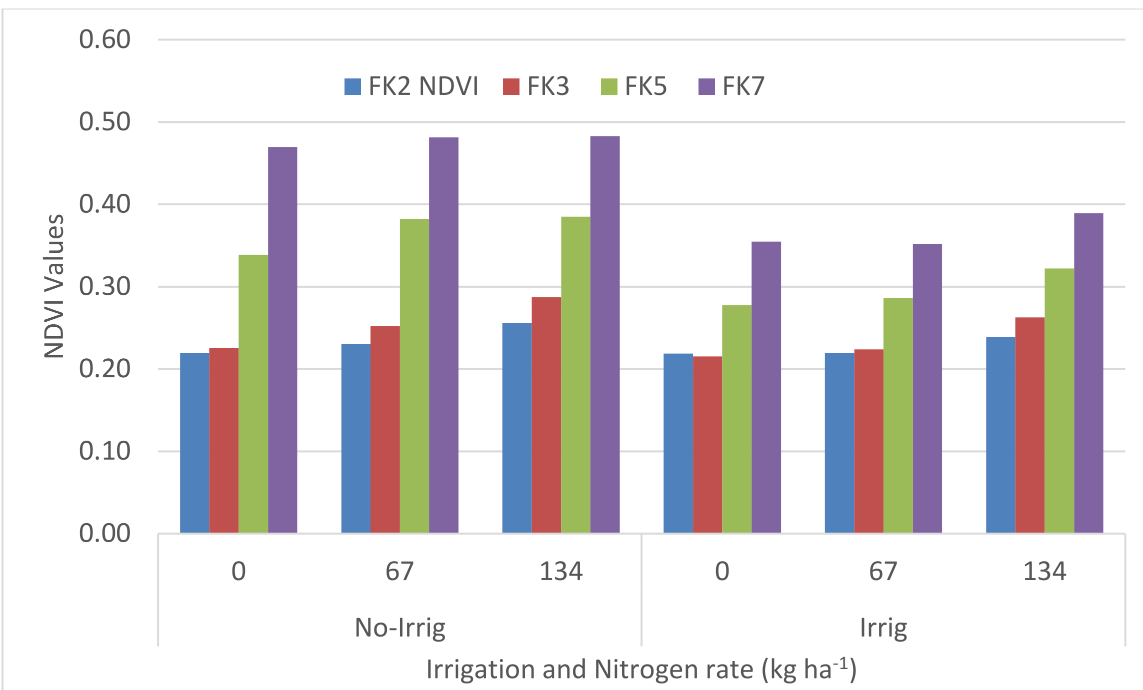

Figure 6. Average NDVI values collected at Feekes growth stages with preplant N rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2013-14 at Stillwater, OK.

