I. UTILIZING SOIL MOISTURE DATA WITH OPTICAL SENSORS TO DETERMINE NITROGEN FERTILIZER RECOMMENDATIONS IN WINTER WHEAT

II. ALTERNATIVE NITROGEN FERTILIZATION STRATEGIES FOR MAIZE IN A WATER LIMITED ENVIRONMENT

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Abstract: The impact soil moisture can have on nitrogen (N) fertilizer management can be substantial. A series of trials were conducted to evaluate the effect of soil moisture on N management practices in winter wheat and maize. The first series of trials focused on improvements of in-season N fertilizer recommendation in winter wheat. In winter wheat, optical sensors coupled with mathematical algorithms have been used to improve mid-season N fertilizer rate recommendations. One of the key components to these algorithms is the in-season estimate of grain yield. To improve upon current algorithms, soil moisture parameters were incorporated into the yield prediction models. Slight improvements were observed in the ability to predict grain yield by utilizing soil moisture data at the time of sensing. However, no significant differences were observed in the ability of the new yield prediction to determine the agronomic optimum N rate compared to current N fertilizer recommendation algorithms. The other set of trials evaluated the effects of different N fertilizer management practices on grain yield, N use efficiency (NUE), and water use efficiency (WUE) for maize grown in a rain-fed or deficit irrigation environment. Deficit irrigation improved grain yield, WUE, and NUE compared to rain-fed treatments. Split N fertilizer applications typically increased the NUE, but not always the grain yield. Mid-season foliar N applications did have the potential to improve grain yield and NUE, however if significant leaf burn was observed, grain yields were reduced. The preplant application of a pure ammoniacal source of N fertilizer, such as ammonium sulfate (AS), had a tendency to increase grain yields and NUE for rain-fed treatments. The use of urea ammonium nitrate (UAN) as a preplant N fertilizer source performed just as well or better at improving grain yield compared to AS, as long as potential N loss mechanisms were minimized. In conclusion, knowledge of soil moisture and its effects on N fertilizer management can help improve the efficiency of N and sustainability of other resources for cereal grain production.

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CHAPTER 1

UTILIZING SOIL MOISTURE DATA WITH OPTICAL SENSORS TO DETERMINE NITROGEN FERTILIZER RECOMMENDATIONS IN WINTER WHEAT

ABSTRACT

When utilizing optical sensors to make nitrogen (N) fertilizer recommendations in winter wheat, one parameter requrired is the in-season grain yield potential at the time of sensing. Current estimates use a measure of biomass, such as normalized difference vegetation index (NDVI), and growing degree days (GDD's) from planting to sensing. The objective was to incorporate soil moisture data to improve the ability to predict final grain yield in-season. Crop NDVI, GDD's that were adjusted based upon if there was adequate water for crop growth, and the amount of soil profile (0-80cm) water were incorporated into a multiple linear regression model to predict final grain yield. Twenty two site-years of N fertility trials with in-season yield predictions for growth stages ranging from Feekes 3 to 10 were utilized to calibrate the model. Three models were developed, one for all soil types, one for loamy textured sites, and one for coarse textured sites. The models were validated with 11 site-years of sensor and weather data. The results indicated there was no added benefit to having separate models based upon soil types. Typically, the models that included soil moisture, more accurately predicted final grain yield. Across all site years and growth stages, yield prediction estimates that included soil moisture had an R^2= 0.49, while the current model without a soil moisture adjustment had an R^2=0.40. The yield prediction model was then evaluated by determining mid-season N fertilizer recommendations from N fertilizer response trials and comparing those values to the agronomic optimum N rates. Yield predictions that included soil moisture parameters performed similarly to current methods for determining optimum N rates. Including soil moisture parameters improved the ability to predict grain yield at mid-season; however, this improvement did not significantly influence the mid-season N fertilizer rate recommendation.

CHAPTER 1.1

DEVELOPMENT OF AN IN-SEASON ESTIMATE OF YIELD POTENTIAL UTILIZING SOIL MOISTURE DATA FOR WINTER WHEAT

Introduction

Grain yield goals have been used for decades to make important in-season agronomic decisions. How they are derived and defined has been highly debated. Dahnke et al. (1988) simply defined a yield goal as the "yield per acre you hope to grow." Much of the debate is over the difference between a crop's yield potential and maximum yield. Dahnke et al. (1988) stated that yield potential is the highest possible yield obtainable with ideal management, soil, and weather. Evans and Fischer (1999) defined yield potential as "the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled." According to Raun et al. (2001), yield potential as defined by Dahnke et al. (1988) and Evans and Fischer (1999) would be defined as maximum yield because potential yield is associated with site specific soil and climate conditions that can change annually. Other approaches for producers to determine yield goals have been to average the grain yield over the last 4 to 5 years and increase it by ten percent or rely on variety trials or county averages (Fanning 2012; Geisseler and Horwath, 2013). Raun et al. (2001) noted that yield potential is known to change from one site-year to another because of the temporal variability. Refined definitions, adapted from Raun et al. (2001), for measured grain yield, potential grain yield, and maximum grain yield are described below.

> *Measured grain yield:* The grain yield that is actually harvested in a given year for a given site.
>
> *Potential grain yield:* The grain yield that is predicted for a given year and a given site, based upon the assumptions that the level of growth factors that are responsible for early crop development will be maintained.
>
> *Maximum grain yield:* The grain yield that is achievable when all manageable growth factors are non-limiting, and the environment is ideal.

Numerous researchers have documented the significance soil moisture has on estimating final wheat grain yield. Black and Bauer (1988) stated winter wheat yield goal should be based upon the amount of plant available water stored in the soil profile in addition to the amount of potential precipitation throughout the growing season. Rehm and Schmitt (1989) reported that if soil moisture conditions at planting were favorable, they recommended adjusting the grain yield goal to 10 to 20 percent above the recent averages. Rehm and Schmitt (1989) also noted that if soil moisture is limiting, utilizing averages from previous crop years may not be best for estimating grain yield. Robinson et al. (1999) reviewed 30 plus years of climate and wheat grain yield data and concluded that N fertilizer applications would be most profitable if soil moisture measurements indicated above average soil moisture at planting. Girma et al. (2007) evaluated soil moisture content from the previous growing season and its effect on final grain yield. They observed that soil moisture content at 75 cm was a good predictor of grain yield at one research location and soil moisture content at 60 cm provided good prediction of grain yield at another site.

Historically, grain yield goals or a field's yield potential have been utilized to make pre-plant nitrogen (N) fertilizer recommendations. Recent, advancements in sensor-based technologies and crop and weather modeling have allowed for in-season N fertilizer adjustments based upon crop grain yield potential (Raun et al., 2001). Research conducted over the last three decades has advanced the capability of sensor-based methodologies to assist in making agronomic management decisions. Stone et al. (1996) and Solie et al. (1996) first observed that NDVI measurements at Feekes Physiological Growth Stages 4 and 5 (Large, 1954) were able to reliably predict both N uptake and plant/crop biomass. Raun et al. (2001) reported that the sum of two post-dormancy NDVI measurements divided by the cumulative growing degree days (GDD) from the first to the second reading was an accurate predictor of final grain yield and could assist in adjusting in-season applications of N fertilizer. Using 30 site-years of grain yield data, Raun et al. (2005) built upon their earlier work and determined that yield could then be predicted at any growth stage when the NDVI was divided by the cumulative number of GDD with a growing threshold temperature value of 4.4ºC. They reported that the non-linear relationship of in-season estimate of yield (INSEY) and grain yield was highly correlated and essentially provided an estimate of biomass produced per day.

Researchers have attempted to incorporate some form of soil moisture measurement into sensor based technologies to predict wheat grain yield. Girma et al. (2006) evaluated mid-season measurements in wheat of sensor derived NDVI and soil moisture, as well as leaf color, chlorophyll content, plant height, canopy temperature, tiller density, plant density, soil NH_4-N, NO_3-N, organic C, total N, pH, and N mineralization potential. They noted that mid-season NDVI, chlorophyll content, plant height, and total N uptake were good predictors of final wheat grain yield; however, they observed soil moisture to be well associated with grain yield, but not a reliable predictor of final grain yield. Walsh et al. (2013) measured soil water content at sowing and utilized it along with mid-season NDVI values to predict grain yield in winter wheat. They evaluated soil moisture at three different depths (5, 25, 60 cm). By combining the NDVI-based approach with 5 cm soil moisture data at the time of planting and sensing at Feekes 5 growth stage they could better predict wheat grain yield.

Crop growth, development, and subsequently grain yield are affected by temperature (Porter and Moot, 1998). The concept of GDD or accumulation of heat units has been proven to more accurately describe and predict crop development and phenological stages of growth much better than the number of days since planting or time of year (McMaster and Wilhelm, 1997). For wheat, extensive research has shown relatively small and consistent standard errors of the cardinal temperatures for many crop growth stages and processes (Porter and Gawith, 1999). Other researchers have utilized the concept of biological days to document crop growth, in which there is not only optimal temperature for growth, but other factors such as photoperiod, and lack of water stress and nutrient stress are included (Hunt and Pararajasingham, 1995; Soltani and Sinclair, 2012).

Knowledge of water use or evapotranspiration (ET) by a wheat crop could assist in predicting final grain yield, in that a producer would know if the soil moisture content they have at a given time will be enough to carry the crop to maturity. Nix and Fitzpatrick (1969) evaluated how the ratio of plant available soil water to the potential evaporative demand of a growing wheat crop affected final grain yield. They reported highly significant correlations with what was referred to as a stress index (SI), and final grain yield. Similar results of a strong relationship between a derived SI and grain yield were observed by Stephens et al. (1989), in that they concluded the lack of adequate water to maintain growth strongly impacts final grain yield.

The early February to June water usage by winter wheat grown in the Southern Great Plains of North American would be most important, as this is the time grain yield potentials would be utilized to make agronomic management decisions, such as in-season N fertilizer applications. Howell et al. (1997) measured ET on winter wheat and observed season ET values were 877 mm, with daily uses of 3 to 4 mm per day, and values rarely exceed 10 mm per day, but did on days with high sustained wind speeds. Liu et al. (2002) determined in wheat grown in northern China that after the over-wintering period daily ET values were about 1.2 mm per day and rapidly increased to approximately 4 to 6 mm per day during the jointing and booting stages. In the semi-arid portion of India, Singandhupe and Sethi (2005) reported daily ET values ranged from 2.6 to 9.6 mm per day between February and April.

Objectives

The objective of this study was to develop a model that incorporates climatic parameters, such as soil moisture, with NDVI measurements to increase the reliability of predicting wheat grain yield in-season. We hypothesize that the ability to predict grain yield in-season will improve when soil moisture measurements are incorporated into current methodologies for predicting grain yield in winter wheat.

Materials and Methods

Site Descriptions

Grain yield and parameters utilized to calibrate a model to determine grain yield potential were collected from three long-term soil fertility experiments at Stillwater (222), Lahoma (502), and Perkins (N&P), Oklahoma. These fertility trials were established in 1969, 1970, and 1996 for Stillwater (222), Lahoma (502), and Perkins (N&P), respectively. The soils at each experimental site are classified and represent soils utilized for wheat production in the South-central Great Plains region of Oklahoma, Kansas, and Texas and that encompass approximately 650,000 hectares of the geographic area (Soil Survey Staff, 2012a). Grain yield and parameters employed to validate the developed model were collected from the three long-term soil fertility experiments described above as well as three additional sites. The additional sites were regionally based N fertilizer response trials, in which the same amount of pertinent data that was needed to calibrate the model was collected. A brief summary of the soils utilized for each experimental site is reported in Table 1.1-1.

Plots that were analyzed were those that received no N fertilizer treatment throughout the year or received preplant N fertilizer treatments only with no mid-season N fertilizer applications. The N fertilizer treatments and rates for each trial location are listed in Table 1.1-2. The site-years and growth stages where yield potential parameters were collected to develop a yield potential estimate are listed in Table 1.1-3. Altogether, 22 site-years of data were collected to develop the calibration model for yield potential. Gaps in years for data collection were due to the crop not being taken to yield because of natural occurrences (drought, late freeze, hail, etc.). The site-years and growth stages where yield potential parameters were collected to validate the developed model are described in Table 1.1-4. Altogether, 11 site-years of data were collected to validate the developed model.

Current Model for Predicting Yield

The current model utilized for predicting grain yield potential was that described by Raun et al. (2005). The in-season estimate of yield (INSEY) was calculated by dividing the NDVI by the cumulative number of growing degree-days with a growing threshold value of 4.4ºC. A non-linear relationship was established between INSEY and final grain yield, and the equation from this relationship is thus used to predict yield.

Proposed Model Parameters

Normalized Difference Vegetation Index (NDVI). Spectral reflectance expressed as NDVI was measured using a Greenseeker (Trimble, Sunnyvale, CA, USA) ground-based, active, optical sensor. The NDVI was computed from red and near infrared reflectance values. The equation to calculate NDVI is listed below:

$$NDVI = (NIR - Red)/(NIR + Red)$$

Where: NIR and Red are the reflectance measurements in the near-infrared (780 nm) and red bands (660 nm), respectively. The NDVI values were collected at various times throughout the growing season with the ground-based optical sensor and the Feekes (Large, 1954) growth stage was documented as well.

Days of Potential Growth (DPG). This parameter was collected following the biological day concept described by Soltani and Sinclair (2012). We proposed that for considerable growth to occur in wheat there should be adequate temperature along with adequate soil water. Soil moisture data were downloaded from the adjacent Oklahoma Mesonet climate-monitoring station (Mesonet, 2014) for each experimental site for the time periods of data collection. Soil moisture measurements were recorded at depths of 5, 25, and 60 cm below the soil surface. Soil moisture data were collected using a Campbell Scientific 229-L heat dissipation sensor (Campbell Scientific, Inc, Logan, UT, USA). The sensor measures a change in temperature after a pulse of heat is introduced to the system (Basara and Crawford, 2000). The magnitude in change can then be calibrated to an estimate of soil moisture content. The sensor's response can be normalized to a fractional water index (FWI), which is a unitless value that ranges from 0.00 for dry soils to 1.00 for wet/saturated soils (Illston et al, 2008). According to Illston et al. (2008), utilizing the FWI is more ideal when operating on a larger scale and may not be limited by varying soil texture across research sites. The DPG were counted as the number of days that not only met the criteria for a GDD described in the current method for predicting grain yield, but also had a weighted average FWI across the 80 cm soil profile of 0.30 or less. The 0.30 FWI threshold is described by Soltani and Sinclair (2012) as the level at which growth could potentially be inhibited for wheat.

Stress Index (SI). Soil moisture data were downloaded from the adjacent Oklahoma Mesonet climate-monitoring station (Mesonet, 2014) for each experimental site for the time periods of data collection. To determine the amount of plant available water (PAW) at the time of sensing the weighted 80 cm FWI values were converted to volumetric water content. Gravimetric water content values and soil bulk density values were obtained from the USDA-NRCS SSURGO tabular dataset for each respective research site (Soil Survey Staff, 2012b). It was assumed that a FWI of 0.00 was permanent wilting point and a FWI of 1.00 was close to saturated conditions.

One-third bar water or field capacity was then determined by using the soil physical property data and equations 4, 5, and 6 from Illston et al. (2008). Equations were created to predict PAW in the 80 cm profile from the weighted FWI values. A complete list of the soil parameter values and PAW prediction equations are listed in Table 1.1-5a,b. The SI was then determined similarly to Nix and Fitzpatrick (1969) by dividing the amount of PAW by the amount of water needed to maintain yield from the date of sensing to an assumed harvest date of June 10. Water usage by the crop was assumed to be 5 mm per day. This value was chosen because it is likely the highest average potential evapotraspiration (PET) loss in the Southern Great Plains from February 1 to June 10 according to the literature and Oklahoma Mesonet predicted PET losses for the three model calibration sites (Table 1.1-6). To keep from skewing the data for sensing times late in the growing season, SI values were not allowed to exceed 1.00.

<u>*Statistical Analysis*</u>

Weather Data. Weather data were downloaded from the Oklahoma Mesonet and imported into Microsoft Access databases. Structured query language (SQL) queries were developed to retrieve and summarize weather data to create desired model parameter variables.

Model Development. Multiple linear regression techniques were utilized to develop a model for predicting grain yield from the three proposed parameters (NDVI, DPG, SI). Step-wise regression was employed to determine which main and interactive effects of the proposed parameters had a significant impact on final grain yield. The maximized adjusted R^2 values were used to determine the appropriate regression equation parameters that best estimated yield.

To determine if surface soil texture was to have any effect on yield potential, three different models were developed. One model was created from all three calibration sites with no regard to surface texture. The other two models developed were the loamy surface textured model (Stillwater, OK and Lahoma, OK) and the coarse surface textured model (Perkins, OK).

Model Validation. The statistical model developed was validated utilizing datasets from the 2011-2012 and 2012-2013 growing seasons. From this point forward, the growing season will be described by the year of grain harvest. Three of the experimental sites used were the long-term soil fertility trials used in the development of the model. Three additional experimental sites from regional N fertilizer response trials were also used. None of the data sets or site-years used in model validation were part of the model development.

The INSEY values from the current methodology for predicting grain yield and the proposed models described above were evaluated for their effectiveness by regressing the predicted values against the actual grain yield values. Coefficient of determination (R^2) values and root mean square error (RMSE) values were then used to determine which methods performed best for predicting grain yield.

Results

Step-wise regression techniques revealed that the main effect and all interactive effects of the proposed model parameters had significant effects on final grain yield when data from all three calibration sites were used (Table 1.1-7). The same was true when only the data for the two loamy sites were used. For the coarse site model development DPG, SI, and the interaction of DPG and SI didn't have a statistical significant effect on grain yield, however including them in the model maximized the adjusted R^2 (Table 1.1-7). The parameters described in Table 1.1-7 were then employed to evaluate the effectiveness of each model's ability to predict yield for each of the validation sites included in this trial.

In 2012, the Stillwater, OK (222) site did not display much of a difference in model performance between the current INSEY and the proposed INSEY models for the Feekes growth stages 4, 5, 6. The amount of variation accounted for improved in both proposed models later in the growing season when compared to the current INSEY (Figure 1.1-1). When the ability to predict yield was evaluated across all growth stages in 2012, the proposed INSEY model that was developed regardless of soil type performed the best. In 2013, fall moisture at sowing was negligible and the first stand failed. The wheat was replanted in late November and not much growth occurred until later in the following spring. One sensor reading was recorded at Feekes 7, however, the ability to predict yield was good for the three different models, but no model seemed to be superior (Figure 1.1-1). When the Stillwater, OK (222) plots were pooled across growth stages and growing season, the proposed INSEY developed from all validation sites and that utilized soil moisture performed better than the current INSEY model and the model developed for loamy textured sites (Figure 1.1-1). The RMSE values were not that different from one another within each growth stage for the three models evaluated (Table 1.1-8). The trend seemed to be that the RMSE values decreased as the growth stage increased.

For Lahoma, OK (502) in 2012, the ability of the three models to predict grain yield tended to improve later into the growing season (Figure 1.1-2). At Feekes 4 there was no difference between the three model's ability to predict yield. However, as the growing season progressed the two proposed INSEY models that used soil moisture parameters outperformed the current INSEY model. This trend was also observed when the plots were analyzed across all growth stages for 2012 (Figure 1.1-2). In 2013, fall moisture was negligible, so very little growth occurred until later in the spring when the area received significant rainfall. With low biomass accumulation at Feekes 4 and 5, the ability to predict grain yield was poor. After rain had occurred and vegetative growth resumed, yield prediction for the three models improved at the Feekes 7 growth stage. As in 2012, the two proposed models utilizing soil moisture data outperformed the current INSEY model. When yield prediction was analyzed across growth stages in 2013, the poor prediction values at Feekes 4 and 5 seemed to dictate an overall poor performance of predicting yield for the 2013 growing season (Figure 1.1-2). When the ability to predict yield was analyzed across all growth stages and growing seasons, again the two proposed INSEY models that utilized soil moisture outperformed the current INSEY model (Figure 1.1-2). The RMSE values for the three models' regression of the predicted versus actual grain yield decreased throughout the growing season (Table 1.1-8). Very little difference was observed in the values between the different models except at the Feekes 5, 7, and 10 growth stages in 2012, and there was a slight improvement for the two models utilizing soil moisture compared to the current INSEY model (Table 1.1-8).

The ability of the three models to predict grain yield improved as the growing season progressed in 2012 at the Hennessey, OK (Reg) site (Table 1.1-3). Negligible, but lower coefficient of determination values were observed between the current INSEY model and the two proposed INSEY models for all growth stages in 2012. This was also observed when the 2012 data were analyzed across all growth stages; however the proposed INSEY model developed from all calibration sites had improved yield predictions as compared to the proposed INSEY model that was developed for loamy textured soils (Figure 1.1-3). In 2013, it was impossible to predict yield at Feekes 3 due to minimal available water for vegetative growth. After the site had received significant rainfall, the trend of improving yield prediction as the growing season progressed was observed. At Feekes 4, 5, and 6 no differences were observed in the three models' performances; however, at Feekes 7 and 10 the models utilizing soil moisture gave slight improvements in predicting yield (Figure 1.1-3). When analyzed across all growth stages for the 2013 growing season, the same trend as 2012 for the proposed INSEY model developed from all sites outperformed the other two models. This was then again observed when the data were analyzed across all growth stages and both growing seasons (Figure 1.1-3). No differences were observed in the RMSE values for each model, but again the values decreased as the growing season progressed. Of all the site-years analyzed, the values were the highest for the 2012 growing season (Table 1.1-8). This could likely be explained by significantly higher average grain yields harvested at this site for that growing season.

In 2012 at the Lake Carl Blackwell, OK (Reg) site, slight improvements in the ability to predict grain yield were observed for the proposed INSEY models that included soil moisture parameters (Figure 1.1-4). When the data were analyzed across all growth stages in 2012, the proposed INSEY model that was developed from all sites outperformed the other two models (Figure 1.1-4). For the 2013 growing season, very little differences were observed in the three models' abilities to predict grain yield until they were analyzed across all growth stages. Unlike the other previously described site-years, there was a decrease in model performance between Feekes 7 and 9. This may be because of a potentially damaging freeze that occurred between the two growth stages. When analyzed across all growth stages, the current INSEY model outperformed the other two proposed INSEY models. This same trend, though not as drastic, was observed when the data were analyzed across growth stages and both growing seasons (Figure 1.1-4). The RMSE values for the 2012 growing season decreased as the season progressed and there wasn't any difference between the values for each model (Table 1.1-8). In 2013, the RMSE values were not different amongst models and there was no observable trend (Table 1.1-8).

When all the validation sites classified as loamy were analyzed across site and growing season, no distinct patterns between model performance and growth stage were observed (Figure 1.1-5). When just observing the Feekes 4 through 10 growth stages, the ability to predict grain yield did tend to increase throughout the growing season (Figure 1.1-5) with the exception of the Feekes 9 growth stage which can likely be explained by the late season freeze at Lake Carl Blackwell, OK (Reg) in 2013. When all loamy sites were analyzed across all growth stages, the two proposed INSEY models outperformed the current INSEY model with the proposed INSEY model developed from all sites performing the best with a coefficient of determination value of 0.55 (Figure 1.1-5).

Days with above average temperatures prior to and during grain fill at Perkins, OK (N&P) in 2012 likely led to the very poor performance of the three models at predicting grain yield, with all coefficient of determination values being less than 0.20 (Figure 1.1-6). In 2013, grain yield prediction values decreased from Feekes 4 to 5 and 6, but increased for Feekes 7 and 10. The current INSEY model had slightly higher prediction capabilities at Feekes 3 and 4 compared to the two proposed models that utilize soil moisture parameters. The opposite trend was observed for Feekes 5 and 6, but there was no difference between the three models at Feekes 7 and 10. When the data were analyzed across all growth stages in 2013, the proposed INSEY model that was developed from all soil types outperformed the other two models. (Figure 1.1-6). When the data were analyzed across all growth stages and both growing seasons, no discernable best model was revealed. This again is likely due to grain yields that were marred by climatic conditions post sensing in 2012. No observable differences were detected in the RMSE values between models and growth stages for the 2012 growing season. In 2013, the RMSE tended to decrease throughout the growing season, much like the previously described loamy textured sites (Table1.1-8).

To add more plots to the coarse textured validation dataset, another N fertilizer response trial was added at Lake Carl Blackwell, OK (Val) on a coarse textured soil in 2013. The three models failed to predict yield early in the growing season when growth was limited due to lack of water. When rainfall returned, vegetative growth resumed and differences were observed at the remaining growth stages (Figure 1.1-7). At Feekes 4, 5, 7, and 10 the proposed INSEY models that incorporated soil moisture parameters performed slightly better than the current INSEY model. The ability to predict yield did increase from Feekes 4 to 7, but decreased from 7 to 10. This decrease is likely due to an unseasonably late freeze. When data were analyzed across all growth stages, extremely poor yield predictions were observed (Figure 1.1-7). Though the current INSEY performed the best of the three models, all the coefficient of determination values were less than 0.15. Like the previously described validation sites, the RMSE values decreased throughout the growing season from Feekes 3 to 7, but increased from 7 to 10 (Table 1.1-8).

No observable trends could be reported when the coarse textured validation sites were aggregated across site-years and analyzed (Figure 1.1-8). This could be because of a lack of site-years and the 2012 data collected from the Perkins, OK (N&P) research site. One item to note would be when the data were analyzed across site-years and growth stages the proposed INSEY model that was developed by all the calibration sites slightly outperformed the current INSEY model. The model that was developed for coarse textured soils performed poorly with a coefficient of determination value < 0.10 (Figure 1.1-8).

When the data were grouped across all site-years and analyzed at all growth stages, differences were observed between the current INSEY and proposed INSEY developed using soil moisture data. At growth stages Feekes 3 and 4 the current INSEY outperformed the proposed INSEY, but the proposed INSEY outperformed the current INSEY at Feekes 5, 6, 8, and 10. No discernable difference was observed between the two models at Feekes 7 and 9. (Figure 1.1-9). When the data were aggregated across all site-years and growth stages the proposed INSEY model outperformed the current INSEY model with a coefficient of determination value of 0.49 compared to 0.40 (Figure 1.1-10). The RMSE values didn't differ between the two models. It should also be noted that the linear regression equation for the proposed INSEY did not have a slope significantly different from one and an intercept different from zero. The regression equation for the current INSEY model had a slope significantly different than one, but the intercept was not significantly different from zero.

Discussion

Proper validation of developed predicted models should be conducted to determine the legitimacy of a model to accurately predict yield. Little to no work similar to that described in this paper has been published that truly validates a developed yield prediction model that could be compared. The current model for predicting INSEY (Raun et al., 2005), described the goodness of fit of the data used to develop the exponential relationship. The yield prediction model was only evaluated on its ability to improve N fertilizer recommendations and was not evaluated with an independent data set to predict yield. Other researchers have employed multi-parameter models that utilize NDVI and climate parameters to try and predict yield. Both Girma et al. (2006) and Walsh et al. (2013) developed models and made suggestions of what type of parameters could be reliable predictors of grain yield, but did not validate their conclusions with an independent dataset.

The common trend of the ability to accurately predict grain yield increasing with the progression of the growing season seems logical. As one moves later in the growing season the probability of unexpected and rare climatological events, such as freeze or extreme heat, between sensing and grain harvest decreases. The decrease in yield and thus a decrease in the ability to predict yield for the Perkins (N&P) validation site in 2012 is a prime example of what can happen even when there is just a short period of time in which temperatures exceed 31 to 35ºC during the grain filling process. Wheat grain yields can be significantly impacted even when as little as five percent of the grain filling process occurs under excess heat (Stone and Nicolas, 1994; Wheeler et al., 1996; Ferris et al., 1998). The decrease in the models' ability to predict yield for the Feekes 10 growth stages for the Lake Carl Blackwell (Reg) and Lake Carl Blackwell (Val) validation sites in 2013 may be attributed to a yield damaging late freeze. The amount of damage to grain yield would depend on the stage of the wheat crop at the time of the freeze (Thakur et al., 2010). Because dry matter accumulation and partitioning during grain fill can be strongly influenced by N fertilizer nutrition (Demotes-Mainard et al., 1999), the fact that the data utilized in this experiment came from N response trials would explain why plots had differential damaged due to the freeze. This would also explain the increase in RMSE values later in the growing season for the 2013 Lake Carl Blackwell sites.

Based on the results, there is no benefit to having a different model based on soil type. Though no similar winter wheat research exists, Sharma and Franzen (2013) reported contrary results while investigating the ability to predict maize grain yield with optical sensors and other maize plant measurements. They developed two different yield prediction curves for clayey and medium textured soils. The differences in the curves were due to soils potentially being water-logged and having different responses to N fertilization. Excess water, typically is not a problem for winter wheat grown in the region of the calibration and validation trials. Likely, the fact that soil physical properties were incorporated into the SI model parameter for the proposed INSEY model would negate the need for different yield prediction models based on soil type.

Conclusions

The ability of grain yield prediction models to estimate winter wheat grain yield in-season will aid producers in making better agronomic management decisions. Regardless of the model, the ability and the accuracy at which yield could be predicted increased as the growing season progressed, unless rare unseasonable climatic events occurred post-sensing. No added benefit was observed for creating two separate models based on soil type. One universal model developed with soil moisture data was sufficient for predicting grain yield. When comparing the ability to estimate grain yield of proposed INSEY models that utilize soil moisture data with the current INSEY model, the proposed INSEY models typically outperformed the current INSEY model at most validation sites. When data were combined over sites the current INSEY model did perform better at earlier growth stages (Feekes 3 and 4), but the opposite was observed for the mid to late growth stages (Feekes 5 to 10). Lastly, the proposed INSEY model outperformed the current INSEY model, with a coefficient of determination value of 0.49 compared to 0.42, when data were analyzed across all growth, thus providing a model in which producers wouldn’t be required to stage wheat growth in order to determine an appropriate model for grain yield prediction.

Table 1.1-1. Soil information for experimental sites utilized for model development and validation utilized in this experiment.

Location (Experiment)	--------Soil Mapping Unit--------	-----Major Component Taxonomy[a]-----	Major Component Hectares[a]
Stillwater, OK (222)	Kirkland silt loam, 1 to 3 percent slopes	Fine, mixed, superactive, thermic Udertic Paleustolls	274,050
Lahoma, OK (502)	Grant silt loam, 1 to 3 percent slopes	Fine-silty, mixed, superactive, thermic Udic Argiustolls	246,692
Perkins, OK (N&P)	Konawa fine sandy loam, 1 to 3 percent slopes	Fine-loamy, mixed, active, thermic Ultic Haplustalfs	130,241
Hennessey, OK (Reg)	Bethany silt loam, 0 to 1 percent slopes	Fine, mixed, superactive, thermic Pachic Paleustolls	2,122,838
LCB[b], OK (Reg)	Port silt loam, 0 to 1 percent slopes, occasionally flooded	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	2,662,838
LCB, OK (Val)	Konawa and Teller soils, 3 to 8 percent slopes, eroded	Fine-loamy, mixed, active, thermic Ultic Haplustalfs	130,241

[a] Soil Survey Staff (2014a)

[b] LCB, Lake Carl Blackwell.

Table 1.1-2. Nitrogen fertilizer application treatments for research plots utilized in the model calibration and validation of the study.

Trial (replications) N Source	Pre-Plant N Fertilizer Applied -----kg N ha^{-1}-----
Lahoma 502 (4)	0
urea (46-0-0)	22
	45
	67
	90
	112
Stillwater 222 (4)	0
urea (46-0-0)	40
	90
Perkins N&P (3)	0
urea (46-0-0)	56
	112
	168
Hennessey Reg. (4)	0
UAN (28-0-0)	28
	56
	84
	112
	140
	168
	224
Lake Carl Blackwell Reg. (4)	0
UAN[a] (28-0-0)	28
	56
	84
	112
	140
	168
	224

[a] UAN, urea ammonium nitrate.

Table 1.1-3. Years and Feekes growth stages that yield potential measurements were collected for three long-term trials utilized in developing a model for wheat yield potential.

Location (Experiment)	Years	Feekes Growth Stages
Stillwater, OK (222)	2003	5
	2004	3, 4, 5, 6, 7, 8, 9
	2005	3[a], 4, 5, 6, 8
	2006	3, 4[a], 5, 6, 7, 8, 9
	2008	4, 5[a]
	2011	4, 6
Lahoma, OK (502)	2003	5
	2004	3, 5[a], 6, 8, 9, 10
	2005	4, 5, 6, 7, 9
	2006	3, 4, 5[a], 6, 7, 8, 10
	2007	5[a]
	2008	5[a], 6
	2009	5[a]
	2010	5
	2011	5
Perkins, OK (N&P)	2003	5
	2004	3[a], 4[a], 5, 6, 7, 8, 9
	2005	3, 4, 5, 6 , 7, 9
	2006	3[a], 4, 5[a], 6 , 7, 9
	2009	3[b], 4[a], 5, 6, 7, 8, 9, 10
	2010	5
	2011	5

[a] Yield potential measurements collected two times for this Feekes growth stage.
[b] Yield potential measurements collected three times for this Feekes growth stage.

Table 1.1-4. Years and Feekes growth stages that yield potential measurements were collected for three long-term trials and three regional N fertilizer response trials utilized in validating a model for wheat yield potential.

Location (Experiment)	Years	Feekes Growth Stages
Stillwater, OK (222)	2012	4, 5, 6, 8, 10
	2013	7
Lahoma, OK (502)	2012	4, 5, 6, 7, 10
	2013	4, 5, 7
Perkins, OK (N&P)	2012	4, 5, 6, 8, 10
	2013	3, 4, 5, 6, 7, 10
Hennessey, OK (Reg)	2012	4, 5, 6, 7
	2013	3, 4, 5, 6, 7, 10
LCB[a], OK (Reg)	2012	4[b], 5, 8
	2013	3, 7, 9
LCB, OK (Val)	2013	3, 4, 5, 7, 10

[a] LCB, Lake Carl Blackwell.
[b] Yield potential measurements collected two times for this Feekes growth stage.

Table 1.1-5a. Soil parameters utilized for determining plant available water to 80 cm depth at research locations used in study.

---------------Lahoma 502---------------

			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}
1	0	25	0.430	1.40	0.291	1.40	0.141	1.46
2	25	41	0.420	1.40	0.293	1.40	0.144	1.50
3	41	80	0.390	1.55	0.314	1.55	0.175	1.62
	weighted average		0.409	1.47	0.303	1.47	0.158	1.55
	PAW (cm)		48.14		35.66		19.56	
	equation		$PAW=19.905e^{0.8691*FWI}$					

---------------Stillwater 222---------------

			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}
1	0	18	0.430	1.40	0.287	1.40	0.135	1.46
2	18	36	0.410	1.48	0.354	1.48	0.314	1.84
3	36	80	0.410	1.48	0.354	1.48	0.314	1.84
	weighted average		0.415	1.46	0.339	1.46	0.274	1.75
	PAW (cm)		48.48		39.64		38.42	
	equation		$PAW=37.199e^{0.2052*FWI}$					

---------------Perkins N&P---------------

			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}	g H_2O g soil^{-1}	g cm^{-3}
1	0	23	0.390	1.53	0.186	1.53	0.090	1.60
2	23	43	0.370	1.40	0.159	1.40	0.063	1.65
3	43	80	0.370	1.58	0.239	1.58	0.156	1.65
	weighted average		0.376	1.53	0.206	1.53	0.117	1.63
	PAW (cm)		46.00		25.24		15.27	
	equation		$PAW=14.241e^{1.0513*FWI}$					

Table 1.1-5b. Soil parameters utilized for determining plant available water to 80 cm depth at research locations used in study.

			---------------Hennessey (Reg)---------------					
			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	g cm^{-3}
1	0	38	0.43	1.40	0.291	1.40	0.141	1.46
2	38	46	0.37	1.58	0.242	1.58	0.224	1.80
3	46	80	0.38	1.55	0.334	1.55	0.276	1.93
	weighted average		0.37	1.32	0.280	1.32	0.180	1.51
	PAW (cm)		38.73		29.67		22.32	
	equation		$PAW=21.625e^{0.5496*FWI}$					

			---------------Lake Carl Blackwell (Reg)---------------					
			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	g cm^{-3}
1	0	74	0.420	1.43	0.287	1.43	0.135	1.50
2	74	80	0.420	1.45	0.299	1.45	0.152	1.65
	weighted average		0.420	1.43	0.290	1.43		1.51
	PAW (cm)		48.10		32.97		16.48	
	equation		$PAW=15.864e^{1.0872*FWI}$					

			---------------Lake Carl Blackwell (Val)---------------					
			Saturated		Field Capacity		Wilting Point	
Horizon	Top Depth	Bottom Depth	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density	Grav. H_2O	Bulk Density
	-----cm-----		g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	g cm^{-3}	g H_2O g $soil^{-1}$	--g cm^{-3}--
1	0	23	0.390	1.53	0.186	1.53	0.090	1.60
2	23	43	0.370	1.40	0.159	1.40	0.063	1.65
3	43	80	0.370	1.58	0.239	1.58	0.156	1.65
	weighted average		0.376	1.53	0.206	1.53	0.117	1.63
	PAW (cm)		46.00		25.24		15.27	
	equation		$PAW=14.241e^{1.0513*FWI}$					

Table 1.1-6. Average, minimum, and maximum potential evapotranspiration (PET) amounts (mm) from February 1 to June 10 for three long-term soil fertility locations.

	-------Stillwater, OK-------			-------Lahoma, OK-------			-------Perkins, OK-------		
Year	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
2003	3.3	0.3	8.1	3.3	0.3	8.1	3.5	0.3	8.6
2004	3.5	0.3	8.4	3.7	0.3	10.9	3.7	0.3	9.4
2005	3.5	0.3	7.9	3.7	0.3	9.1	3.8	0.3	9.4
2006	4.1	0.3	9.4	4.7	0.3	11.9	4.4	0.3	9.9
2007	3.1	0.3	7.4	3.1	0.3	8.9	3.2	0.3	7.6
2008	3.7	0.3	8.9	3.8	0.3	11.2	3.8	0.3	9.9
2009	3.6	0.8	8.4	3.8	0.5	10.2	3.7	0.8	9.4
2010	3.4	0.3	7.9	3.5	0.3	9.4	3.5	0.3	8.4
2011	4.1	0.3	9.4	4.5	0.3	12.4	4.4	0.3	9.7
2012	3.9	0.3	10.4	4.0	0.3	11.4	3.9	0.3	11.7

Table 1.1-7. Model parameter estimates for estimating wheat grain yield.

	---All Sites---		---Loamy Sites---		---Coarse Sites---	
Parameter	Est.	Pr > |t|	Est.	Pr > |t|	Est.	Pr > |t|
Intercept	8.32	---	9.62	---	4.68	---
DBG[a]	-0.09	<0.0001	-0.08	0.0320	-0.06	0.1261
SI[a]	-10.66	<0.0001	-13.82	<0.0001	-5.03	0.2157
NDVI[a]	-15.68	<0.0001	-17.17	0.0005	-13.19	0.0356
DPG*SI	0.11	<0.0001	0.11	0.0029	0.05	0.2408
DPG*NDVI	0.22	<0.0001	0.18	0.0051	0.23	0.0014
NDVI*SI	25.80	<0.0001	31.44	<0.0001	16.51	0.0250
NDVI*DPG*SI	-0.28	<0.0001	-0.27	<0.0001	-0.22	0.0064

[a] DPG, days of potential growth; SI, stress index; NDVI, normalized difference vegetative index.

Table 1.1-8. Root mean square error values for current and proposed models for predicting final wheat grain yield by Feekes (FK) growth stage.

	FK 3	FK 4	FK 5	FK 6	FK 7	FK 8	FK 9	FK 10
Stillwater, OK (222)								
2012-Current INSEY	---	0.57	0.38	0.50	---	0.29	---	0.25
2012-New INSEY-All	---	0.56	0.39	0.50	---	0.23	---	0.20
2012-New INSEY-Loamy	---	0.56	0.39	0.50	---	0.23	---	0.20
Stillwater, OK (222)								
2013-Current INSEY	---	---	---	---	0.13	---	---	---
2013-New INSEY-All	---	---	---	---	0.13	---	---	---
2013-New INSEY-Loamy	---	---	---	---	0.13	---	---	---
Lahoma, OK (502)								
2012-Current INSEY	---	0.64	0.66	0.74	0.50	---	---	0.37
2012-New INSEY-All	---	0.65	0.59	0.73	0.35	---	---	0.29
2012-New INSEY-Loamy	---	0.65	0.59	0.73	0.35	---	---	0.29
Lahoma, OK (502)								
2013-Current INSEY	---	0.50	0.49	---	0.33	---	---	---
2013-New INSEY-All	---	0.50	0.49	---	0.31	---	---	---
2013-New INSEY-Loamy	---	0.50	0.49	---	0.31	---	---	---
Perkins, OK (N&P)								
2012-Current INSEY	---	0.29	0.31	0.31	---	0.30	---	0.30
2012-New INSEY-All	---	0.29	0.31	0.31	---	0.30	---	0.30
2012-New INSEY-Coarse	---	0.29	0.31	0.31	---	0.30	---	0.30
Perkins, OK (N&P)								
2013-Current INSEY	0.23	0.21	0.25	0.25	0.17	---	---	0.18
2013-New INSEY-All	0.23	0.22	0.24	0.24	0.17	---	---	0.18
2013-New INSEY-Coarse	0.23	0.22	0.24	0.24	0.17	---	---	0.18
Hennessey, OK (Reg)								
2012-Current INSEY	---	0.96	0.97	0.88	0.46	---	---	---
2012-New INSEY-All	---	0.94	0.96	0.85	0.43	---	---	---
2012-New INSEY-Loamy	---	0.94	0.96	0.85	0.43	---	---	---
Hennessey, OK (Reg)								
2013-Current INSEY	0.71	0.59	0.53	0.41	0.32	---	---	0.32
2013-New INSEY-All	0.71	0.60	0.53	0.41	0.29	---	---	0.27
2013-New INSEY-Loamy	0.71	0.60	0.53	0.41	0.29	---	---	0.27
LCB[a], OK (Reg)								
2012-Current INSEY	---	0.37	0.33	---	---	0.24	---	---
2012-New INSEY-All	---	0.35	0.32	---	---	0.24	---	---
2012-New INSEY-Loamy	---	0.35	0.32	---	---	0.24	---	---
LCB, OK (Reg)								
2013-Current INSEY	0.23	---	---	---	0.18	---	0.23	---
2013-New INSEY-All	0.23	---	---	---	0.18	---	0.23	---
2013-New INSEY-Loamy	0.23	---	---	---	0.18	---	0.23	---
LCB, OK (Val)								
2013-Current INSEY	0.47	0.41	0.28	---	0.28	---	---	0.35
2013-New INSEY-All	0.47	0.40	0.27	---	0.27	---	---	0.34
2013-New INSEY-Coarse	0.47	0.40	0.27	---	0.27	---	---	0.34

[a] LCB, Lake Carl Blackwell.

Figures

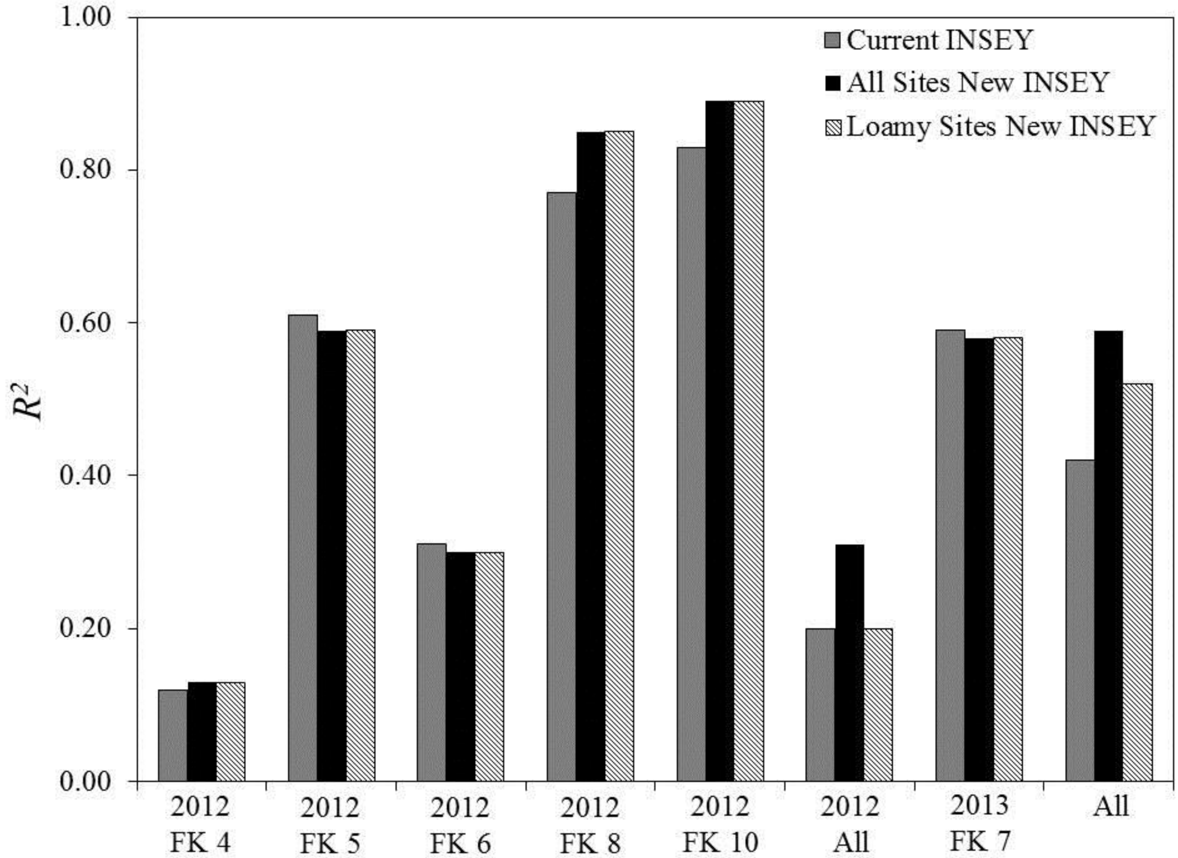

Figure 1.1-1. Stillwater, OK (222) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage, growing season, and across all growth stages and growing seasons.