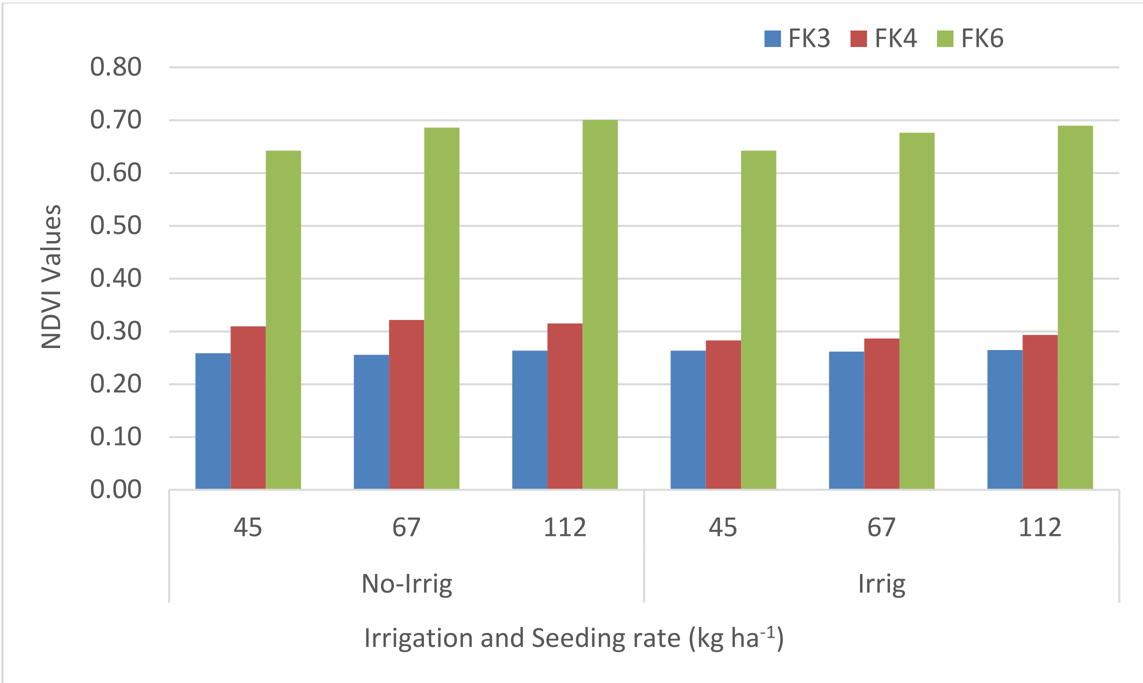

Figure 7. Average NDVI values collected at Feekes growth stages with seeding rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2014-15 at Stillwater, OK.

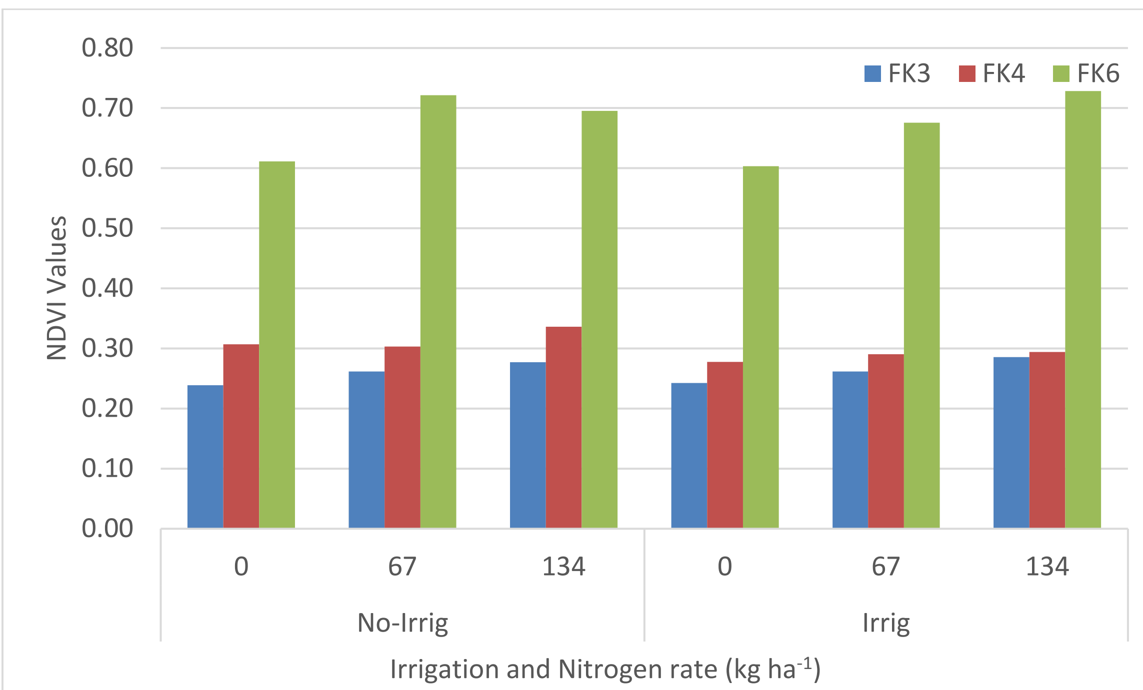

Figure 8. Average NDVI values collected at Feekes growth stages with preplant N rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2014-15 at Stillwater, OK.

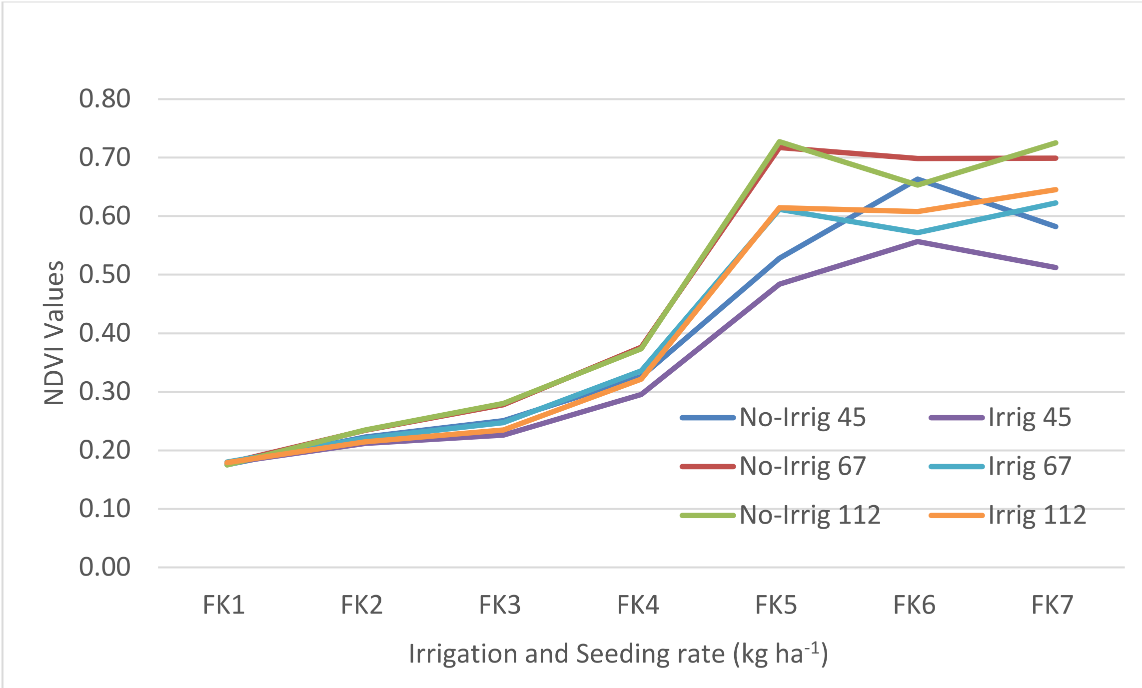

Figure 9. Average NDVI values collected at Feekes growth stages with seeding rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2015-16 at Stillwater, OK.

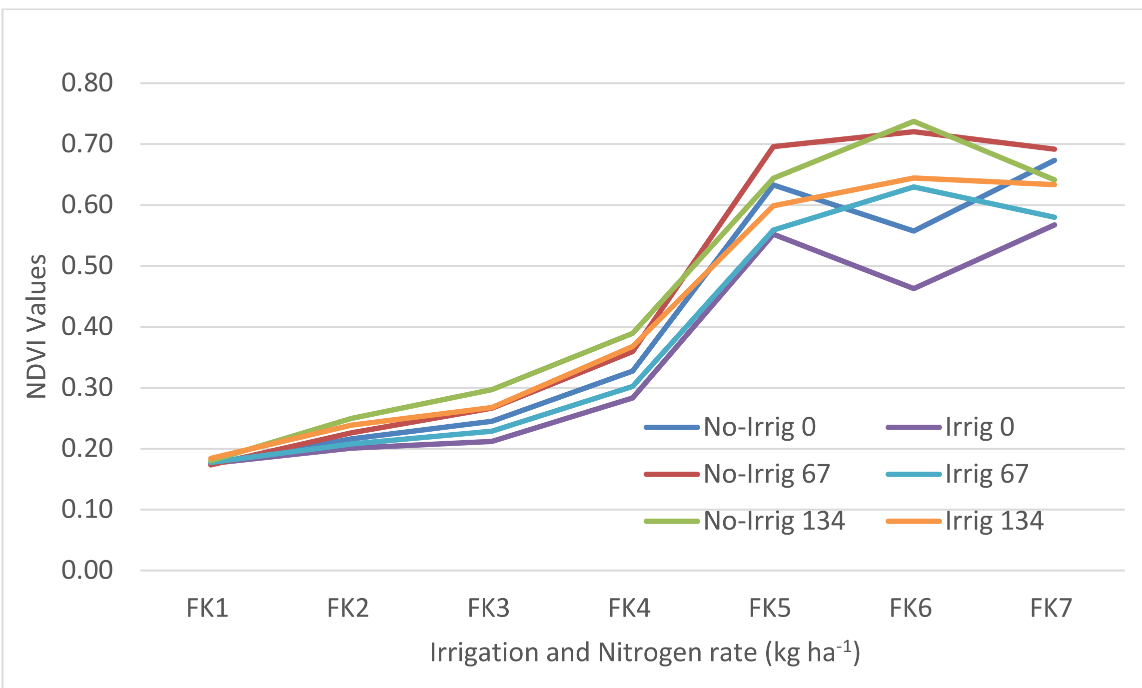

Figure 10. Average NDVI values collected at Feekes growth stages over different nitrogen rates for irrigated and non-irrigated plots of winter wheat for the cropping season 2015-16 at Stillwater, OK.