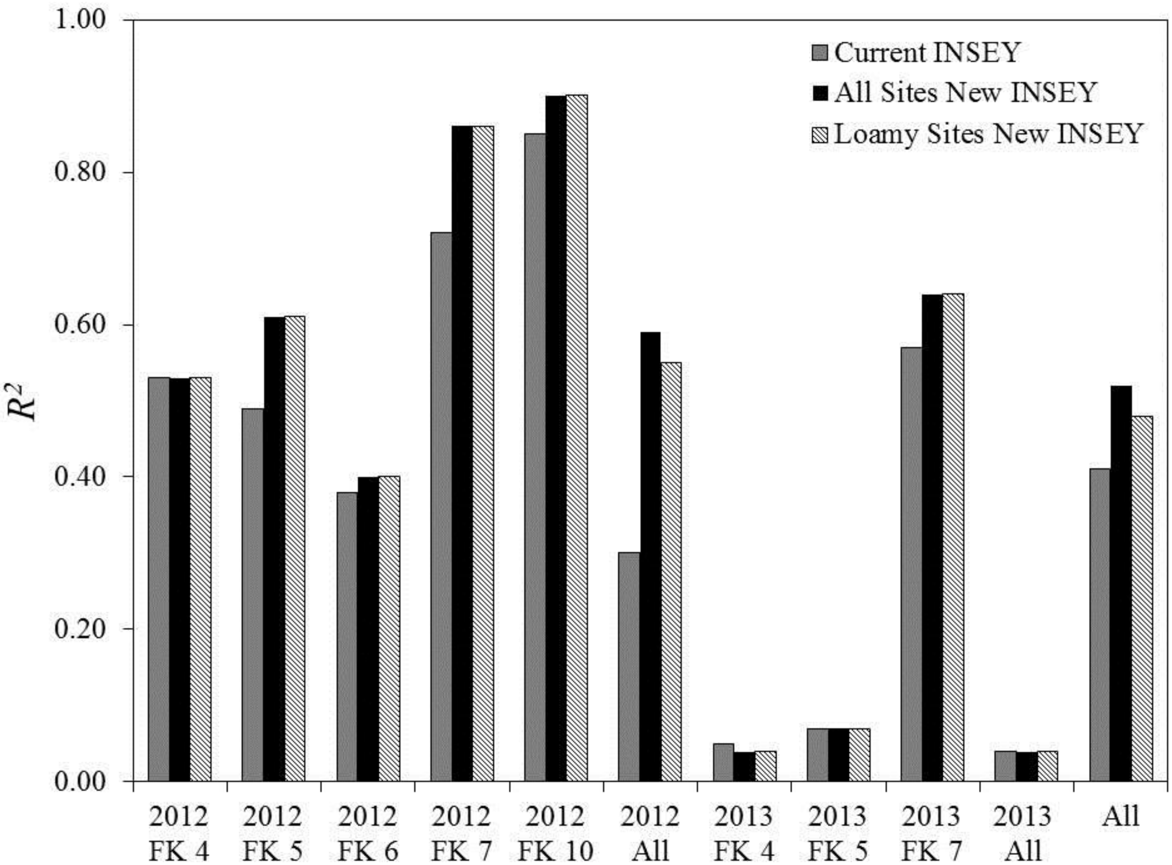

Figure 1.1-2. Lahoma, OK (502) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage, growing season, and across all growth stages and growing seasons.

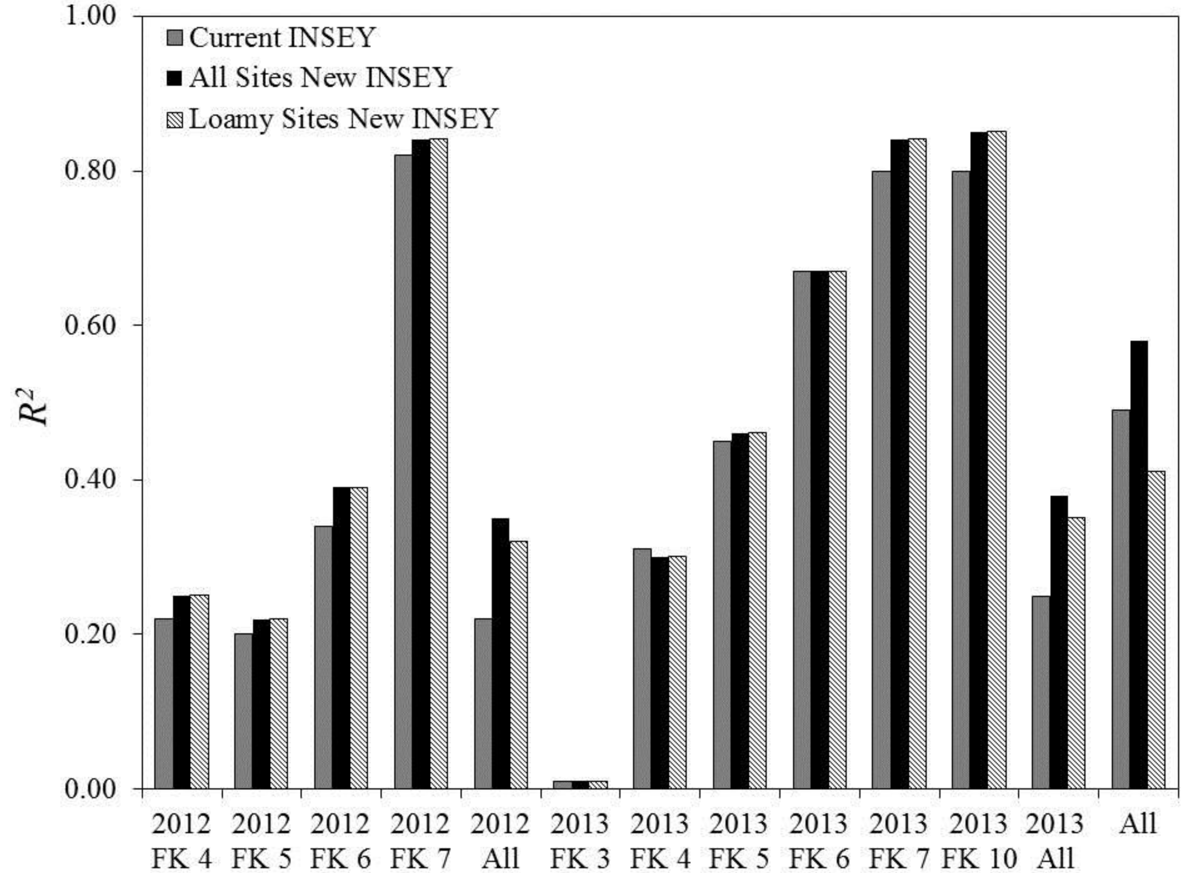

Figure 1.1-3. Hennessey, OK (Reg) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage, growing season, and across all growth stages and growing seasons.

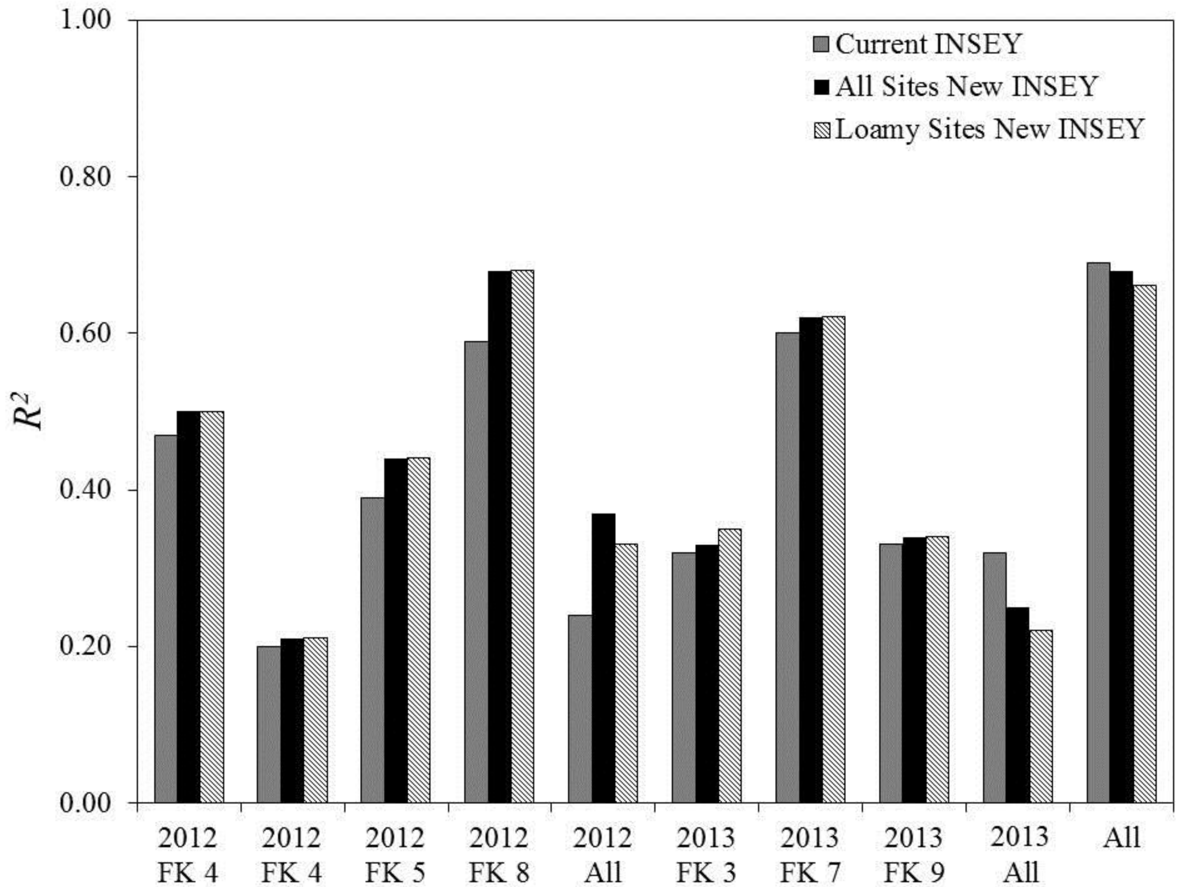

Figure 1.1-4. Lake Carl Blackwell, OK (Reg) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage, growing season, and across all growth stages and growing seasons.

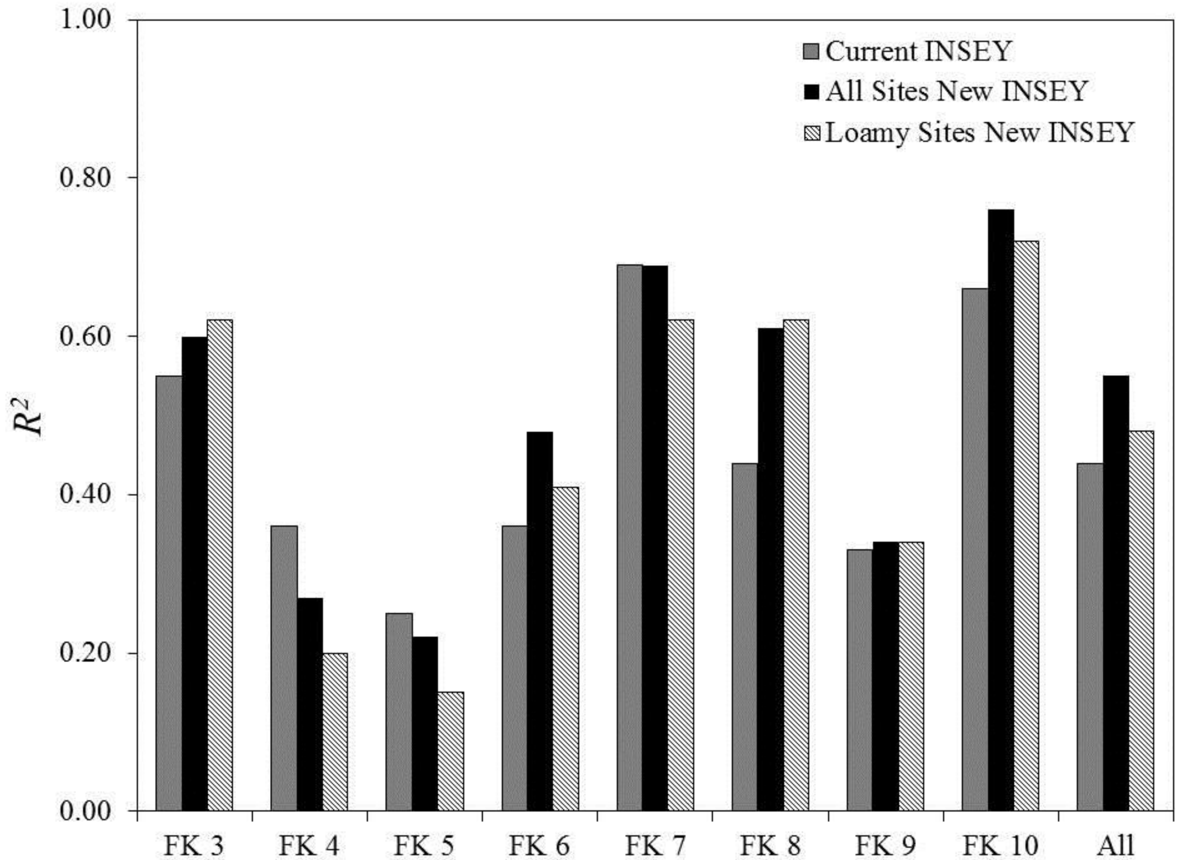

Figure 1.1-5. Validation sites with a loamy surface soil texture coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage across the 2012 and 2013 growing seasons.

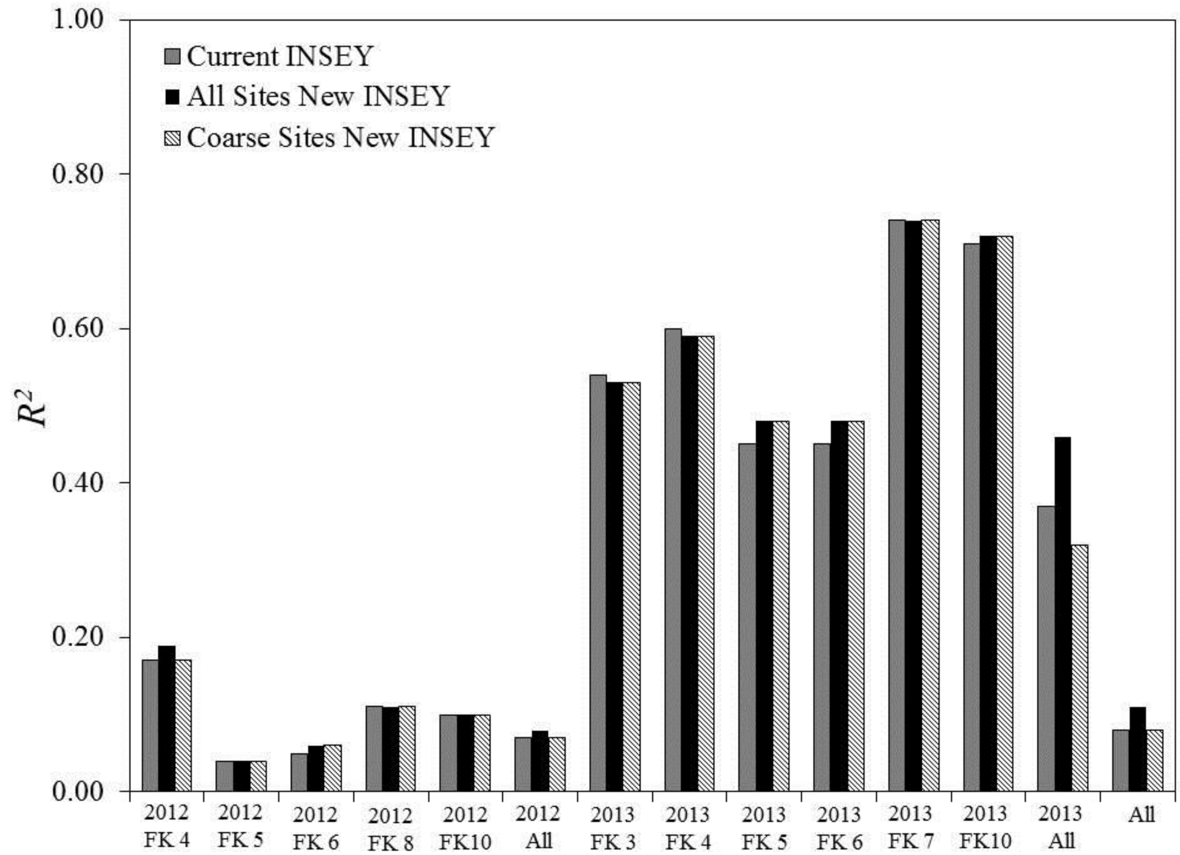

Figure 1.1-6. Perkins, OK (N&P) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a coarse textured surface. Predictions are grouped together by Feekes (FK) growth stage, growing season, and across all growth stages and growing seasons.

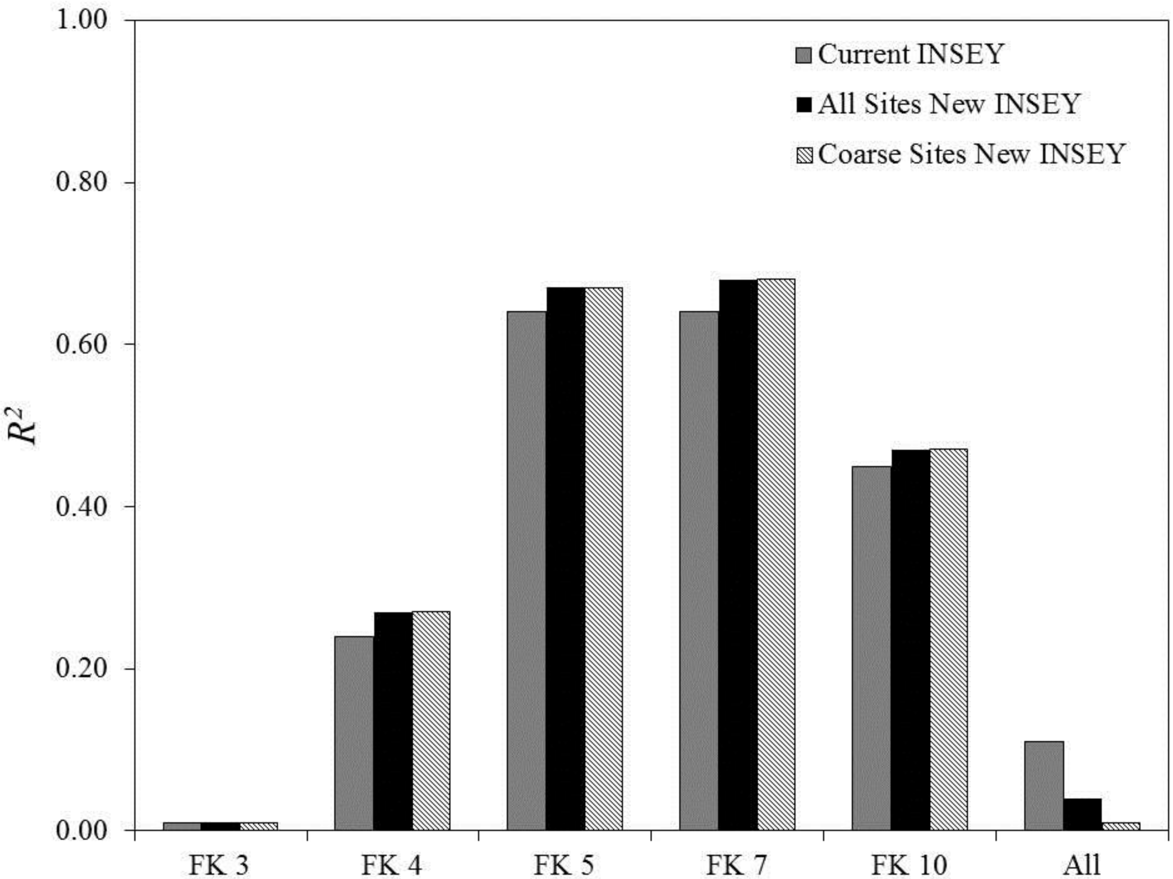

Figure 1.1-7. Lake Carl Blackwell, OK (Val) coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a coarse textured surface. Predictions are grouped together by Feekes (FK) growth stage and across all growth stages for the 2013 growing season.