Table 1. Treatment structure employed at Central Oklahoma Station near Stillwater, Oklahoma, 2013-2014, 2014-2015 and 2015-2016.

TRT	Early/preplant Irrigation	Nitrogen rate (lb/acre)	(kg/ha)	Seeding Rate (lb/acre)	(kg/ha)
1	Yes	0	0	40	45
2	Yes	0	0	60	67
3	Yes	0	0	100	112
4	Yes	60	67	40	45
5	Yes	60	67	60	67
6	Yes	60	67	100	112
7	Yes	120	134	40	45
8	Yes	120	134	60	67
9	Yes	120	134	100	112

TRT	Early/preplant Irrigation	Nitrogen rate (lb/acre)	(kg/ha)	Seeding Rate (lb/acre)	(kg/ha)
1	No	0	0	40	45
2	No	0	0	60	67
3	No	0	0	100	112
4	No	60	67	40	45
5	No	60	67	60	67
6	No	60	67	100	112
7	No	120	134	40	45
8	No	120	134	60	67
9	No	120	134	100	112

Table 2. Preplant gravimetric water content, bulk density and volumetric water content for irrigated and non-irrigated plots for cropping season 2013-14 and 2014-15.

Year	Replication	Irrigation	Gravimetric Water Content g water g soil^{-1}	Bulk Density (g cm^{-3})	Volumetric Water Content cm^3 cm^{-3}
2013-14	Rep 1	No	0.12	1.14	0.14
2013-14	Rep 2	No	0.13	1.12	0.14
2013-14	Rep 3	No	0.14	1.28	0.17
2013-14	Rep 1	Yes	0.15	1.15	0.17
2013-14	Rep 2	Yes	0.15	1.38	0.21
2013-14	Rep 3	Yes	0.16	1.26	0.20
2014-15	Rep 1	No	0.15	1.44	0.21
2014-15	Rep 2	No	0.15	1.49	0.22
2014-15	Rep 3	No	0.18	1.40	0.25
2014-15	Rep 1	Yes	0.16	1.53	0.24
2014-15	Rep 2	Yes	0.17	1.45	0.25
2014-15	Rep 3	Yes	0.17	1.50	0.25

Table 3. Soil map unit and taxonomic classification for cropping season 2013-14, 2014-15 and 2015-16.

Year	Location	Soil Mapping Unit	Major Component Soil Taxonomic Classification
2013-14	Efaw	Norge silt loam	Fine-silty, mixed, active, thermic Udic Paleustoll
2014-15, 2015-16	Efaw	Easpur loam, occasionally flooded, 0-1% slope	Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls

Table 4. Surface soil (0- 15 cm) test characteristics at Efaw for cropping season 2013-14, 2014-15 and 2015-16.

Year	Replication	Irrigation	Time	NH_4- N	NO_3- N†	P‡	K£	pH±
				---------------- (kg ha^{-1}) -------------				
2013-14		No	preplant	40	118	233	1281	5.2
2013-14		Yes	preplant	35	75	219	677	6.3
2014-15		No	preplant	8.4	16	220	145	6.5
2014-15		Yes	preplant	6	20	201	302	7
2014-15	R1	No	post-harvest	5	15	293	453	6.5
2014-15	R2	No	post-harvest	2	11	294	217	6.6
2014-15	R3	No	post-harvest	3	13	288	194	6.7
2014-15	R1	Yes	post-harvest	3	12	288	169	6.7
2014-15	R2	Yes	post-harvest	3	11	292	159	6.9
2014-15	R3	Yes	post-harvest	3	14	322	333	6.2
2015-16	R1	No	preplant	3	12	218	323	6.9
2015-16	R2	No	preplant	2	10	241	76	6.9
2015-16	R3	No	preplant	2	11	221	177	6.9
2015-16	R1	Yes	preplant	2	14	211	102	7.1
2015-16	R2	Yes	preplant	2	15	231	50	7.3
2015-16	R3	Yes	preplant	1	17	211	187	6.6
2015-16	R1	No	midseason	1	14	204	312	6.7
2015-16	R2	No	midseason	1	17	239	225	7.2
2015-16	R3	No	midseason	1	17	242	260	7.0
2015-16	R1	Yes	midseason	0	18	235	112	7.0
2015-16	R2	Yes	midseason	1	16	247	108	7.3
2015-16	R3	Yes	midseason	1	19	269	313	6.6

Table 5. Date for the field activities performed during the winter wheat growing season.