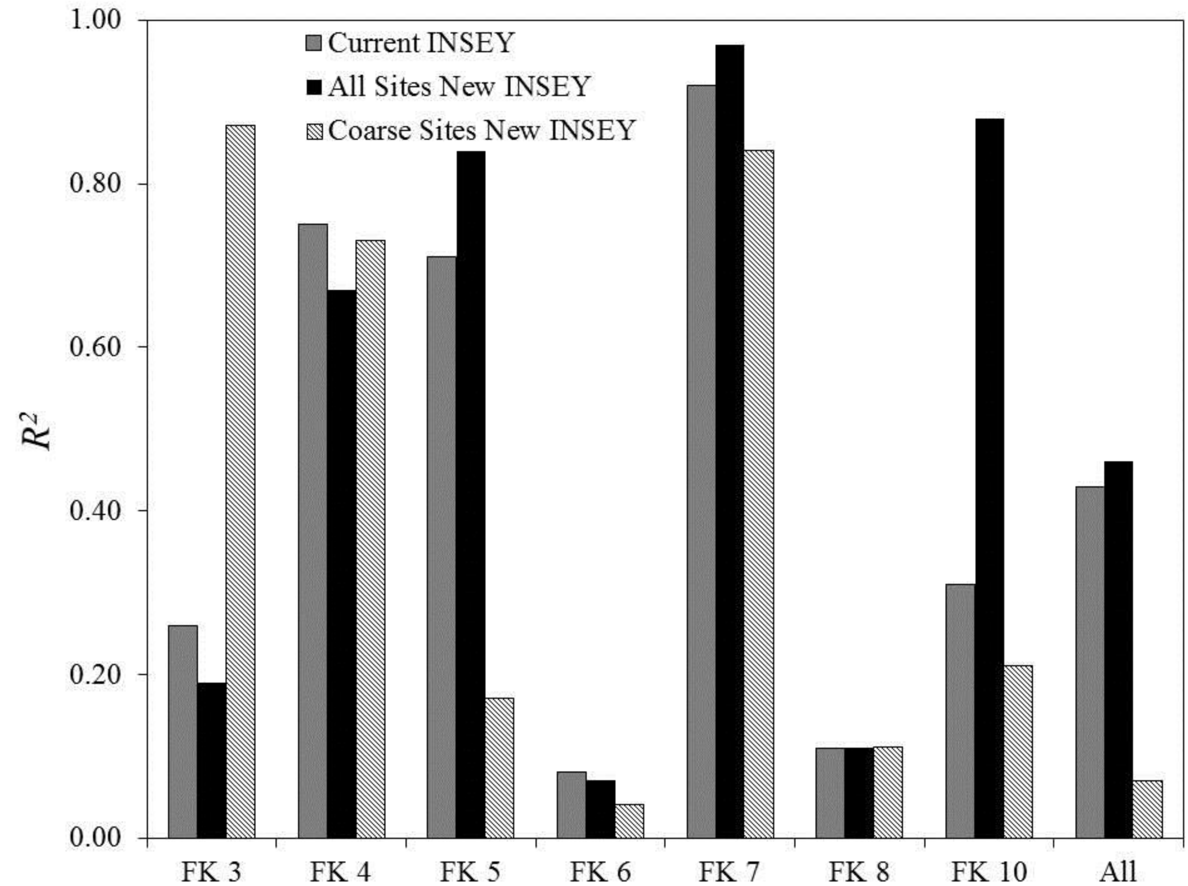

Figure 1.1-8. Validation sites with a coarse surface soil texture coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage across the 2012 and 2013 growing seasons.

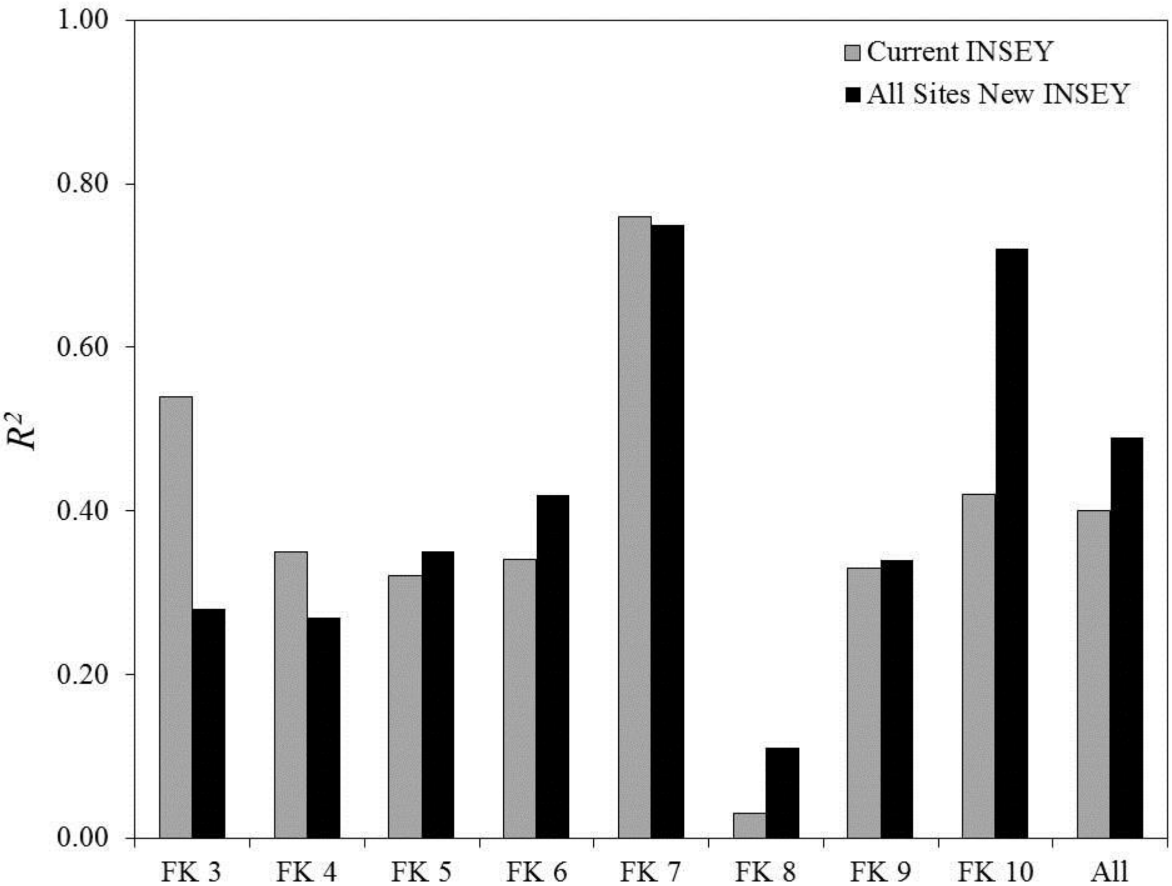

Figure 1.1-9. Coefficient of determination (R^2) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and a proposed new model that incorporate soil moisture data into yield prediction. Predictions are grouped together by Feekes (FK) growth stage across all validation sites for the 2012 and 2013 growing seasons.

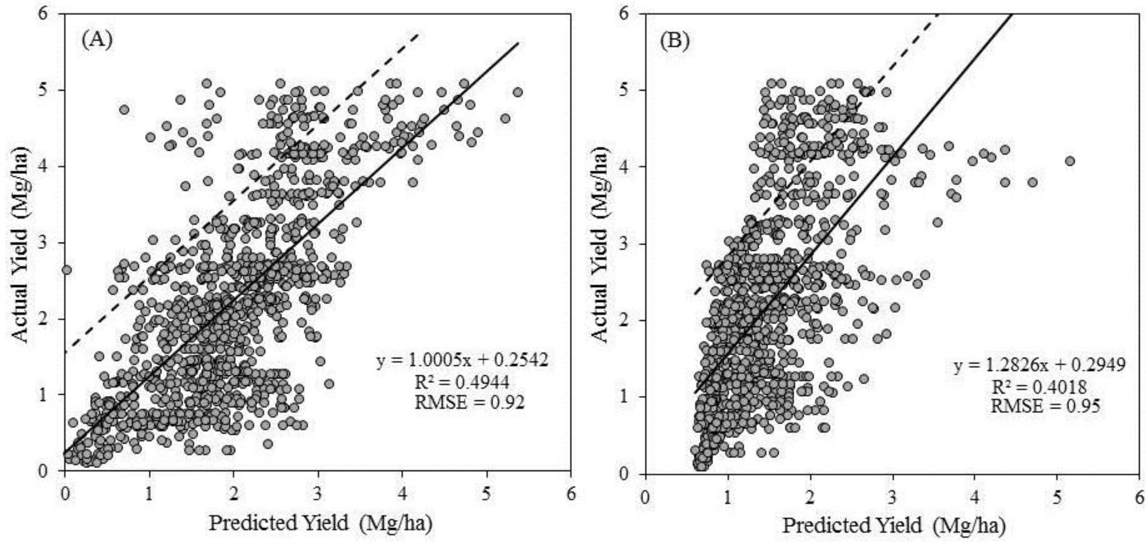

Figure 1.1-10. Linear relationships between predicted winter wheat in-season estimations of yield based upon soil moisture parameters (A) or the current model (B) used to predict actual grain yield. Data presented is from all validation sites across all growth stages. Dashed line represents one standard deviation above the actual yield.

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CHAPTER 1.2

EVALUATION OF SENSOR BASED MID-SEASON NITROGEN FERTILIZER RECOMMENDATIONS FOR WINTER WHEAT WITH DIFFERENT ESTIMATES OF YIELD POTENTIAL

Introduction

Average nitrogen (N) fertilizer use efficiency for cereal grain production in the developed world is estimated to be about 42 percent (Raun and Johnson, 1999). For winter wheat, these can typically range from 27 to as high as 50 percent depending on the growing season and production practices (Olson and Swallow, 1984; Lees et al., 2000; Raun et al, 2002). Current soil testing based N fertilizer recommendation for winter wheat in Oklahoma recommends that 33 kg N ha^{-1} be applied for each Mg ha^{-1} a producer hopes to produce minus the amount of N available in a soil nitrate test (Zhang and Raun, 2006). This methodology has proven to deliver more profitable N fertilizer recommendations (Makowski and Wallach, 2001); however, when grain yield goals are employed the risk of predicting environmental conditions is placed on the producer, especially if all N fertilizer is to be applied prior to planting (Raun et al., 2005).

Mid-season N fertilizer applications in winter wheat have reportedly increased N fertilizer use efficiency and at times grain yields (Olson and Swallow, 1984; Alcoz et al., 1993; Boman et al., 1995). The advent of ground based active optical sensors that measure the normalized difference vegetative index (NDVI) has allowed for more accurate N fertilizer recommendations along with variable fertilizer rate application (Solie et al., 2012) as long as N is the main growth-limiting factor (Zillmann et al., 2006). The use of these optical sensors has proven to increase N fertilizer use efficiency as well as at times increase economic return for producers (Raun et al., 2002; Ortiz-Monasterio and Raun, 2007). These sensor measurements are coupled with mathematical algorithms to produce sensor based N fertilizer recommendations.

Numerous parameters have been evaluated to aid in making sensor based N fertilizer recommendations. Raun et al. (2010) reported that data from three long-term soil fertility experiments revealed that maize and wheat grain yields were consistently independent of the crop response to N fertilization. They concluded that because of their independence and that they both affect the demand for N fertilizer, both should be utilized in determining in-season N fertilizer recommendations. These conclusions were further confirmed in the work of Arnall et al. (2013) who reported the same independence between grain yield and N fertilizer response from seven long-term soil fertility experiments in Oklahoma, Nebraska, Iowa, and Wisconsin.

The concept of a grain harvest index, calculated as the maximum yield of fertilized plots divided by yield of unfertilized plots, was first proposed by Johnson and Raun (2003) to predict adjustments to N fertilizer requirements. Raun et al. (2010) and Arnall et al. (2013) also reported the index to be extremely variable from year to year and unpredictable. In an effort to be able to predict the grain harvest index in-season Mullen et al. (2003) utilized the concept of Biggs et al. (2002), which compares the crop reflectance of an unfertilized field or typical farmer practice to a high N reference strip. They reported the ratio of the NDVI of the high N reference area divided by the NDVI of the farmer practice or unfertilized area correlated well with the harvest index ratio for Feekes (Large, 1954) growth stages 5, 9, and 10.5. The equations from the linear relationships between the two response indexes (RI) could then be employed to predict the harvest response index value.

Using the sum of two post-dormancy NDVI readings divided by the difference in growing degree-days (GDD) between the two readings, Raun et al. (2001) was able to accurately predict wheat grain yield in-season or yield potential (YP_0) . Building on this work, Lukina et al. (2001) observed that NDVI sensor measurements between Feekes growth stages 4 and 6 divided by the number of days from planting to sensing was highly correlated with final wheat grain yield and their in-season estimation of yield was then subsequently used to calculate the potential N removed in the grain. With the ability to then accurately predict grain yield and the harvest index, Raun et al. (2002) incorporated these two parameters into an algorithm and later adjusted the algorithms (Raun et al. 2005) to determine N fertilizer recommendations for winter wheat. The use of these algorithms coupled with the use of variable rate technology was reported to increase N fertilizer use efficiency by more than 15 percent (Raun et al., 2002).

To improve the accuracy of the algorithms' ability to determine N fertilizer rate recommendations, researchers have attempted to improve the prediction capability of some of the parameters. One of these parameters is the in-season estimate of YP_0. Currently estimates of YP_0 are determined from non-linear relationships with actual grain yield and the NDVI divided by the number of GDD's from planting to sensing (Raun et al., 2005). One parameter researchers have evaluated has been the effect of soil moisture properties on YP_0 (Walsh et al., 2013; Bushong 2014). Bushong (2014) reported improved ability to predict grain yield compared to current estimates by altering the GDD's to only count if soil moisture was adequate for growth and also included a crop water stress index (SI) at the time of sensing.

Concerned with some of the limitations of Lukina et al. (2001) and Raun et al. (2005), Solie et al. (2012) developed a generalized algorithm for variable rate N applications. Some of the concerns addressed by Solie et al. (2012) were that the maximum yield potential was not incorporated into a continuous function, boundary conditions were not included, and crop growth stage and differing rates of biomass accumulation at each growth stage were not fully accurate. Using sigmoidal relationships and boundary parameters determined from bare soil NDVI measurements and maximum grain yield for the region, Solie et al. (2012) was able to produce a model that could accurately recommend N fertilizer rates for changing growth stages for both maize and wheat.

Objectives

The objective of this experiment was to evaluate the effectiveness of four sensor-based N fertilizer rate recommendations to predict the potential yield parameters that affect N rate recommendations, and thus their effect on reliably estimating the agronomic optimum N rate (AONR).

Materials & Methods

Site Information

To evaluate the effectiveness of different sensor based N fertilizer recommendations data were collected from 34 mid-season N fertilizer response trials. Each of these sites received a range of N fertilizer rates from 0 to as high as 183 kg N ha^{-1}. Fertilizer was applied at approximately the Feekes 5 (Large, 1954) growth stage. Normalized difference vegetative index readings were recorded either the day before or the day of mid-season N fertilizer application with a Greenseeker (Trimble, Sunnyvale, CA, USA) active optical sensor. Site soil characteristics along with ranges in N fertilizer application rates are described in Table 1.2-1.

Agronomic optimum N rate (AONR) was calculated post-harvest by plotting actual grain yield versus the mid-season N fertilizer rate (Table 1.2-2). The maximum grain yield that was achieved and maintained even with added N fertilizer was quantified for each site-year using a linear-plateau model.

Sensor Based Recommendations

Current Nitrogen Fertilization Optimization Algorithm (CNFOA). As previously reported by Raun et al. (2010) and Arnall et al. (2013), the use of both the crop's YP_0 and the predicted harvest RI should be employed to make accurate mid-season sensor based N fertilizer recommendations. The theory for the CNFOA is that described by Raun et al. (2005). The determination of YP_0 was derived by dividing the NDVI by the cumulative number of growing degree-days (GDD) with a growth threshold value of 4.4ºC. This gives an empirical value known as the in-season estimate of yield (INSEY). An exponential relationship has been established between final grain yield and INSEY. The equation below describes this relationship and is thus used to predict final grain yield.

Equation [1] $YP_0 = 590*\exp(INSEY*258.2)$

The parameters listed in equation 1 are not the same values published in Raun et al. (2005). These values have been updated with more recent field data and are maintained and published by Oklahoma State University (2014).

The predicted harvest RI was determined using the relationship established between the principals proposed by Mullen et al. (2003). The harvest RI was predicted from the in-season RI derived by dividing the NDVI of an N rich area ($NDVI_{NR}$) by the NDVI of the farmer practice ($NDVI_{FP}$). The equation below describes the relationship and was used to predict the harvest RI.

Equation [2] $\text{Harvest RI} = 1.69*(NDVI_{NR}/ NDVI_{FP}) – 0.70$

The parameters listed in equation 2 are not the same values published in Raun et al. (2005). These values have been updated with more recent field data and are maintained and published by Oklahoma State University (2014).

The N fertilizer rate recommendation (N_{rec}) was calculated using equation 7 described in Raun et al. (2005).

Equation [3] $N_{rec} = [(YP_N – YP_0)*(GN\%)*(GW)/\eta$

The parameters YP_N are defined using the following equation.

Equation [4] $YP_N = YP_0 * \text{Harvest RI}$, but cannot exceed the YP_{max}

The YP_{max} is defined by the maximum yield for the region and η is assumed N fertilizer use efficiency. The GN% is the grain N percentage and the GW is the grain weight.

Proposed Nitrogen Fertilization Optimization Algorithm (PNFOA). The process for determining a N fertilizer recommendation from the PNFOA was conducted using the same theories and principals of the CNFOA. The only difference between the two is the PNFOA utilizes the proposed method described by Bushong (2014) for determining YP_0.

The method utilizes a multiple linear regression model that incorporates NDVI measurements as well as soil moisture data to estimate grain yield. The three parameters included are NDVI, days of potential growth (DPG), and stress index (SI). The NDVI is that of the unfertilized or farmer practice area. The DPG is the number of days where temperature and soil moisture exceed thresholds for substantial growth. The SI is the ratio of soil profile water at the time of sensing compared to the estimated evapotranspiration from sensing to harvest. Model parameters computed for each site are listed in Tables 1.2-2 and 1.2-3. A complete description of how each parameter is calculated and the model intercept and parameter estimates is described in Chapter 1.1 of Bushong (2014).

Generalized Algorithm (GA). For the GA, the N fertilizer recommendation was determined by equation 3 described above. However, the difference being that the GA uses parameterized, symmetric, sigmoidal models to determine the YP_0 and $YP_{N\ is}$ calculated using a similar sigmoidal relationship that accounts for the NDVI RI. The YP_{max} is used as the plateau for both sigmoidal models. The equations for determining the YP_0 and YP_N are described below in equations 5 and 6, respectively.

Equation [5] $YP_{0} = YP_{max}/(1 + \exp[-(NDVI_{FP} – Inf)/K])$

Equation [6] $YP_{N} = YP_{max}/(1 + \exp[-(NDVI_{RI} * NDVI_{FP} – Inf)/K])$

The inflection point (Inf) and curvature (K) parameters were a function of the $NDVI_{FP}$. For a complete description of the model and model parameters for predicting these parameters for wheat only, reference Solie et al. (2012).

Modified Generalized Algorithm (MGA). This algorithm follows the same principals and utilizes the same sigmoidal models for estimating the YP_0 and YP_N as described by Solie et al.

(2012). Modifications were made in the estimations of the inflection point and curvature values based upon bare soil NDVI readings (Oklahoma State University, 2014).

Assumptions. For all three algorithms described above, assumptions were made concerning some of the inputs. To evaluate the effectiveness of each model to predict the AONR these assumptions were consistent across all algorithms. Below is a list of the assumptions used.

YP_{max} = The maximum recorded yield for the trial location.

Fertilizer Use Efficiency (η) = 0.50

Grain Nitrogen percent = 2.39 percent

Grain weight = 773 kg m^{-3}

Bare soil NDVI = 0.150

Soil NO_3 Test

As previously stated, the current non-sensor based N fertilizer recommendation is to utilize a pre-plant soil NO_3 test (PPNT) along with a yield goal or YP_{max} (Zhang and Raun, 2006). Of the 34 research sites, 18 research sites had recorded a PPNT value (Table 1.2-2). Subtracting out the NO_3 concentrations and the preplant N fertilizer applied from the required N rate that was based upon YP_{max}, delivered a mid-season N fertilizer rate recommendation that could then be compared to the AONR.

Statistical Analysis

Simple linear regression analysis was conducted to determine if the algorithms' measurements of YP_0 and YP_N accurately predicted the actual grain yield with no added N fertilizer and the optimum grain yield achieved at the AONR, respectively. After the linear-plateau regression models derived the mid-season AONR, these values were then compared to the N fertilizer rate recommendation for each research site. Linear regression techniques were employed to evaluate if significant relationships were observed between the AONR and predicted N rate recommendations for the above stated methods. Coefficient of determination (R^2) values, root mean square error (RMSE), and number of sites within ± 20 kg N ha^{-1} were employed to determine the effectiveness of each N rate recommendation method.

Results

The difference between the grain yield potential with and without added N fertilizer is what ultimately determines the sensor based N fertilizer recommendation (Lukina et al, 2001; Raun et al., 2002). How these variables are determined is what differentiates the N fertilizer recommendation algorithms. Calculated YP_0 and YP_N values were observed to be different based upon the algorithm used. Both the CNFOA and PNFOA displayed a wide range of values from approximately 1 to 6 Mg ha^{-1} (Table 1.2-4). The GA and MGA displayed a much narrower range, approximately 2 Mg ha^{-1} of yield potential values. In comparing the GA and MGA, the MGA yield potential values were drastically lower with values less than 3 Mg ha^{-1} (Table 1.2-4).

To evaluate if the yield potential values were reliable estimates of the actual grain yield value, the values were compared to the optimum grain yield at the AONR. Linear regression analysis revealed that there were significant relationships between the optimum grain yield and YP_N for the CNFOA and PNFOA (Figure 1.2-1). The CNFOA predicted optimum yield best with a coefficient of determination value of 0.25. Non-significant relationships were observed between the derived YP_N and the optimum grain yield for both the GA and the MGA (Figure 1.2-2). The narrow range in YP_N values displayed its limitations with these algorithms, especially with the data set used that had a range in optimum grain yields of approximately 1 to 6 Mg ha^{-1}. All algorithms had significant relationships between the YP_0 and the yield of the plots that did not receive any mid-season N fertilizer (Figures 1.2-3 and 1.2-4). The CNFOA performed the best (R^2 = 0.46) of the four algorithms evaluated. Not much difference was observed between the performance of the GA and the MGA to estimate YP_0. However, the range in YP_0 values for the GA was more similar to the actual range in grain yields compared to the MGA (Figure 1.2-4).

The ultimate objective of this project was to determine which algorithm would provide an N fertilizer recommendation closest to the AONR. Based upon the 34 yield responses to mid-season N fertilizer application, the range in AONR for this evaluation was 0 to 140 kg N ha^{-1} (Table 1.2-2). When the sensor based N fertilizer recommendations for each research site were regressed against the AONR for each research site, negligible differences were observed in the coefficient of determination and RMSE values for each algorithm (Table 1.2-5). However, differences were observed in the percent of sites under and over predicted as well the number of sites within 20 kg N ha^{-1} (Table 1.2-5). For approximately 75 percent of the sites, both the CNFOA and PNFOA reported N recommendations lower than the AONR. Linear regression equations support this with slopes greater than one and intercepts greater than zero (Figure 1.2-5). The GA and MGA nearly split the number of sites in which they recommended less N and the sites where they recommended more than the AONR (Table 1.2-5). A more appealing spread in N rate recommendation values was observed for both the GA and MGA compared to the CNFOA and PNFOA (Figure 1.2-6). The recommendation values for the GA and MGA ranged from near zero to approximately 140 kg N ha^{-1}, much higher than the CNFOA and PNFOA, which did not exceed 85 kg N ha^{-1}. The sensor based N fertilizer recommendations outperformed the non-sensor based PPNT (Table 1.2-5). The PPNT was only able to account for 11 percent of the variability and could only deliver N recommendations within 20 kg N ha^{-1} one out of every five site years.

Discussion

The lack of correlation for YP_N and the grain yield at the AONR for the GA and MGA didn't seem to hinder either algorithm's ability to predict an AONR compared to the other algorithms. If improvements could be made in the estimation of YP_N, the overall ability of the algorithms to determine a more accurate N fertilizer rate would increase. The use of YP_{max} as the numerator in the sigmoidal models of the GA proposed by Solie et al. (2012) could explain the lack of prediction in YP_N values. The YP_{max}, which was defined as the maximum grain yield ever achieved for the area of that particular research trial, though theoretically achievable, is likely only to occur less than 10 percent of the time. The estimation of YP_N from the CNFOA and PNFOA is extrapolated from the YP_0 and the $NDVI_{RI}$ which are taking into account the potential yield variability for that growing season and logically makes more sense and was supported with the range in predicted values being similar to the actual grain yield values.

As previously stated, the only difference between the CNFOA and PNFOA is the parameters used to estimate the YP_0. The results observed were somewhat contrary to the results reported by Bushong (2014) in that the CNFOA predicted YP_0 better than the PNFOA. The estimation of YP_0 using the PNFOA uses an algorithm developed across all growth stages and soil types. As reported by Bushong (2014), when YP_0 estimates were broken down by individual growth stages the CNFOA actually predicted yield better at lower growth stages (Feekes 3, 4), but there was a shift in improved performance around the Feekes 5 growth stage for the PNFOA estimate of yield. With the mid-season N fertilizer being applied to the research sites just prior to first hollow-stem (Feekes 6) this could have coincided with when the shift in model performance occurred.

One of the underlying objectives of Bushong et al. (2014) was to improve grain yield prediction in order to better estimate the AONR. Without a substantial improvement in determining a better N rate recommendation, the need to include soil moisture parameters in yield prediction may be redundant and unnecessary. Perhaps the NDVI values are already an indication of the soil moisture status and how it has affected crop growth as researchers have already reported that NDVI can be used in monitoring drought and scheduling irrigation (Duchemin et al., 2006).

Using the same techniques as the CNFOA, Biermacher et al. (2009) observed that the N rate recommendations of the algorithm did not apply enough N. They also subsequently reported that because of this the algorithms were to be modified. Based on the results observed in this study the modifications did not seem to improve the N rate recommendation. Close to threequarters of the sites under predicted the appropriate N rate for agronomic optimum yield. This could be alleviated by decreasing the N fertilizer use efficiency factor (η) for determining the N rate recommendation. Raun et al. (2005) recommended using a η value that more than 50 percent. Research published by others though reported N fertilizer use efficiency values for fertilizer application practices employing sensor based methods for wheat rarely exceeded 50 percent using agronomic rates (Raun et al., 2002; Arnall and Raun, 2013).

The inability of the PPNT to reliably deliver an accurate N fertilizer recommendation is not surprising. The use of yield goals or maximum yield values to set a N fertilizer rate prior to planting is not effective for improving N fertilizer use efficiency. Actual grain yields ranged from approximately 1 to 6 Mg ha^{-1} for the sites utilized in this experiment. This range in grain yield supports the findings of Raun et al. (2010) and Arnall et al. (2013) where grain yield potential can vary year to year and should be accounted for when making N fertilizer rate determinations.

Conclusions

The ability to make more accurate mid-season N fertilizer recommendations will improve N fertilizer use efficiency and potentially winter wheat grain yield. These improvements will have both environmental and economic benefits. Although some algorithms performed better at predicting YP_0 or YP_N, the four algorithms evaluated performed equally, in regards to coefficient of determination values, RMSE values and number of site years within 20 kg N ha^{-1}, on delivering an N rate recommendation that correlates with the AONR. The four algorithms differed in that the CNFOA and the PNFOA under-predicted the AONR, whereas the GA and MGA predicted N rate values that were closer to a one to one relationship with the AONR. The underestimation of the CNFOA and PNFOA could be adjusted if lower NUE values are used as inputs into the algorithms. The sensor based techniques are clearly a more accurate means of determining mid-season N fertilizer recommendations in winter wheat than conventional, non-sensor based approaches and accounted for year to year variability in grain yield due to climate.

Table 1.2-1. Site characteristics of mid-season N fertilizer response trials used to evaluate sensor based N fertilizer recommendations.

Trial No.	Location (Year)	Soil Series	USDA Taxonomic Classification	Maximum Yield (YP_{max})	Range of N Rates	Preplant N Rate
				Mg ha^{-1}	kg N ha^{-1}	kg N ha^{-1}
1	Lahoma, OK (2013)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0 - 134	28
2	Lahoma, OK (2012)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0 - 134	28
3	Lahoma, OK (2011)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0 - 134	28
4	Lahoma, OK (2010)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0 - 134	28
5	Hennessey, OK (2013)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0 - 134	28
6	Hennessey, OK (2012)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0 - 134	28
7	Hennessey, OK (2011)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0 - 134	28
8	Hennessey, OK (2010)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0 - 134	28
9	LCB[a], OK (2013)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0 - 134	28
10	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0 - 134	28
11	LCB, OK (2011)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0 - 134	28
12	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0 - 134	28
13	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0 - 134	0
14	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0 - 134	45
15	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0 - 134	0
16	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0 - 134	45
17	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 155	0
18	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 168	45
19	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 184	90
20	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	0
21	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	45
22	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	90
23	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 190	0
24	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 190	45
25	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 190	90
26	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 224	0
27	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 224	45
28	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0 - 224	90
29	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	0
30	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	45

table continued from previous page.

31	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0 - 184	90
32	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 215	0
33	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 215	45
34	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0 - 215	90

[a] LCB, Lake Carl Blackwell.

Table 1.2-2. Preplant NO_3 test (PPNT) values, NDVI measurements, computed response index (RI) values, and agronomic optimum N rates (AONR) for mid-season N response trials used to evaluate sensor based N fertilizer recommendations.

Trial No.	PPNT	$NDVI_{FP}$ [a]	$NDVI_{NR}$ [a]	$NDVI_{RI}$ [a]	Predicted Harvest RI [b]	AONR
	kg N ha^{-1}					kg N ha^{-1}
1	15	0.206	0.213	1.03	1.05	46
2	10	0.562	0.639	1.14	1.22	113
3	---	0.456	0.503	1.10	1.16	132
4	16	0.440	0.554	1.26	1.43	56
5	12	0.369	0.520	1.41	1.68	66
6	21	0.558	0.708	1.27	1.44	112
7	---	0.649	0.752	1.16	1.26	140
8	25	0.669	0.777	1.16	1.26	97
9	20	0.246	0.335	1.36	1.60	56
10	11	0.544	0.646	1.19	1.31	68
11	---	0.753	0.794	1.05	1.08	56
12	12	0.708	0.786	1.11	1.18	0
13	---	0.419	0.441	1.05	1.08	0
14	---	0.408	0.441	1.08	1.13	0
15	---	0.695	0.764	1.10	1.16	101
16	---	0.753	0.764	1.01	1.01	0
17	11	0.461	0.554	1.20	1.33	77
18	11	0.508	0.554	1.09	1.14	73
19	11	0.537	0.554	1.03	1.04	0
20	25	0.636	0.746	1.17	1.28	108
21	25	0.709	0.746	1.05	1.08	21
22	25	0.734	0.746	1.02	1.02	0
23	13	0.376	0.641	1.70	2.18	108
24	13	0.503	0.641	1.27	1.45	75
25	13	0.609	0.641	1.05	1.08	93
26	---	0.411	0.631	1.54	1.89	128
27	---	0.509	0.631	1.24	1.40	56
28	---	0.592	0.631	1.07	1.10	26
29	---	0.509	0.613	1.20	1.34	45
30	---	0.535	0.613	1.15	1.24	21
31	---	0.574	0.613	1.07	1.10	0
32	---	0.625	0.889	1.42	1.70	108
33	---	0.805	0.889	1.10	1.17	46
34	---	0.866	0.889	1.03	1.03	16

[a] $NDVI_{FP}$, NDVI farmer practice; $NDVI_{NR}$, NDVI N-rich strip; $NDVI_{RI}$, NDVI response index.
[b] Computed using the linear equation of Harvest RI = 1.69($NDVI_{RI}$) - 0.70.

Table 1.2-3. Nitrogen fertilization optimization algorithm parameters utilized in estimating yield potential.

Trial No.	GDD[ab]	DPG[b]	SI[b]
1	92	6	0.98
2	93	69	0.99
3	93	93	1.00
4	79	79	1.00
5	93	67	0.72
6	117	106	0.86
7	89	46	0.70
8	90	90	0.78
9	102	17	1.00
10	111	99	0.97
11	98	55	1.00
12	81	81	1.00
13	81	81	1.00
14	81	81	1.00
15	111	99	0.97
16	111	99	0.97
17	77	77	0.80
18	77	77	0.80
19	77	77	0.80
20	94	94	0.81
21	94	94	0.81
22	94	94	0.81
23	108	108	0.78
24	108	108	0.78
25	108	108	0.78
26	83	78	0.78
27	83	78	0.78
28	83	78	0.78
29	82	82	0.94
30	82	82	0.94
31	82	82	0.94
32	122	28	0.91
33	122	28	0.91
34	122	28	0.91

[a] Cumulative day counts with a temperature threshold of 4.4ºC.

[b] GDD, growing degree days; DPG, days of potential growth; SI, stress index.

Table 1.2-4. Estimates of grain yield potential without N fertilizer (YP_0) and with N fertilizer (YP_N) for different sensor based N fertilizer recommendation algorithms. Estimates are reported in Mg ha^{-1}.

Trial No.	---CNFOA[a]---		---PNFOA[a]---		---GA[a]---		---MGA[a]---	
	YP_0	YP_N	YP_0	YP_N	YP_0	YP_N	YP_0	YP_N
1	1.1	1.1	1.2	1.2	3.5	3.6	0.4	0.4
2	2.8	3.4	3.7	4.2	3.7	5.0	0.3	2.0
3	2.1	2.4	2.9	3.2	3.8	4.8	0.4	1.2
4	2.5	3.6	2.9	3.7	2.7	4.9	0.1	1.5
5	1.6	2.8	2.8	3.9	1.2	3.2	0.1	0.9
6	2.0	2.9	3.4	4.3	1.9	3.3	0.1	1.6
7	3.9	4.9	3.8	4.4	2.4	3.4	0.2	1.8
8	4.0	5.1	4.0	4.7	2.4	3.4	0.2	1.9
9	1.1	1.8	1.6	2.1	1.7	3.2	0.1	0.5
10	2.1	2.7	3.3	3.9	2.6	3.8	0.1	1.6
11	4.3	4.6	5.2	5.5	3.5	3.9	1.1	2.3
12	5.6	6.6	4.3	4.8	3.2	3.9	0.5	2.3
13	2.2	2.4	2.8	2.9	3.8	4.3	0.5	0.9
14	2.2	2.4	2.7	3.0	3.6	4.3	0.4	0.9
15	3.0	3.4	3.9	4.3	3.9	4.8	0.7	2.6
16	3.4	3.5	4.1	4.2	4.6	4.8	2.2	2.6
17	2.8	3.7	3.1	3.7	2.5	4.0	0.1	1.2
18	3.2	3.7	3.3	3.6	3.3	4.0	0.4	1.2
19	3.6	3.7	3.5	3.6	3.8	4.0	0.8	1.2
20	3.4	4.3	3.8	4.5	2.5	3.6	0.2	1.9
21	4.1	4.5	4.2	4.4	3.3	3.6	1.0	1.9
22	4.4	4.5	4.3	4.3	3.5	3.6	1.6	1.9
23	1.5	3.2	2.6	4.4	0.8	3.6	0.1	1.4
24	2.0	2.9	3.2	4.1	2.0	3.6	0.1	1.4
25	2.5	2.7	3.7	3.9	3.2	3.6	0.7	1.4
26	2.1	4.0	2.9	4.4	1.3	4.1	0.1	1.6
27	2.9	4.0	3.3	4.1	2.4	4.1	0.1	1.6
28	3.7	4.1	3.7	3.9	3.6	4.1	0.7	1.6
29	2.9	3.9	3.3	3.9	2.3	3.5	0.1	1.3
30	3.2	3.9	3.4	3.9	2.6	3.5	0.2	1.3
31	3.6	4.0	3.6	3.8	3.1	3.5	0.5	1.3
32	2.2	3.8	4.5	6.4	1.6	3.7	0.1	2.6
33	3.2	3.8	5.7	6.3	3.0	3.7	0.6	2.6
34	3.7	3.8	6.1	6.3	3.5	3.7	1.9	2.6

[a] CNFOA, current N fertilizer optimization algorithm; PNFOA, proposed N fertilizer optimization algorithm; GA, generalized algorithm; MGA, modified generalized algorithm.

Table 1.2-5. Coefficient of determination (R^2), root mean square error (RMSE), and percent of sites that predicted N fertilizer recommendations under, over, and within 20 kg N ha^{-1} of agronomic optimum N rate (AONR).

Method	R^2	RMSE	Percent Under AONR	Percent Above AONR	Percent Within 20 kg N ha^{-1}
CNFOA [a]	0.33	37.1	74	26	44
PNFOA [a]	0.32	37.0	76	24	50
GA [a]	0.34	36.8	53	47	41
MGA [a]	0.33	37.1	50	50	41
PPNT [a]	0.11	39.8	50	50	22

[a] CNFOA, current N fertilizer optimization algorithm; PNFOA, proposed N fertilizer optimization algorithm; GA, generalized algorithm; MGA, modified generalized algorithm; pre-plant NO_3 soil test.

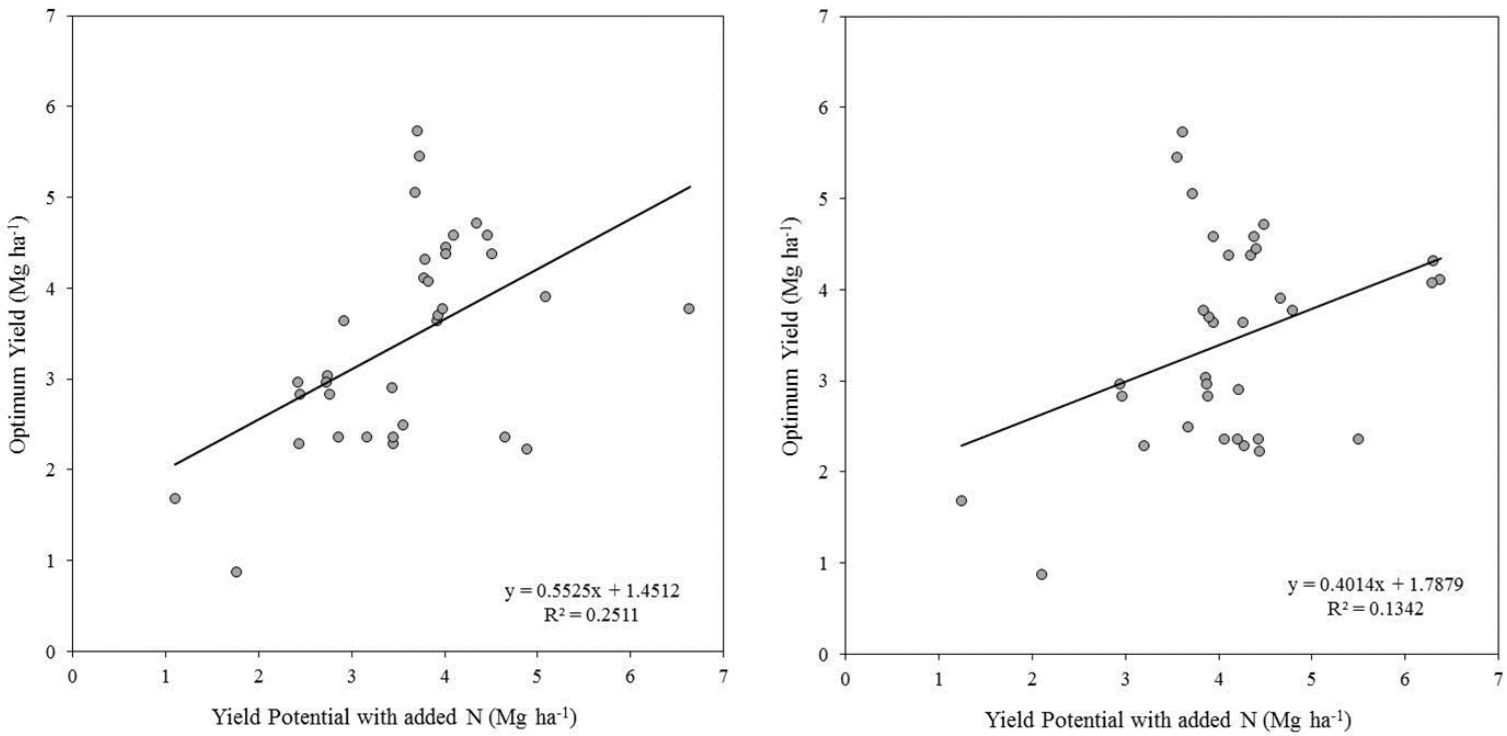

Figure 1.2-1. Linear regression of measured optimum grain yield with estimates of yield potential with added N derived from the Current N Fertilizer Optimization Algorithm (Left) and the Proposed N Fertilizer Optimization Algorithm (Right).

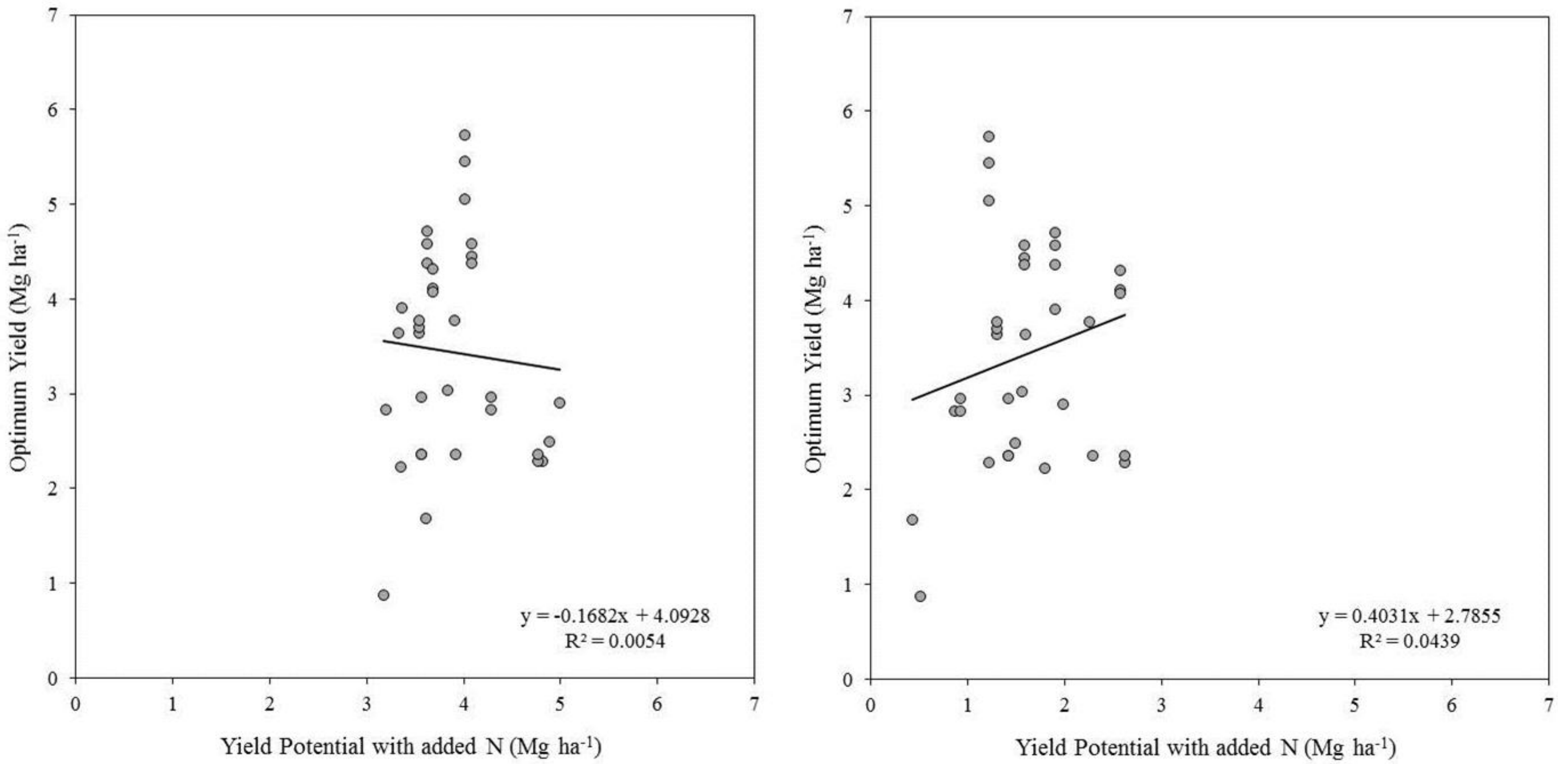

Figure 1.2-2. Linear regression of measured optimum grain yield with estimates of yield potential with added N derived from the Generalized Algorithm (Left) and the Modified Generalized Algorithm (Right).