Activities	2013-14	2014-15	2015-16
Preplant N	11/13/2013	11/11/2014	11/24/2015
Soil Moisture	11/13/2013	11/11/2014	11/24/2015
Planting	11/19/2013	11/11/2014	11/24/2015
Irrigation	11/7/2013- 11/11/2013 (4.5 cm)	12/11/2014- 12/17/2014 (5.0 cm)	12/08/2015- 1/28/2016 (4.5cm)
Variety	Gallaghar	Iba	Iba
Mid-season Biomass	-	4/1/2015	3/24/2016
Tiller count	4/18/2014	-	-
Head Count	6/17/2014	6/17/2015	6/10/2016
Harvest	6/17/2014	6/22/2015	6/10/2016

Table 6. Treatment means for all NDVI, number of tillers, number of heads, grain yield, and grain N for winter wheat affected by the early irrigation, nitrogen rates, and seeding rates, Stillwater, Oklahoma 2013-14

TRT	Irrigation	Seed Rate	N Rate	F2 NDVI	F3 NDVI	F5 NDVI	F7 NDVI	Tiller ($\#m^{-2}$)	Heads ($\#m^{-2}$)	Grain Yield ($kg\ ha^{-1}$)	Grain N ($g\ kg^{-1}$)
1	No	45	0	0.223	0.230	0.335	0.434	331	170	1915	21.3
2	No	67	0	0.216	0.220	0.343	0.478	270	144	1908	24.0
3	No	112	0	0.219	0.226	0.338	0.497	404	143	1937	24.7
4	No	45	67	0.238	0.257	0.363	0.457	370	149	1790	20.3
5	No	67	67	0.234	0.257	0.394	0.481	358	147	1682	23.7
6	No	112	67	0.219	0.242	0.390	0.506	413	169	1900	25.3
7	No	45	134	0.257	0.290	0.371	0.431	344	160	1793	21.3
8	No	67	134	0.254	0.275	0.379	0.507	308	210	1900	24.3
9	No	112	134	0.257	0.296	0.405	0.510	418	183	1783	24.7
	Means			**0.24**	**0.25**	**0.37**	**0.48**	**357.26**	**163.78**	**1845.37**	**23.30**
	CV, %			**9.66**	**12.14**	**12.21**	**9.86**	**28.56**	**22.48**	**10.32**	**8.06**
	SED			**0**	**0.01**	**0.01**	**0.01**	**19.64**	**7.09**	**36.64**	**0.36**
1	Yes	45	0	0.223	0.211	0.275	0.349	301	113	1341	24.0
2	Yes	67	0	0.212	0.211	0.265	0.338	270	122	1336	25.0
3	Yes	112	0	0.221	0.224	0.292	0.377	228	141	1512	26.0
4	Yes	45	67	0.215	0.224	0.277	0.334	275	110	1347	23.3
5	Yes	67	67	0.222	0.225	0.287	0.358	300	123	1404	25.0
6	Yes	112	67	0.221	0.222	0.295	0.364	241	136	1397	25.3
7	Yes	45	134	0.235	0.265	0.310	0.373	317	156	1445	22.3
8	Yes	67	134	0.243	0.266	0.339	0.409	222	183	1472	25.3
9	Yes	112	134	0.237	0.257	0.317	0.386	197	158	1378	25.7
	Means			**0.23**	**0.23**	**0.3**	**0.37**	**261.15**	**138**	**1403**	**24.67**
	CV, %			**5.79**	**9.73**	**9.76**	**7.54**	**29**	**21.33**	**13.33**	**7.37**
	SED			**0**	**0**	**0.01**	**0.01**	**14.57**	**5.66**	**36.01**	**0.35**

CV – coefficient of variation, %

SED, standard error of the difference between two equally replicated means

Table 7. Anova, main effect and interactions effect for NDVI at different Feekes growth stages, tillers count, head count, grain yield, and grain N for winter wheat affected by early irrigation, N rates, and seeding rates, Stillwater, Oklahoma 2013-14.

Source of Variation	DF	F2 NDVI	F3 NDVI	F5 NDVI	F7 NDVI	Tillers (# m^{-2})	Heads (# m^{-2})	Grain Yield (kg ha^{-1})	Grain N (g kg^{-1})
Replication	2	0.0074±	ns	<.0001*	<.0001*	<.0001*	<.0001*	0.0338¶	0.0058±
Irrigation	1	0.0006±	0.0033±	<.0001*	<.0001*	<.0001*	<.0001*	0.0027±	<.0001*
Irrig*Rep	2	ns	ns	0.0001*	<.0001*	0.0148¶	0.0067±	ns	0.0338¶
Seed Rate (SR)	2	ns	0.001±	ns	ns	<.0001*	<.0001*	<.0001*	0.0176¶
Irrig*SR	2	ns	ns	ns	ns	0.0034±	ns	ns	ns
Irrig*Rep*SR	8	ns	ns	<.0001*	ns	<.0001*	0.0184¶	0.0024±	0.022¶
N Rate (NR)	2	ns	ns	ns	<.0001*	ns	ns	ns	<.0001*
Irrig*NR	2	0.039¶	ns	ns	0.0222¶	ns	ns	ns	ns
SR*NR	4	ns	ns	ns	ns	ns	ns	ns	ns
Irrig*SR*NR	4	ns	ns	ns	ns	0.011¶	ns	ns	ns

ns - not significant,

* - significant at 0.001 probability level

± - significant at 0.01 probability level

¶ - significant at 0.05 probability level

Table 8. Treatment means for all NDVI, mid-season biomass, number of heads, grain yield, harvest index, and grain N for winter wheat affected by the by early irrigation, N rates, and seeding rates, Stillwater, Oklahoma 2014-15.

TRT	Irrigation	Seed Rate	N Rate	F3 NDVI	F4 NDVI	F6 NDVI	Mid_B g m^{-2}	Heads (#m^{-2})	Grain Yield (kg ha^{-1})	Harvest Index	Grain N (g kg^{-1})
1	No	45	0	0.242	0.299	0.563	30.9	195	1200	0.24	23.0
2	No	67	0	0.237	0.306	0.610	31.8	214	1017	0.33	23.7
3	No	112	0	0.237	0.316	0.661	61.5	138	1017	0.24	24.0
4	No	45	67	0.253	0.305	0.666	64.6	171	1767	0.29	21.7
5	No	67	67	0.263	0.309	0.753	47.3	211	1367	0.33	22.3
6	No	112	67	0.269	0.295	0.746	59.8	198	1400	0.30	24.0
7	No	45	134	0.280	0.324	0.697	49.4	245	1683	0.30	21.7
8	No	67	134	0.266	0.350	0.695	58.2	230	1383	0.29	23.0
9	No	112	134	0.285	0.334	0.694	63.5	192	1267	0.26	23.0
	Means			**0.26**	**0.32**	**0.68**	**51.9**	**199.41**	**1344.44**	**0.29**	**22.93**
	CV, %			**8.4**	**14.36**	**11.18**	**42.82**	**26.78**	**28.91**	**28.42**	**28.42**
	SED			**0**	**0.01**	**0.01**	**4.28**	**10.28**	**74.79**	**0.02**	**0.22**
1	Yes	45	0	0.234	0.284	0.572	23.5	199	1367	0.27	23.3
2	Yes	67	0	0.241	0.266	0.629	31.2	186	1517	0.45	22.3
3	Yes	112	0	0.253	0.283	0.609	40.3	227	1267	0.43	23.7
4	Yes	45	67	0.256	0.284	0.629	33.9	213	1600	1.32	22.3
5	Yes	67	67	0.273	0.297	0.685	32.5	200	1583	0.27	23.0
6	Yes	112	67	0.256	0.291	0.713	41.2	172	1483	0.24	23.0
7	Yes	45	134	0.301	0.280	0.725	47.8	289	2017	0.27	21.3
8	Yes	67	134	0.271	0.297	0.714	61.3	307	1717	0.29	22.7
9	Yes	112	134	0.285	0.306	0.747	37.8	225	1267	0.58	22.7
	Means			**0.26**	**0.29**	**0.67**	**38.84**	**224.19**	**1535.19**	**0.46**	**22.7**
	CV, %			**9.41**	**13.71**	**10.54**	**42.77**	**27.64**	**24.78**	**137.49**	**5.01**
	SED			**0**	**0.01**	**0.01**	**3.2**	**11.93**	**73.23**	**0.12**	**0.22**

CV – coefficient of variation, %
SED, standard error of the difference between two equally replicated means

Table 9. Anova, main effect and interactions effect for NDVI at different Feekes growth stages, head m^{-2}, grain yield, harvest index, and grain N for winter wheat affected by early irrigation, N rates, and seeding rates, Stillwater, Oklahoma 2014-15.