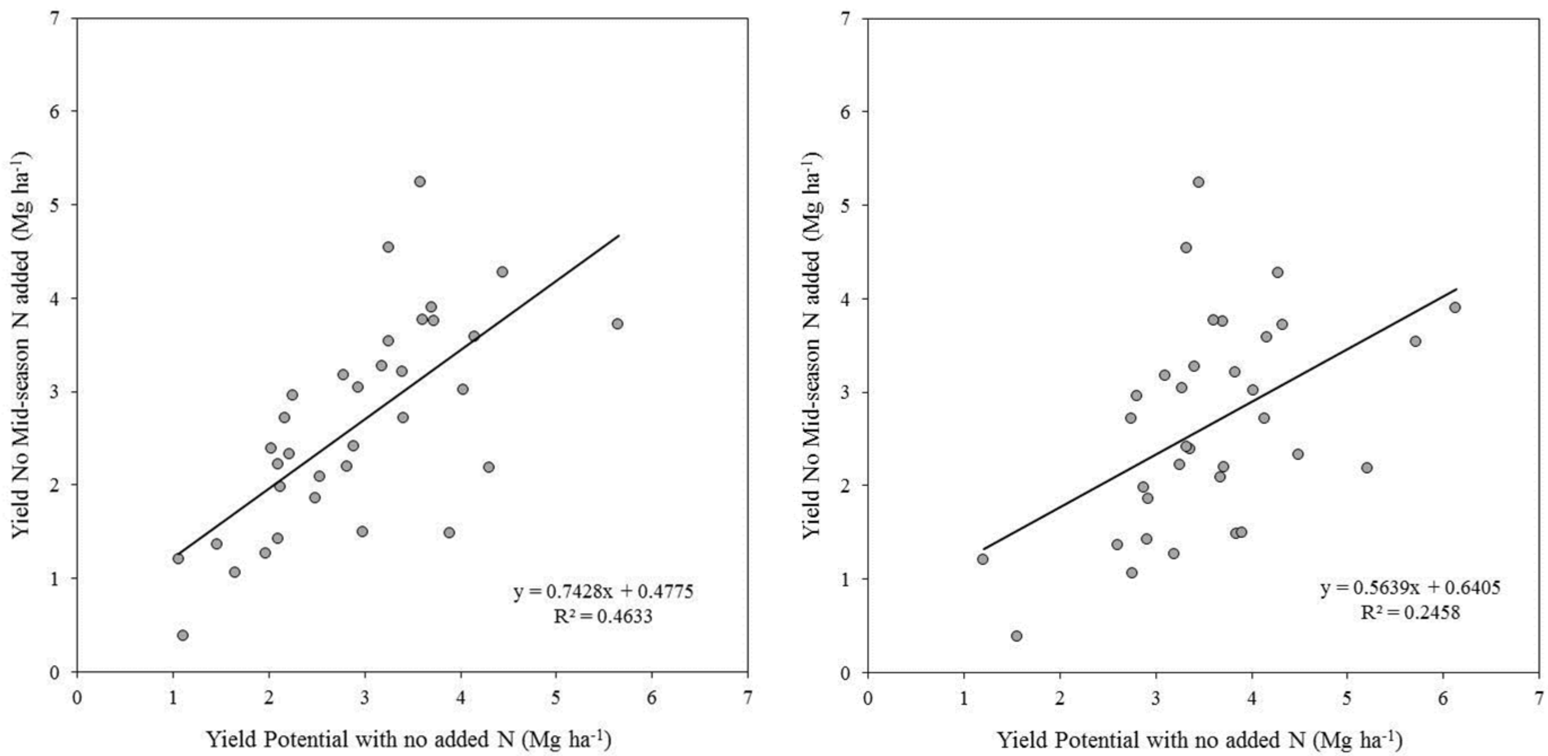

Figure 1.2-3. Linear regression of measured grain yield of plots with no mid-season N fertilizer with estimates of yield potential without added N derived from the Current N Fertilizer Optimization Algorithm (Left) and the Proposed N Fertilizer Optimization Algorithm (Right).

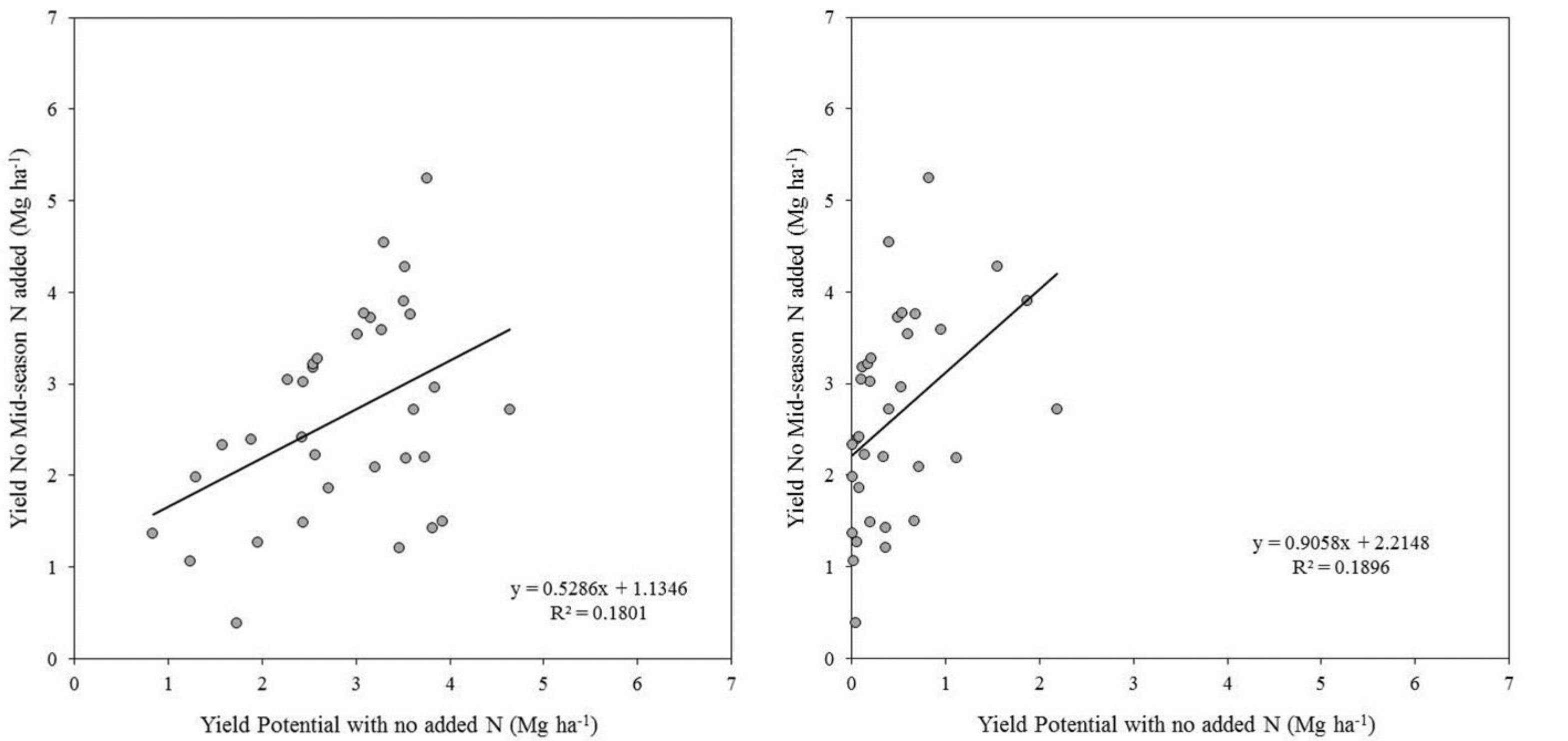

Figure 1.2-4. Linear regression of measured grain yield of plots with no mid-season N fertilizer with estimates of yield potential without added N derived from the Generalized Algorithm (Left) and the Modified Generalized Algorithm (Right).

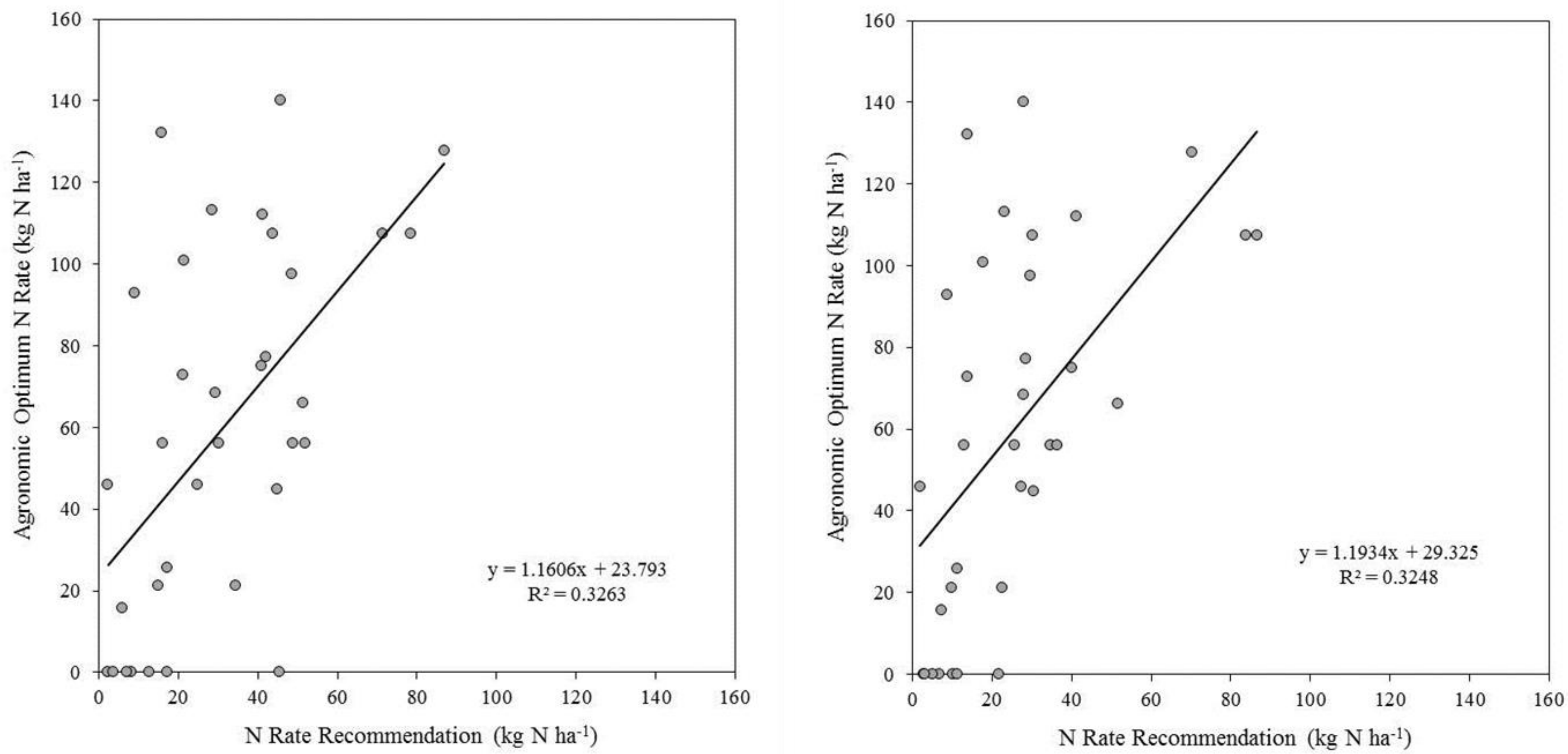

Figure 1.2-5. Linear regression of agronomic optimum N rates with N fertilizer rate recommendations derived from the Current N Fertilizer Optimization Algorithm (Left) and the Proposed N Fertilizer Optimization Algorithm (Right).

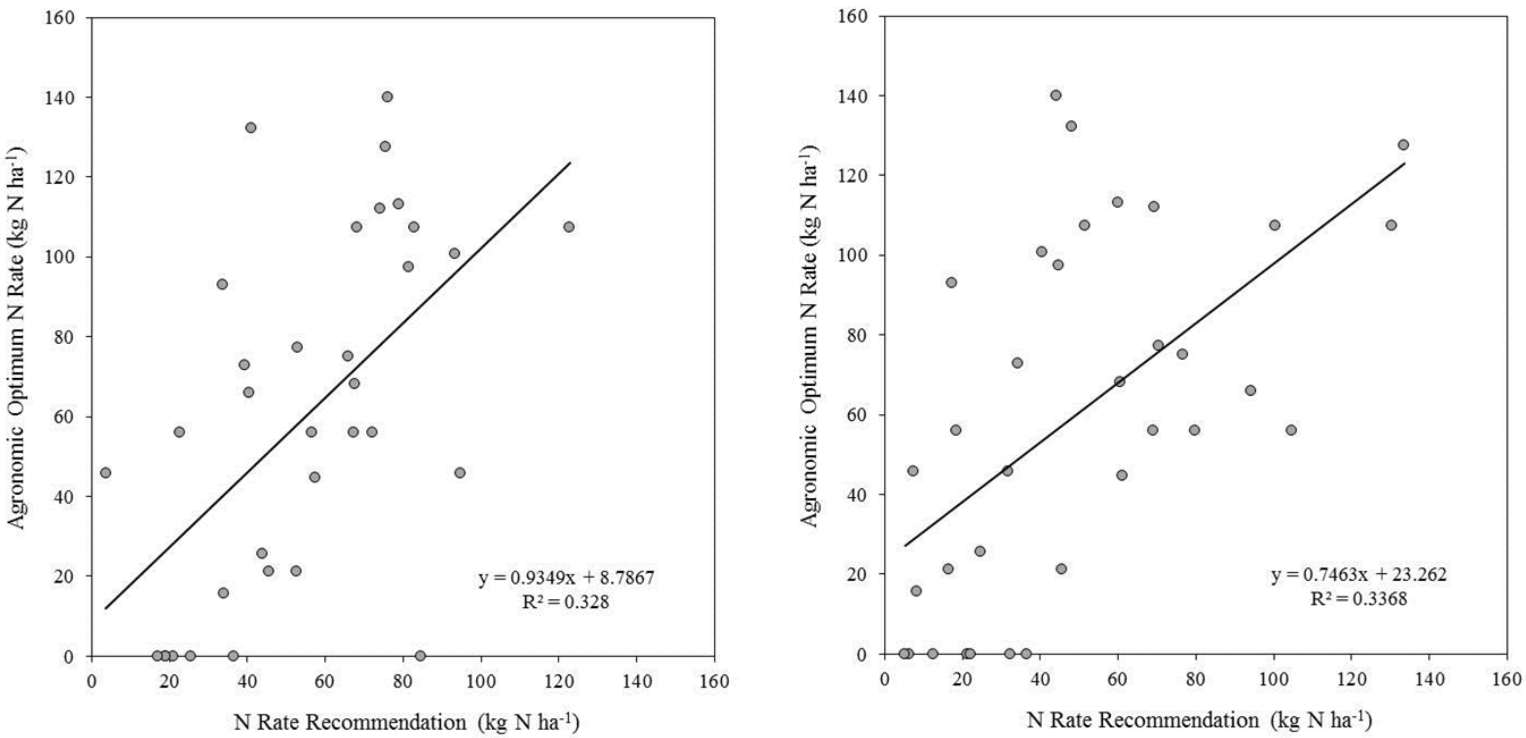

Figure 1.2-6. Linear regression of agronomic optimum N rates with N fertilizer rate recommendations derived from the Generalized Algorithm (Left) and the Modified Generalized Algorithm (Right).

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CHAPTER 2

ALTERNATIVE NITROGEN FERTILIZATION STATEGIES FOR MAIZIE IN A WATER LIMITED ENVIRONMENT

ABSTRACT

With the demand for maize increasing, production has spread into more water limited, semi-arid regions. Couple this with increasing nitrogen (N) fertilizer costs and environmental concerns and the need for proper management practices has increased. Two trials were established to evaluate the effects of different N fertilizer management practices on maize grown under deficit irrigation or rain-fed conditions on grain yield, N use efficiency (NUE), and water use efficiency (WUE). These trials evaluated different application timings and methods, as well as different preplant N fertilizer sources. Deficit irrigation improved grain yield, WUE, and NUE compared to rain-fed treatments. Split N fertilizer applications typically increased the NUE, but not always the grain yield. Mid-season foliar N applications did have the potential to improve grain yield and NUE; however, if significant leaf burn was observed, grain yields were reduced. The preplant application of a pure ammoniacal source of N fertilizer, such as ammonium sulfate (AS), had a tendency to increase grain yields and NUE for rain-fed treatments. The use of urea ammonium nitrate (UAN) as a preplant N fertilizer source performed just as well or better at improving grain yield compared to AS, as long as potential N loss mechanisms were minimized.

CHAPTER 2.1

RAIN-FED AND IRRIGATED MAIZE RESPONSE TO DIFFERENT NITROGEN FERTILIZER APPLICATION METHODS AND TIMINGS

Introduction

According to the U.S. Department of Commerce (2012), the world population is over 7 billion people and will be nearing 8 billion people by the year 2025. This increase in population raises the concern for the need of an abundant food supply. Cereal grains are a staple for feeding the world. Nearly 2.5 billion metric tonnes of cereal grains were produced in the world in 2009 (FAO, 2012). To meet the growing demand for grain, cultivated agriculture has spread into areas that historically have not been in production due to the areas being in a drier, more semi-arid environment. In areas where irrigation is available, water is becoming less available for food production and instead is being utilized for human and industrial consumption (Hokam et al., 2011).

Research has shown that maize hybrid selection based upon N use efficiency (NUE) does not appear to be influenced by amount of water supplied and often parallels selection based upon water use efficiency (WUE) (Eghball and Maranville, 1991). Without question, irrigation increases maize grain yield; however, several researchers have reported that WUE, based upon yield, decreases as the amount of water supplied by irrigation increases (Stone et al., 1987, 1993; Hergert et al., 1993). Typically, increases in water added to the maize crop result in greater yield response to N fertilization as well as fertilizer N uptake by the plant (Eck, 1984; Martin et al., 1982).

Several researchers have investigated the interactive effect of N fertilization and water use in maize production. Russelle et al. (1981) investigated the effects of time and rate of N fertilizer application and the frequency of irrigation on maize grain yield, N uptake, and fertilizer use efficiency. They reported that grain yield and N uptake were not influenced by time of N application, and yields were maximized with light frequent irrigation. The highest NUE was obtained with low N rates applied at sidedressing, and with light frequent irrigations. Martin et al. (1982) evaluated maize production management practices using irrigation water high in nitrate. They concluded that nitrogen uptake was strongly influenced by the rate of fertilizer applied and irrigation water applied. Eck (1984) studied maize yield response in the Southern High Plains to different fertilizer rates as well as different application timings and amounts of water stress. He reported significant yield losses for each day of water stress during the grain filling period, but he found that adequate N only slightly increased grain yield under stress and greatly increased yield when water was adequately applied. He also stated that excess N did not reduce grain yield with water stress, thus he reported no reason to reduce N rates to reduce crop water stress. Weinhold et al. (1995) researched the interaction of different N application rates with supplemental irrigation rates applied according to differing levels of maize evapotranspiration. They reported that supplemental irrigation is a viable technology for increasing maize grain yields, as long as excess water wasn't added that could lead to N losses via leaching and/or denitrification. Norwood (2000) investigated water use and grain yield of maize grown under limited irrigation or dryland conditions in conventional tillage systems and no-till systems. He concluded that no-till increased grain yield and WUE and that maize grown under limited irrigation can produce adequate yields with proper fertility and plant populations. Al-Kaisi and Yin (2003) attempted to establish an accurate irrigation and N management system for maize grown in the Great Plains. They reported plant N uptake typically responded positively to irrigation, N rate, and plant population. They also observed that irrigation supplied at 80 percent of the estimated evapotranspiration losses yielded higher WUE values regardless of N rate. Di Paolo and Rinaldi (2008) investigated the interaction of irrigation and N fertilization on maize yield in the Mediterranean region. Their results showed that at certain irrigation levels crop N response and NUE improved, but there was a valid compromise between N rates and irrigation if the goal was productivity and resource use efficiency. Mansouri-Far et al. (2010) researched the effect of water deficit during early growth stages and N rate on maize yield. The observed grain yield was less affected when water deficits occurred in early growth stages, but there were substantial yield losses when water was deficient during reproductive stages. They also noted the addition of N fertilizer applied increased yield and WUE when water deficit occurred earlier in the growing season.

The timing of N fertilizer applications has been shown to be critical in improving NUE. Historically, in the Midwestern United States' maize-belt the most common N fertilizer application is a single pre-plant rate applied in the fall (Randall et al., 1997). This practice is attributed to lower fertilizer N prices, better soil conditions for incorporation, and it allows producers to better distribute their time and labor (Randall and Schmitt, 1998; Randall et al., 2003). Several researchers have reported the best practice for optimizing NUE of applied N fertilizer in maize is to supply the N fertilizer as close to the time of need and the maximum N uptake (Aldrich, 1984; Olson and Kurtz, 1982; Russelle et al., 1981; Stanley and Roads, 1977; Welch et al., 1971; Walsh et al., 2012).

Numerous researchers have studied the effects of different N fertilizer application times on grain yield and NUE. Stevenson and Baldwin (1969) investigated the effects of fall, spring preplant and sidedress N fertilizer application in maize and observed that both spring preplant and sidedress N applications produced higher NUE and grain yield and that there was no fall N application that gave the same yield or higher than the optimum spring application rate. Stevenson and Baldwin (1969) also reported that averaged over various research locations, grain yields were 80 to 100 kg ha^{-1} higher for sidedress treatments compared to spring preplant treatments. Welch et al. (1971) compared maize grain yields that received fall, spring, or sidedress N. They reported considerable year to year variability in the efficiency of the three application times. Sidedress and spring applied N were most effective for one location over a four year average when compared to fall application. Sidedress and spring applications were more effective for lower N rates (67 and 134 kg N ha^{-1}), but not any more effective than fall application with higher N rates (201 and 268 kg N ha^{-1}). Olson et al. (1986) compared urea ammonium nitrate applied preplant to a sidedress application in maize over 15 years. Yield increases averaged 5 percent more with the sidedress application treatments when compared to the preplant application treatments. Vetsch and Randall (2004) investigated N application timing for different tillage systems in maize. They reported that regardless of tillage system the risk of N loss was far greater when N fertilizer was applied in the fall when compared to spring applications. Freeman et al. (2007) evaluated the effects of N fertilization applications after harvest in the fall and preplant in the spring. They observed that applying N after harvest was not as efficient because of potential soil loss mechanisms such as denitrification and the uncertainty of weather conditions between fall harvest and spring planting. Walsh et al. (2012) evaluated several combinations of preplant and sidedress N application rates at different growth stages. They reported grain yields were maximized when 90 kg N ha^{-1} were applied preplant followed by 90 kg N ha^{-1} at V6 or V10 growth stage, and NUE values were lowest when higher rates of N were applied and also when all N fertilizer was applied preplant.

Over the last half century, foliar applications of nutrients have grown in popularity and according to Raun and Johnson (1999), foliar applications of N can potentially increase NUE. Fertilizer nutrients that are soluble in water can be applied to a growing crop in season using equipment customarily used for spraying pesticides. Much of the yield increases and nutrient use efficiencies of foliar fertilizer applications have been observed in the application of micronutrients. However, the major drawback in supplying adequate amounts highly demanded nutrients, such as N, P, K, in foliar applications is that over application can potentially lead to leaf burn and to avoid leaf burn multiple applications would need to be made (Tisdale et al., 1993).