Source of Variation	DF	F3 NDVI	F4 NDVI	F6 NDVI	Mid_B g m^{-2}	Heads (# m^{-2})	Grain Yield (kg ha^{-1})	Harvest Index	Grain N (g kg^{-1})
Replication	2	ns	0.05¶	ns	ns	ns	ns	ns	ns
Irrig	1	ns	0.0002±	ns	0.0103¶	0.0264¶	ns	ns	ns
Irrig*Rep	2	ns	ns	ns	ns	0.0006±	ns	ns	ns
Seed Rate (SR)	2	<.0001*	0.0168¶	<.0001*	0.0278¶	0.0002±	0.0219¶	ns	0.0321¶
Irrig*SR	2	ns	ns	0.0443¶	ns	ns	ns	ns	ns
Irrig*Rep*SR	8	0.0015±	<.0001*	0.0373±	ns	ns	ns	ns	ns
N Rate (NR)	2	ns	ns	0.0045±	ns	0.0405¶	0.0446¶	ns	0.0082±
Irrig*NR	2	ns	ns	ns	ns	ns	ns	ns	ns
SR*NR	4	0.0231¶	ns	ns	ns	ns	ns	ns	ns
Irrig*SR*NR	4	ns	ns	ns	ns	ns	ns	ns	ns

ns - not significant,
* - significant at 0.001 probability level
± - significant at 0.01 probability level
¶ - significant at 0.05 probability level

Table 10. Treatment means for all NDVI, mid-season biomass, number of heads, grain yield, harvest index, and grain N for winter wheat affected by the by early irrigation, N rate, and seeding rate, Stillwater, Oklahoma 2015-16.

TRT	Irrigation	Seed Rate	N Rate	F1 NDVI	F2 NDVI	F3 NDVI	F4 NDVI	F5 NDVI	F6 NDVI	F7 NDVI	Mid_B g m^{-2}	Heads (#m^{-2})	Grain Yield (Kg ha^{-1})	Harvest Index	Grain N (g kg^{-1})
1	No	45	0	0.176	0.211	0.233	0.302	0.494	0.553	0.607	25.8	231	1436	0.32	19.0
2	No	67	0	0.177	0.225	0.257	0.355	0.702	0.571	0.705	29.8	307	1512	0.23	20.7
3	No	112	0	0.172	0.212	0.245	0.325	0.703	0.548	0.708	35.0	284	1134	0.21	21.3
4	No	45	67	0.172	0.211	0.235	0.312	0.551	0.712	0.589	30.3	204	1384	0.23	17.0
5	No	67	67	0.175	0.230	0.276	0.379	0.766	0.759	0.735	35.8	243	1119	0.19	19.3
6	No	112	67	0.173	0.237	0.288	0.387	0.771	0.690	0.751	32.4	284	1799	0.23	19.3
7	No	45	134	0.178	0.246	0.284	0.364	0.540	0.725	0.550	34.1	318	1315	0.23	16.7
8	No	67	134	0.182	0.247	0.300	0.395	0.684	0.765	0.657	35.3	281	1572	0.24	18.3
9	No	112	134	0.180	0.256	0.307	0.409	0.708	0.722	0.717	36.3	319	1202	0.18	19.5
	Means			**0.18**	**0.23**	**0.27**	**0.36**	**0.66**	**0.66**	**0.67**	**32.76**	**274**	**1393**	**0.23**	**19.08**
	CV, %			**4.5**	**9**	**12**	**13**	**18**	**18**	**14**	**23**	**26**	**26**	**31**	**9**
	SED			**0**	**0**	**0.01**	**0.01**	**0.02**	**0.02**	**0.02**	**1.46**	**13.69**	**71.98**	**0.01**	**0.35**
1	Yes	45	0	0.173	0.191	0.189	0.248	0.450	0.442	0.489	28.8	186	1043	0.26	18.7
2	Yes	67	0	0.178	0.208	0.229	0.302	0.609	0.467	0.615	29.4	221	1421	0.21	19.3
3	Yes	112	0	0.176	0.203	0.217	0.300	0.597	0.479	0.598	25.6	199	1376	0.23	19.3
4	Yes	45	67	0.178	0.206	0.222	0.287	0.487	0.622	0.505	28.2	183	1542	0.33	18.0
5	Yes	67	67	0.178	0.217	0.247	0.333	0.583	0.602	0.571	27.0	265	1497	0.27	18.7
6	Yes	112	67	0.176	0.200	0.217	0.286	0.607	0.665	0.663	27.8	220	1089	0.18	19.7
7	Yes	45	134	0.183	0.239	0.267	0.351	0.514	0.606	0.543	30.0	272	1815	0.32	18.3
8	Yes	67	134	0.184	0.236	0.266	0.373	0.643	0.647	0.682	32.7	283	1648	0.25	19.3
9	Yes	112	134	0.185	0.241	0.270	0.379	0.639	0.680	0.675	30.3	289	1860	0.27	20.0
	Means			**0.18**	**0.22**	**0.24**	**0.32**	**0.57**	**0.57**	**0.59**	**28.87**	**235**	**1477**	**0.26**	**19.04**
	CV, %			**4.0**	**10**	**13**	**16**	**16**	**16**	**17**	**23**	**38**	**30**	**26**	**5**
	SED			**0**	**0**	**0.01**	**0.01**	**0.02**	**0.02**	**0.02**	**1.24**	**17.39**	**86.15**	**0.01**	**0.18**

CV – coefficient of variation, %

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

Table 11. Anova, main effect and interactions effect for NDVI at different Feekes growth stages, head count, grain yield, harvest index, and grain N for winter wheat affected by early irrigation, N rates, and seeding rates, Stillwater, Oklahoma 2015-16.

Source of Variation	DF	F1 NDVI	F2 NDVI	F3 NDVI	F4 NDVI	F5 NDVI	F6 NDVI	F7 NDVI	Mid_B g m^{-2}	Heads (# m^{-2})	Grain Yield (kg ha^{-1})	Harvest Index	Grain N (g kg^{-1})
Replication	2	<.0001*	ns	ns	ns	ns	ns	ns	0.0002±	<.0001*	ns	ns	0.0179¶
Irrigation	1	0.0091±	0.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	0.0161¶	0.003	ns	ns	ns
Irrig*Rep	2	ns	0.0235¶	0.0472¶	0.0248¶	ns	ns	ns	0.0185¶	ns	ns	ns	ns
Seed Rate (SR)	2	<.0001*	<.0001*	<.0001*	<.0001*	ns	ns	ns	ns	0.0005±	ns	ns	0.0044±
Irrig*SR	2	ns	ns	ns	ns	0.0169¶	0.0169¶	ns	ns	ns	ns	ns	0.0028±
Irrig*Rep*SR	8	0.0058±	ns	ns	ns	<.0001*	<.0001*	ns	ns	ns	ns	ns	ns
N Rate (NR)	2	ns	ns	0.0015±	0.0003±	<.0001*	<.0001*	<.0001*	ns	0.0425¶	ns	ns	<.0001*
Irrig*NR	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SR*NR	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Irrig*SR*NR	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns - not significant,

* - significant at 0.001 probability level

± - significant at 0.01 probability level

¶ - significant at 0.05 probability level

VITA

Sulochana Dhital

Candidate for the Degree of

Doctor of Philosophy

Thesis: EFFECT OF PREPLANT/EARLY IRRIGATION, NITROGEN AND SEEDING RATE ON WINTER WHEAT GRAIN YIELD

Major Field: Soil Science

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Soil Science at Oklahoma State University, Stillwater, Oklahoma/USA; December, 2016.

Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma/USA; May, 2013.

Completed the requirements for the Bachelor of Science in Agriculture at, Institute of Agriculture and Animal Science, Rampur, Chitwan/Nepal; July, 2007.

Experience:
Graduate Research Assistant (2011-2016)
Research Assistant (August 2010- Feb 2011) National Adaptation Program for Action.
Worked as Junior Consultant Officer (Oct. 2009-July 2010) and Technical Assistant (Jan 2008-Jan 2009) for Sustainable Soil Management Program (SSMP/Helvetas, Nepal).

Professional Memberships:
American Society of Agronomy (ASA)
Soil Science Society of America (SSSA)
Crop Science Society of America (CSSA)