Researchers have proposed that there may potentially be a foliar fertilizer by moisture stress interaction that is likely due to the fact that as the soil becomes drier plant roots grow deeper into less fertile soil seeking water, thus supplying nutrients via the leaves may allow the plant to function at a productive level (Harder et al., 1982a). Harder et al. (1982a,b) evaluated the effect of foliar fertilization during grain fill under different moisture stress levels on maize grain yield, N response, and leaf photosynthetic rate. They observed that foliar fertilization resulted in significant grain yield decreases and there was no evidence of an interaction effect of moisture stress and foliar fertilizer application. However, grain N values were increased in treatments receiving foliar N applications compared to the control. They also reported that leaf photosynthetic rates did decrease immediately after foliar fertilizer application, but recovered by the second day and that there were no significant differences in the seasonal trends of photosynthetic rates between control and foliar fertilizer treatments. Below et al. (1984a,b) examined the effects of foliar nutrient applications before and after anthesis on maize grain yield and grain N content as well as the physiological responses. They hypothesized that foliar N applications could potentially delay the remobilization of leaf N and leaf senescence, thus maintaining photosynthesis and sustaining productivity. They reported that foliar N applications did not affect grain yields, but did increase grain N concentrations. They noted adverse effects were stalk lodging and foliar N applications did not delay the remobilization of N from the leaves likely because it did not increase the N concentration of the leaves and it decreased the accumulation of carbohydrates by the stalks. Foliar applications also appeared to interfere with indigenous N metabolism leading to the ineffectiveness of foliar N applications to increase grain yield. Sawyer and Barker (1999) evaluated the impact of foliar N fertilizer applied at several growth stages on maize grain yield and grain components. They reported there was no significant yield response to foliar N application, regardless of timing, and also that there was no significant effects on the grain yield components and thus they did not recommend foliar N applications for maize production. Ling and Silberbush (2002) compared N foliar fertilizer products and a mixture of urea with soil applied N and how it could affect maize leaf area, chlorophyll, and N content. They concluded that the effectiveness of foliar fertilizers may be limited to the leaf surface area for the liquid fertilizer and that foliar applications could only partially compensate for insufficient plant uptake, but must have adequate leaf area to be effective.

Objectives

The objectives of this study were to evaluate the interactive effects of N fertilizer application timing, application method, and irrigation on maize grain yield, NUE, and WUE.

Materials & Methods

The study was conducted at two locations (Stillwater, OK and Lake Carl Blackwell, OK) during the 2012 and 2013 growing seasons. Site soil descriptions and basic soil nutrient testing results are provided in Table 2.1-1. To insure N was the only limiting nutrient, sites were fertilized prior to planting to 100 percent sufficient levels based upon soil test P and K results and the fertilizer recommendations described in Zhang and Raun (2006).

A split-block experimental design with three replications per site-year was utilized in this study. Irrigated or rain-fed treatments served as the main plot, while six N fertilizer treatments served as the sub-plot. Various combinations of application timings, application methods, and fertilizer rates were evaluated to determine best management practices for N fertilization in irrigated or rain-fed maize grown in the Southern Great Plains. Plots receiving pre-plant N were fertilized with urea ammonium nitrate (UAN) (28-0-0) in which the fertilizer was broadcast applied and mechanically incorporated prior to planting. For some treatments fertilizer was applied at two mid-season timings. The first timing (V8-V10) included a surface application of UAN and foliar applied treatments. The second timing (V10-V12) included only the foliar applied treatments. The mid-season surface application N source was UAN. The surface applied fertilizer was applied mid-row with streamer nozzles. Nitamin (Koch Agronomic Services, LLC, Wichita, KS, USA) (30-0-0), a low salt N source derived from urea triazone, methylene urea, and urea, was utilized for the foliar application treatments. Foliar treatments were applied using a CO_2 backpack sprayer. A complete list of the six N fertilizer treatments applied to both irrigated and rain-fed plots is provided in Table 2.1- 2.

For all site-years, the plot size was 3.1 m wide by 6.2 m long. Four rows spaced at 76 cm apart were planted per plot and all measured observations were collected on the middle two rows. Field activities including planting dates, hybrids, seeding rates, N fertilizer application dates, and harvest dates are provided in Table 2.1-3. Planting took place in the spring using different maize hybrids that had higher WUE. Seeding rates were based on best agronomic practices. Field activities including planting dates, hybrids, seeding rates, N fertilizer application dates, and harvest dates are provided in Table 2.1-3. The type of irrigation used was surface drip irrigation. Two strips of drip tape were placed through each plot between the first and second rows and between the third and fourth rows. The amount of irrigation water (mm) distributed over each plot was determined by measuring the liters of water applied over the given area.

To evaluate the severity of leaf burn for foliar treatments, visual ratings of the estimated percent leaf area damaged in the upper most leaves was recorded. To obtain a subjective idea of leaf burn, normalized difference vegetative index values (NDVI) were collected prior to the foliar applications and after foliar applications. The NDVI measurements were collected with a Greenseeker (Trimble, Sunnyvale, CA, USA) active optical sensor. Because of the impact certain climatic conditions (temperature, relative humidity, and wind speed) may have on potential leaf burn, these parameters were collected from adjacent climate monitoring sites for the time period after foliar fertilizer application (Table 2.1-4).

Grain yield was determined by harvesting the center two rows of the four row plots with a Massey Ferguson 8XP self-propelled plot combine (Massey Ferguson, Duluth, GA, USA). Plot grain yields were adjusted for a standard moisture content of 15.5 percent. Oven-dried and processed to pass 140 mesh screen grain-subsamples were analyzed for total N content using a dry combustion analyzer. Total grain N uptake was calculated by multiplying the total grain yield (kg ha^{-1}) by the percent N in the grain sample, and thus the NUE was then calculated by employing the difference method described by Varvel and Peterson (1991).

The WUE (kg ha^{-1} mm^{-1}) was measured for both site locations for the 2013 growing season. It was calculated as the ratio of dry grain yield (kg ha^{-1}) to the seasonal water use/evapotranspiration (ET). The ET was estimated using a modified water balance proposed by Heerman (1985) detailed in the following equation:

$$\mathrm{ET} = \pm\Delta\mathrm{SWC} + R + I$$

where ΔSWC is the change in soil profile (0 to 80 cm) volumetric soil water content from planting to harvest, *R* the rainfall, and *I* the irrigation. It was assumed that water losses due to deep percolation or surface runoff were negligible. The ΔSWC was determined by collecting volumetric soil water samples from each plot with a 5 cm diameter probe long enough to encompass the 80 cm depth. The samples were collected using a hydraulic push probe (Giddings Machine Company, Windsor, CO, USA). Daily rainfall was measured from the adjacent Oklahoma Mesonet (Mesonet, 2014) climate-monitoring station.

To understand the impact the climate and added irrigation could have on the parameters being evaluated, daily water balances were created. These balances were based upon the daily potential evapotranspiration (PET) for the trial area, as well as the measured rainfall and added irrigation. The PET values were determined from the ASCE Standardized Reference Evapotranspiration Equation described by Walter et al. (2002). Data collected to determine PET and rainfall was downloaded from the adjacent Oklahoma Mesonet (Mesonet, 2014) climate-monitoring site.

Analysis of variance techniques were employed to detect significant differences for the main and interactive effects of treatments on grain yield, NUE, and WUE. Single degree-of-freedom contrasts were used to partition statistical differences in treatment grouping means. Because visual leaf burn ratings are subjective, only the treatment means were reported, however, statistical differences in NDVI values were determined using analysis of variance along with Fisher's Protected LSD. Because of varying climatic conditions and soil types for each site-year, all site-years were analyzed separately and thus results reported separately. For all analysis, an alpha level of 0.10 was used to determine statistical significance.

Results

Stillwater, OK (2012)

Water Balance. Irrigation was started at Stillwater, OK shortly before the time the water balance fell below zero (Figure 2.1-1). This coincided with the V6 maize growth stage. Early irrigation was applied at rates of approximately 40percent PET. Irrigation rates increased throughout the reproductive growth stages and irrigation was ceased at growth stage R6.

Grain yield. Irrigated and rain-fed grain yield values ranged from 5494 to 10675 kg ha^{-1} and 2611 to 6153 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 2.1-5). On average, irrigated plots yielded about 4000 kg ha^{-1} more than rain-fed plots (Table 2.1-6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effects were observed (Table 2.1-5). Single degree-of-freedom contrasts did reveal some differences in treatment groupings. Regardless of plots being irrigated or rain-fed, plots receiving 180 kg N ha^{-1} had increased yields when the rate was split either foliarly or surface applied compared to all 180 kg N ha^{-1} being applied pre-plant (Table 2.1-7). Irrigated treatments that were fertilized didn't display any significant differences in yield; however, the 90 kg N ha^{-1} preplant application did yield 1300 kg ha^{-1} more than the split foliar application (Table 2.1-7). Rain-fed always yielded more when the N application was split compared to pre-plant only applications, especially for the split surface applications. The split foliar application did yield about 1400 kg ha^{-1} more than the pre-plant only treatments for both the 90 and 180 kg N ha^{-1} rates, however, they were not as effective as the split surface applied treatments at improving yield for rain-fed conditions.

NUE. Irrigated and rain-fed NUE values ranged from 13.1 to 58.1 percent and nearly zero to 19.2 percent, respectively. Analysis of variance determined the effect of irrigation to be significant on NUE (Table 2.1-5). NUE values on average increased more than 10 percent for plots that received irrigation (Table 2.1-6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect on NUE was observed (Table 2.1-5). Single degree-of-freedom contrasts did reveal treatment grouping differences. For the 90 kg N ha^{-1} treatments no increase in NUE was observed when foliar applications were compared to the pre-plant only application, in fact the irrigated plots had significantly higher NUE values (Table 2.1-7). When evaluating the plots that received a total of 180 kg N ha^{-1}, slight increases in NUE were observed regardless of irrigation or rain-fed conditions. No differences were observed for the irrigated plots, but there was always an increase in NUE for the rain-fed plots that received a split application instead of just the pre-plant application (Table 2.1-7).

Foliar leaf burn. No difference was observed in visual leaf burn ratings between irrigated and rain-fed treatments. The majority of the leaf burn for this site-year occurred after the first application with minimal additional burn after the second application. Plots that received a total of 90 kg N ha^{-1} applied foliarly, displayed overall higher burn ratings than the plots receiving 45 kg N ha^{-1} (Figure 2.1-2). This was reflected in the change in NDVI values taken prior to foliar applications and after foliar applications. Decreased changes in NDVI were observed for the 45 kg N ha^{-1} treatments compared to the check. The 90 kg N ha^{-1} foliar treatments actually reported lower NDVI values post application time compared to pre application and thus a statistically lower change in NDVI compared to the check and 45 kg N ha^{-1} treatments (Figure 2.1-2).

<u>Lake Carl Blackwell, OK (2012)</u>

Water Balance. Irrigation was started at Lake Carl Blackwell, OK shortly after the time the water balance fell below zero (Figure 2.1-3). This coincided with the V6 maize growth stage.

Early irrigation was applied at rates of less than 25 percent PET. Irrigation rates were increased through the reproductive growth stages and irrigation was ceased at growth stage R6.

Grain yield. Irrigated and rain-fed grain yield values ranged from 4490 to 7351 kg ha^{-1} and 1322 to 5914 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 2.1-5). On average, irrigated plots yielded about 1300 kg ha^{-1} more than rain-fed plots (Table 2.1-6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect was observed (Table 2.1-5). Single degree-of-freedom contrasts did not reveal any statistically different treatment groupings. Pre-plant applications had higher grain yields compared to split foliar applications for either N rates, regardless if irrigated or rain-fed (Table 2.1-8). Though not statistically significant, slight increases in yield were observed for split surface applications compared to pre-plant only applications on irrigated treatments (Table 2.1-8).

NUE. Irrigated and rain-fed NUE values ranged from 4.2 to 44.2 percent and nearly zero to 44.0 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 2.1-5). On average, NUE values increased no more than three percent for plots that received irrigation (Table 2.1-6). No significant interaction effect of irrigation and fertilizer treatment was observed, but the main effect of fertilizer treatment was significant and was explained with the single degree-of-freedom contrasts. The only statistically significant contrasts were the increased NUE values of all the 90 kg N ha^{-1} preplant treatments compared to the foliar applied treatments of the irrigated plots and plots grouped across irrigated and rain-fed treatments (Table 2.1-8). For rain-fed treatments, plots receiving either the 90 or 180 kg N ha^{-1} had increases in NUE compared to the split applications. Even though the split applications did not compare well with the preplant applications, when the foliar application was compared to the surface applied method, the surface applied had increased NUE values in both the irrigated and rain-fed treatments.

Foliar leaf burn. No difference was observed in visual leaf burn ratings between irrigated and rain-fed treatments. The majority of the leaf burn for this site-year occurred after the first application with minimal additional burn after the second application. Visual leaf burn ratings were greater than 40 percent of the leaf area burned for plots that received a total of 90 kg N ha^{-1} applied foliarly and greater than 25 percent for plots receiving 45 kg N ha^{-1} (Figure 2.1-4). This was reflected in the change in NDVI values taken prior to foliar applications and after foliar applications. Statistically significant, reduced changes in NDVI were observed for both the 45 and 90 kg N ha^{-1} foliar treatments (Figure 2.1-4).

<u>Stillwater, OK (2013)</u>

Water Balance. Irrigation was intitiated at Stillwater, OK shortly before the time the water balance fell below zero for a significant period of time (Figure 2.1-1). This coincided with the V10 maize growth stage. Irrigation was applied at rates of approximately 30 percent PET. Irrigation was ceased at approximately the R2-3 maize growth stage as substantial, unseasonable moisture fell in the middle to late July.

Grain yield. Irrigated and rain-fed grain yield values ranged from 6224 to 11583 kg ha^{-1} and 1425 to 3856 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 2.1-5). On average, irrigated plots yielded about 6000 kg ha^{-1} more than rain-fed plots (Table 2.1-6). The interactive effect of irrigation and fertilizer treatment, as well as the main effect of fertilizer treatment were also significant and were interpreted with the single degree-of-freedom contrasts. Grain yields as affected by treatment groupings were conflicting between irrigated and rain-fed treatments. For the irrigated treatments pre-plant applications outperformed both methods of split applications (Table 2.1-7). However, in the rain-fed treatments split applications consistently increased yields compared to all N fertilizer being applied pre-plant (Table 2.1-7).

NUE. Irrigated and rain-fed NUE values ranged from 1.2 to 83.7 percent and nearly zero to 60.1 percent, respectively. Analysis of variance determined the effect of irrigation to be significant on NUE (Table 2.1-5). NUE values on average increased more than 20 percent for plots that received irrigation (Table 2.1-6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect on NUE was observed (Table 2.1-5). Single degree-of-freedom contrasts did reveal treatment grouping differences. Regardless of N application rate or mid-season application method, split applications delivered improved, and sometimes significant, NUE values (Table 2.1-7). When comparing the two split application methods, the surface applied method increased NUE compared to foliar application methods for irrigated treatments, but there was no difference observed in the rain-fed treatments (Table 2.1-7).

Foliar leaf burn. Minimal differences were observed in visual leaf burn ratings between irrigated and rain-fed treatments. However, they were not significantly different at the 0.10 level. Very little leaf burn was observed after the first foliar fertilizer application and the majority of the leaf burn occurred as a result of the second application. Visual leaf burn ratings were greater than 20 percent of the leaf area burned for plots that received a total of 45 kg N ha^{-1} applied foliarly and practically double the burned area for the 90 kg N ha^{-1} (Figure 2.1-5). This was supported by the change in NDVI values taken prior to foliar applications and after foliar applications. Though there was no statistical difference between the changes in NDVI between the two fertilized treatments, the 45 kg N ha^{-1} treatment had a higher change in NDVI compared to the 90 kg N ha^{-1} treatment (Figure 2.1-5).

WUE. Irrigated and rain-fed WUE values ranged from 10.5 to 19.3 kg ha^{-1} mm^{-1} and 2.7 to 7.5 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 2.1-5). On average, irrigated plots yielded about 10 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 2.1-6). The interactive effect of irrigation and fertilizer treatment, as well as the main effect of fertilizer treatment on WUE values were also significant and were explained with the single degree-of-freedom contrasts. Conflicting results were observed between the irrigated and rain-fed WUE values. For the irrigated plots, the all preplant fertilizer treatments increased WUE values compared to the two split applications (Table 2.1-7). The opposite was observed for the rain-fed treatments, in which the two split application methods performed similarly at increasing the WUE values compared to the all pre-plant treatments (Table 2.1-7).

Lake Carl Blackwell, OK (2013)

Water Balance. Irrigation was started at Lake Carl Blackwell, OK at approximately the V12 maize growth stage (Figure 2.1-3). Very little irrigation water was applied (27 mm) during the late vegetative and early reproductive stages. Irrigation was ceased at approximately the R2 maize growth stage as substantial, unseasonable moisture fell in the middle to late July. According to the PET reported from the adjacent climate-monitoring site, the rain-fed site water balance only fell below zero for approximately one week during the early reproductive growth stages (Figure 2.1-3)

Grain yield. Irrigated and rain-fed grain yield values ranged from 4675 to 12871 kg ha^{-1} and 1326 to 7173 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 2.1-5). On average, irrigated plots yielded about 5500 kg ha^{-1} more than rain-fed plots (Table 2.1-6). The interactive effect of irrigation and fertilizer treatments was not significant; however, the main effect of fertilizer treatment was significant and was explained with the single degree-of-freedom contrasts. Regardless if plots were irrigated or rain-fed, increases in grain yield were observed for plots receiving a split foliar application compared to a pre-plant only fertilizer application (Table 2.1-8). This was particularly true for the irrigated, 180 kg N ha^{-1} treatment, in which yields increased more than 2000 kg ha^{-1} (Table 2.1-8). Surface applied split applications improved yields for the irrigated treatments, but not for the rain-fed treatment and overall didn't perform as well as the foliar fertilized plots (Table 2.1-8).

NUE. Irrigated and rain-fed NUE values ranged from 6.4 to close to 100 percent and 2.3 to 72.3 percent, respectively. Analysis of variance revealed the effect of irrigation to be insignificant on NUE (Table 2.1-5). NUE values on average increased almost 30 percent for plots that received irrigation (Table 2.1-6). The main effect of fertilizer treatment was significant; however, the irrigation by fertilizer treatment interaction effect did not statistically affect NUE.

Single degree-of-freedom contrasts did reveal several treatment grouping differences. Regardless of plots being irrigated or rain-fed, both methods of split applications increased NUE values (Table 2.1-8). The increase was more prominent and statistically significant for the irrigated treatments (Table 2.1-8). Though not statistically significant, foliar applied treatments increased NUE by at least 11 percent compared to surface applied split applications (Table 2.1-8).

Foliar leaf burn. Less than 10 and 15 percent of the leaf area displayed foliar fertilizer burn symptoms for the 45 and 90 kg N ha^{-1} treatments, respectively (Figure 2.1-6). No significant differences in changes in NDVI were observed for either treatment, supporting the lack of reduced growth from leaf burn (Figure 2.1-6).

WUE. Irrigated and rain-fed WUE values ranged from 5.5 to 17.0 kg ha^{-1} mm^{-1} and 1.7 to 8.5 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation was significant on WUE (Table 2.1-5). On average, irrigated plots yielded about 7 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 2.1-6). The interactive effect of irrigation and fertilizer treatment was not observed to be significant, however, the main effect of fertilizer treatment on WUE values was significant and was explained with the single degree-of-freedom contrasts. Regardless of being irrigated or rain-fed, plots that received foliar fertilizer applications had increased WUE values compared to pre-plant only treatments (Table 2.1-8). No significant difference was observed between surface applied treatments and pre-plant only treatments; however, the surface applied treatments didn’t perform as well as the foliar treatments (Table 2.1-8).

Discussion

Even though the amount of irrigation water was applied at less than 40 percent of the PET demand for all four site-years, significant differences in grain yield were observed. Research studies have reported that for maize, irrigation during moisture sensitive periods, such as reproductive growth stages, can still produce an optimum yield and maximize water use efficiency (Shaozhong et al, 2000). This type of deficit irrigation management is effective at reducing water consumption while not greatly impacting yield (Pandey et al., 2000). The most critical maize growth stage at which water stress begins to affect yield is typically the two weeks prior to and following silking (Singh and Singh, 1995). For all four site-years, irrigation was started in the later vegetative growth stages and continued until reproductive maturity had been reached or ample rainfall was present. The increases in NUE and WUE efficiency when the maize crop was irrigated were to be expected. Improvements in NUE and WUE are likely due to greater N uptake and grain yield response, similarly to what has been reported by other researchers (Martin et al., 1982; Eck, 1984; Al-Kaisi and Yin, 2003; Di Paolo and Rinaldi, 2008).

The variability in grain yield response to mid-season N fertilizer applications between site-years and irrigated or rain-fed treatments is not unexpected. Though some researchers have reported improvement in maize grain yields with mid-season N applications (Stevenson and Baldwin, 1969; Walsh et al., 2012), others have also reported extreme variability in the response to mid-season N applications from year to year (Welch et al., 1971). It is common knowledge that to optimize NUE of applied N fertilizer, the N should be applied at the time of maximized N uptake (Aldrich, 1984; Olson and Kurtz, 1982; Russelle et al., 1981; Stanley and Roads, 1977; Welch et al., 1971; Walsh et al., 2012). For rain-fed conditions the NUE was improved for 3 of the four site-years when a mid-season N application was made. The only rain-fed site-year in which NUE was not increased was at Lake Carl Blackwell, OK (2012). This was likely due to the extreme amount of leaf burn observed in the foliar treatments along with a fairly early water deficit that made water a more limiting factor than N. For all four irrigated site-years the NUE was increased with mid-season surface applications for the 180 kg N ha^{-1} fertilizer rates. In irrigated site-years where foliar leaf burn was substantial, such as Stillwater, OK (2012) and Lake Carl Blackwell (2012), no improvement was observed in in NUE; however, the opposite was observed for the other two site years in which leaf burn was minimized. At the Lake Carl Blackwell site in 2013 observed improvements in grain yield and NUE from split applications may have been due to some of the preplant N being lost to denitrification and/or leaching losses.

The uncharacteristic wet late-spring and summer at this site, left the surface water-logged for extended periods of time. These detrimental effects of water-logging on N fertility in maize have been well documented (Meyer et al., 1987). Foliar applications at this site outperformed the surface applications. Saturated surface conditions likely decreased or didn't facilitate root growth (Lizaso and Ritchie, 1997), which then would not have allowed for greater acquisition of surface applied N fertilizer.

Because lower grain yields decrease the demand for N for maize grown in a more semi-arid environment, it was hypothesized that low fertilizer rates supplemented foliarly could have potential to improve grain yield and NUE, as long as leaf burn was minimized. The rapid drying of the foliar N fertilizer spray on the leaf is what leads to leaf burn. This drying is affected by temperature, relative humidity, and wind speed (Marschner, 2012). When leaf burn was significant, reductions in grain yield and sometimes NUE were typically observed. For the site-years where significant leaf burn was observed, one common trend was that temperatures were above 24ºC the four hours after application and for both of the sites in 2012 at least three days had passed between N foliar application and measurable rainfall (Table 2.1-4). Lack of water in the top soil can lead to reduced nutrient availability and thus be crop growth limiting and not allow roots to obtain water at deeper depths (Marschner, 2012). Foliar fertilization has the potential to alleviate this. For three of the four rain-fed site years, increases in grain yield, NUE, and WUE were observed for foliar applications compared to preplant only applications. The only site-year this trend was not observed was Lake Carl Blackwell (2012), which was the site that exhibited the most damage from leaf burn.

The WUE values reported for both irrigated site-years analyzed fall within the range 2.2 to 39.9 kg ha^{-1} mm^{-1} of what has been reported for maize (Zwart and Bastiaanssen, 2004). The WUE values for the rain-fed treatments were obviously at the lower end of this range for maize and even had values lower than 2.2 kg ha^{-1} mm^{-1} (Zwart and Bastiaanssen, 2004). One trend observed for the WUE values for both site-years analyzed was that the treatment differences coincided with grain yield differences. This is due to the methodology in which WUE was calculated. The calculation is the ratio of actual grain yield to ET. In determining actual ET, the change in soil profile moisture was derived from measurements at the beginning of the growing season and after harvest. It could likely be assumed that much of the water in the soil profile was lost to evaporation and some transpiration during the grain dry-down period after irrigation had been ceased. Because of this, there were no fertilizer treatment differences observed in the quantity of soil moisture between fertilizer treatments (data not reported). If no differences were observed in ET, then differences in WUE based on N fertilizer treatment would be dictated by the differences in grain yield.

Conclusions

With four site-years reporting essentially four differing sets of results that likely came about from differences in weather, one could easily observe why managing N in the Southern Great Plains can be difficult. Managing irrigation with deficit irrigation applications can be beneficial to grain yield, as long as the irrigation is applied at the most water stress sensitive time. Split fertilizer applications typically increased NUE for both irrigated and rain-fed treatments; however, the predictability of when it would increase grain yield was difficult to determine. Split fertilizer applications allow for mid-season adjustment, if enough N has potentially been lost that could be a detriment to final grain yield. The use of foliar N fertilizer showed the potential to increase grain yield and NUE, in an environment in which N demand isn’t as elevated as the high maize producing regions, like the Midwestern United States. However, caution needs to be taken to avoid potential grain yield reducing leaf burn.

Table 2.1-1. Initial surface (0-15cm) chemical characteristics and soil classification of sites utilized in this study.

Location[a]	Year	Soil Mapping Unit	Major Component Soil Taxonomic Classification	pH[b]	NH_4-N[c]	NO_3-N[c]	P[d]	K[d]	Total N[e]	Organic C[e]
					----------------mg kg^{-1}	----------------			-----g kg^{-1}	-----
STW	2012	Easpur loam, 0 to 1 percent slopes, occasionally flooded	Easpur: Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls	6.2	11	4	30	119	0.8	9.4
LCB	2012	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastustalfs	5.6	8	3	22	111	0.6	7.8
STW	2013	Norge loam, 3 to 5 percent slopes	Norge: Fine-silty, mixed, active, thermic Udic Paleustolls	5.0	16	11	87	117	1.2	10.5
LCB	2013	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastustalfs	6.1	6	5	24	139	1.1	9.5

[a]STW, Oklahoma State University Agriculture Experiment Station near Stillwater, OK; LCB, Oklahoma State University Agriculture Experiment Station near Lake Carl Blackwell, OK.
[b]1:1 water.
[c]2 *M* KCl extract (Mulvaney, 1996).
[d]Mehlich III extract (Mehlich, 1984).
[e]Dry combustion (Nelson and Sommers, 1996).

Table 2.1-2. Nitrogen fertilizer treatment structure applied to both irrigated and rain-fed plots in this study.

Treatment no.	Pre-Plant N Rate ---kg N ha^{-1}---	Midseason N Rate ---kg N ha^{-1}---	Midseason Application Method[a]	Total N Applied ---kg N ha^{-1}---
1	0	0	---	0
2	90	0	---	90
3	45	45	foliar	90
4	180	0	---	180
5	90	90	foliar	180
6	90	90	surface	180

[a] Foliar treatments applied as low-salt, foliar N source split 50/50 at growth stage V8 and V10; Surface treatment applied as UAN in a stream between rows at growth stage V8.

Table 2.1-3. Field activities for the four site-years utilized in this study.

	-------------------2012-------------------		-------------------2013-------------------	
Field Activity	---STW[a]---	---LCB[a]---	---STW---	---LCB---
Pre-plant N fertilization date	April 2	April 5	March 18	March 18
Planting Date	April 9	April 10	March 20	March 20
Cultivar	Pioneer P1498HR	Pioneer P0876HR	Pioneer P1498HR	Dekalb 63-55
Seeding Rate (seeds ha^{-1})	49,000	49,000	54,000	54,000
Start of Irrigation	May 16	May 17	June 13	June 14
Cease Irrigation	July 11	July 9	July 9	July 9
Amount of irrigation (mm)	173	89	55	27
Amount of rainfall (mm)	233	201	621	834
Mid-season N fertilization date #1	May 25	May 25	June 3	May 29
Mid-season N fertilization date #2	June 1	June 3	June 14	June 8
Harvest Date	August 6	July 26	September 9	September 4

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 2.1-4. Days until measurable rainfall and average temperature, relative humidity, and wind speed for the first four hours after foliar N fertilizer applications.

Location	First Application	Second Application
STW[a] 2012 (May 25/June 1)		
Temperature (ºC)	24.2	14.7
Relative Humidity (%)	78.0	64.8
Wind Speed (m s^{-1})	2.4	2.9
Days until rainfall (d)	3	1
LCB[a] 2012 (May 25/June 3)		
Temperature (ºC)	25.3	20.8
Relative Humidity (%)	76.0	89.0
Wind Speed (m s^{-1})	3.0	0.6
Days until rainfall (d)	4	<1 [b]
STW 2013 (June 3/June 14)		
Temperature (ºC)	16.7	26.6
Relative Humidity (%)	84.0	74.5
Wind Speed (m s^{-1})	1.2	1.1
Days until rainfall (d)	1	1
LCB 2013 (May 29/June 8)		
Temperature (ºC)	22.8	20.6
Relative Humidity (%)	81.8	70.0
Wind Speed (m s^{-1})	6.2	2.1
Days until rainfall (d)	<1 [b]	<1 [b]

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.
[b] Rainfall occurred less than 24 hours after, but more than 8 hours after foliar application.

Table 2.1-5. P value results from analysis of variance for the main and interactive effects of irrigation (Irr.) and fertilizer treatment (Tmt.) on grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain Yield	NUE	WUE
STW[a] 2012			
Irrigation	0.0145	0.0604	---
Treatment	0.6510	0.5189	---
Irr. X Tmt.	0.1104	0.3773	---
LCB[a] 2012			
Irrigation	0.0131	0.7628	---
Treatment	0.2634	0.0124	---
Irr. X Tmt.	0.9341	0.3206	---
STW 2013			
Irrigation	0.0085	0.0810	0.0023
Treatment	0.0028	0.2609	0.0180
Irr. X Tmt.	0.0013	0.1624	0.0013
LCB 2013			
Irrigation	0.0043	0.1007	0.0021
Treatment	0.0031	0.0186	0.0029
Irr. X Tmt.	0.4462	0.8306	0.3732

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 2.1-6. Irrigated and rain-fed treatment means for grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain Yield ---kg ha^{-1}---	NUE ---%---	WUE ---kg ha^{-1} mm^{-1}---
STW[a] 2012			
Irrigated	8055	19.9	---
Rain-fed	4240	7.3	---
P value	0.0145	0.0604	---
LCB[a] 2012			
Irrigated	5769	15.6	---
Rain-fed	4435	12.0	---
P value	0.0131	0.7628	---
STW 2013			
Irrigated	9061	38.0	15.3
Rain-fed	2918	16.8	5.4
P value	0.0085	0.0810	0.0023
LCB 2013			
Irrigated	9691	68.0	12.4
Rain-fed	4075	39.0	5.3
P value	0.0043	0.1007	0.0021

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 2.1-7. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Stillwater, OK (STW) in 2012 and 2013. Values reported are the difference in mean values for the group after the 'vs.' subtracted from the mean value of the group before the 'vs.'.

	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
Contrast	--------Grain Yield (kg ha^{-1})--------			----------NUE (%)----------			-----Grain Yield (kg ha^{-1} mm^{-1})-----		
<u>STW 2012</u>							---	---	---
90 Pre vs. Split Foliar	10	1363	-1341	6.9	17.2*	-3.3	---	---	---
180 Pre vs. Split Foliar	-396	655	-1448	-1.3	2.8	-5.5	---	---	---
180 Pre vs. Split Surface	-1040	45	-2126*	-6.4	-0.7	-12.0	---	---	---
180 Foliar vs Surface	-644	-610	-678	-5.1	-3.5	-6.6	---	---	---
180 Pre vs. Split	-718	350	-1787*	-3.8	1.1	-8.8	---	---	---
<u>STW 2013</u>									
90 Pre vs. Split Foliar	-6	350	-362	-16.6*	-19.6*	-13.6	-0.1	0.5	-0.7
180 Pre vs. Split Foliar	910*	2949*	-1128	-6.7	-6.9	-20.3*	1.6*	5.4*	-2.2*
180 Pre vs. Split Surface	557	2110*	-997	-12.7	-6.7	-18.7	0.8	3.5	-1.8*
180 Foliar vs Surface	-354	-839	131	-6.0	-13.5	1.6	-0.8	-1.9*	0.4
180 Pre vs. Split	734*	2530*	-1062*	-9.7	0.1	-19.5*	1.2*	4.5*	-2.0*

* Denotes differences significant at least at the 0.10 level.

Table 2.1-8. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Lake Carl Blackwell, OK (LCB) in 2012 and 2013. Values reported are the difference in mean values for the group after the 'vs.' subtracted from the mean value of the group before the 'vs.'.

	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
Contrast	--------Grain Yield (kg ha^{-1})--------			----------NUE (%)----------			-----Grain Yield (kg ha^{-1} mm^{-1})-----		
LCB 2012							---	---	---
90 Pre vs. Split Foliar	894	1228	561	11.2*	19.7*	2.7	---	---	---
180 Pre vs. Split Foliar	563	791	336	5.8	6.1	5.5	---	---	---
180 Pre vs. Split Surface	-90	-437	255	0.3	-2.7	3.3	---	---	---
180 Foliar vs Surface	-653	-1228	-79	-5.4	-8.7	-2.2	---	---	---
180 Pre vs. Split	236	177	296	3.1	1.7	4.4	---	---	---
LCB 2013									
90 Pre vs. Split Foliar	-729	-873	-584	-27.1*	-26.9	-27.3	-1.0	-1.3	-0.8
180 Pre vs. Split Foliar	-1436	-2369*	-503	-41.7*	-55.8*	-27.7	-1.9	-3.4*	-0.4
180 Pre vs. Split Surface	60	-716	835	-27.9*	-39.4*	-16.7	0.1	-1.0	1.1
180 Foliar vs Surface	1496	1653	1338	13.9	16.7	11.0	2.0	2.4	1.5
180 Pre vs. Split	-688	-1542	167	-34.8*	-47.4*	-22.2	-0.9	-8.2*	0.4

[*] Denotes differences significant at least at the 0.10 level.

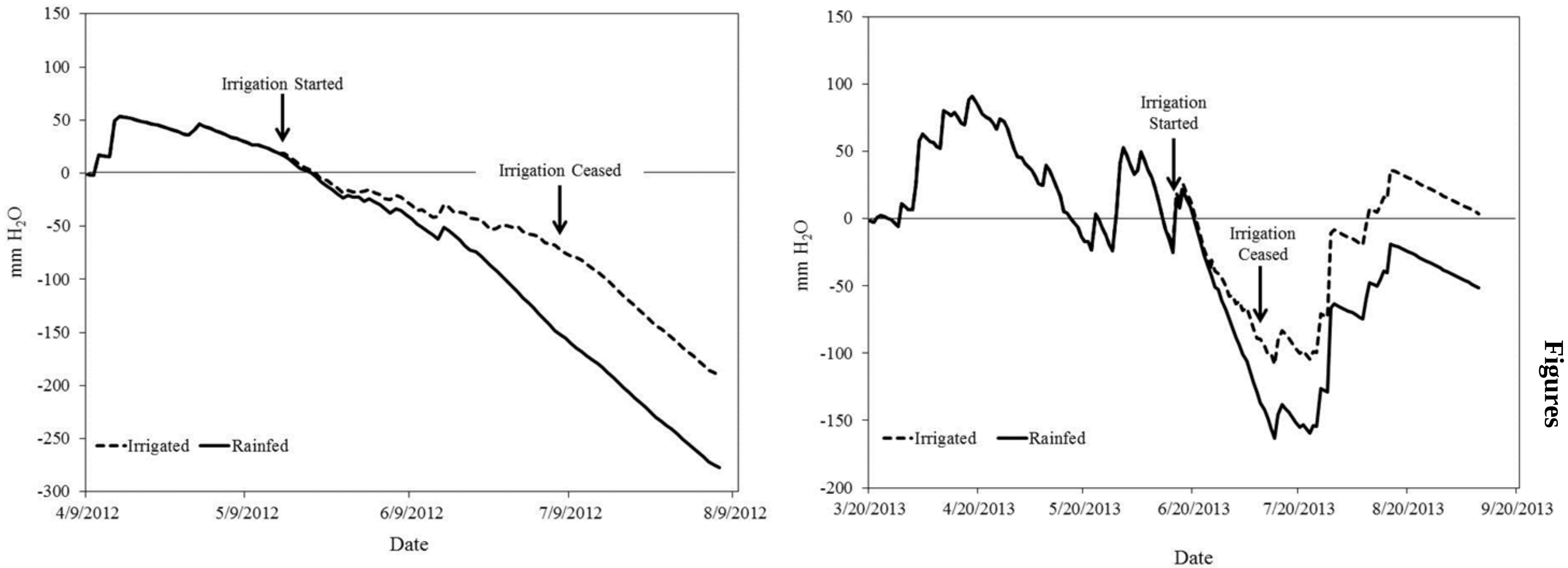

Figure 2.1-1. Stillwater, OK daily water balance for the 2012 (left) and 2013 (right) growing seasons. Potential evapotranspiration estimated from adjacent weather monitoring station (Mesonet, 2014).

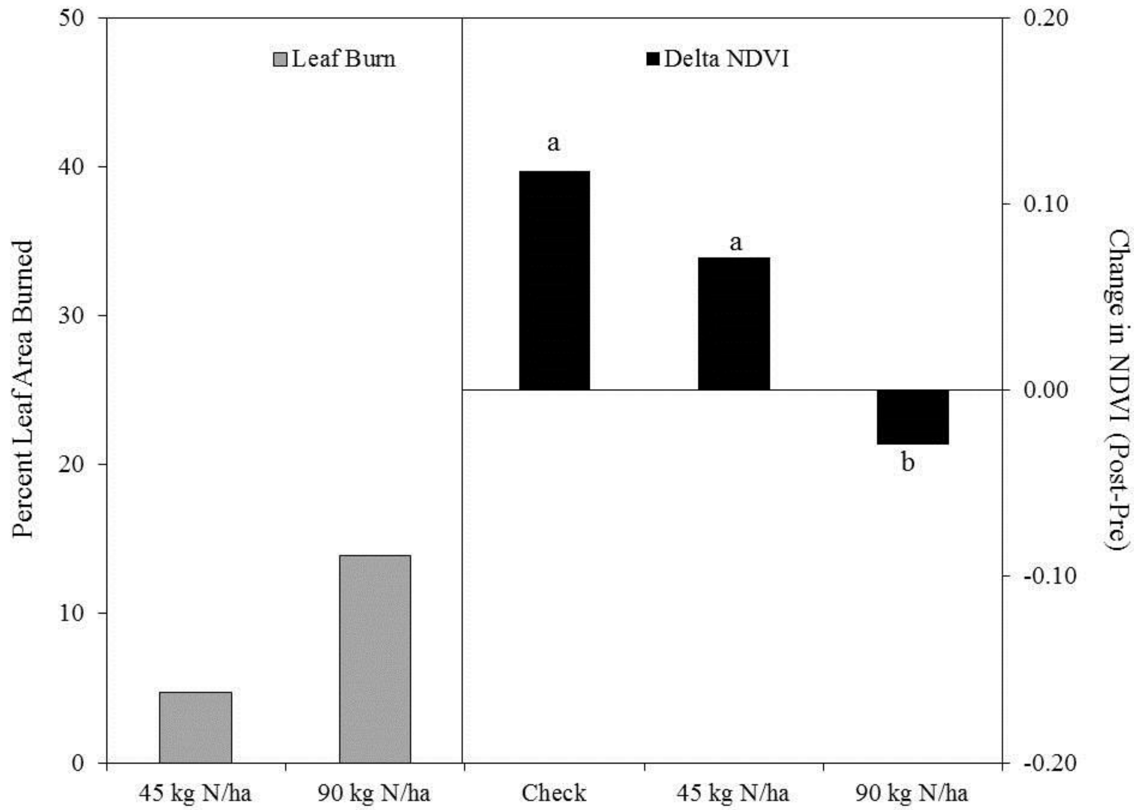

Figure 2.1-2. Stillwater, OK (2012) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 level.

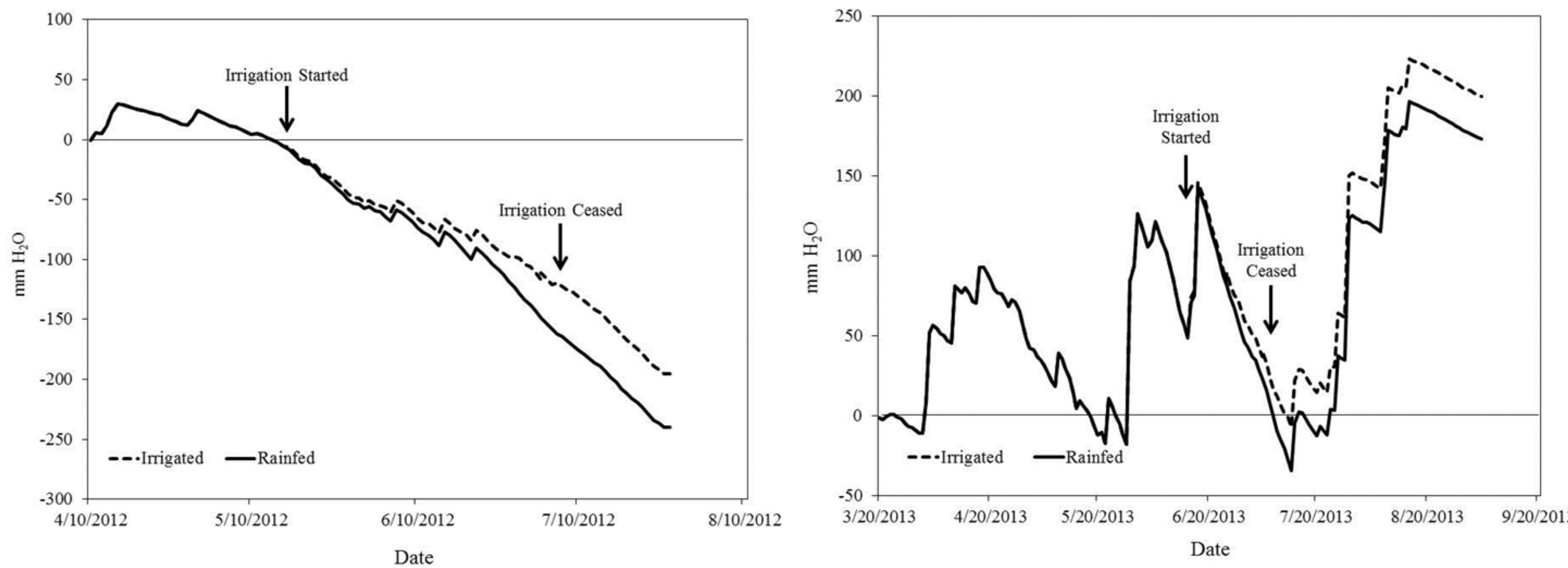

Figure 2.1-3. Lake Carl Blackwell, OK daily water balance for the 2012 (left) and 2013 (right) growing seasons. Potential evapotranspiration estimated from adjacent weather monitoring station (Mesonet, 2014).

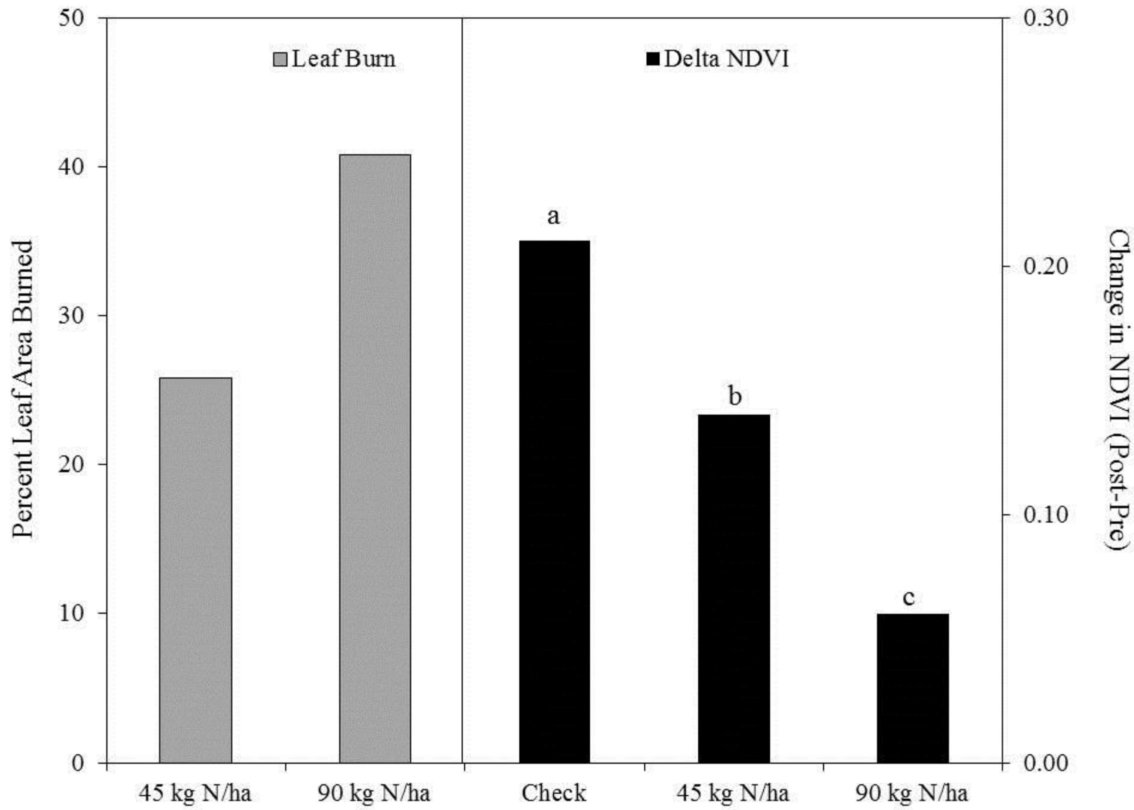

Figure 2.1-4. Lake Carl Blackwell, OK (2012) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 level.

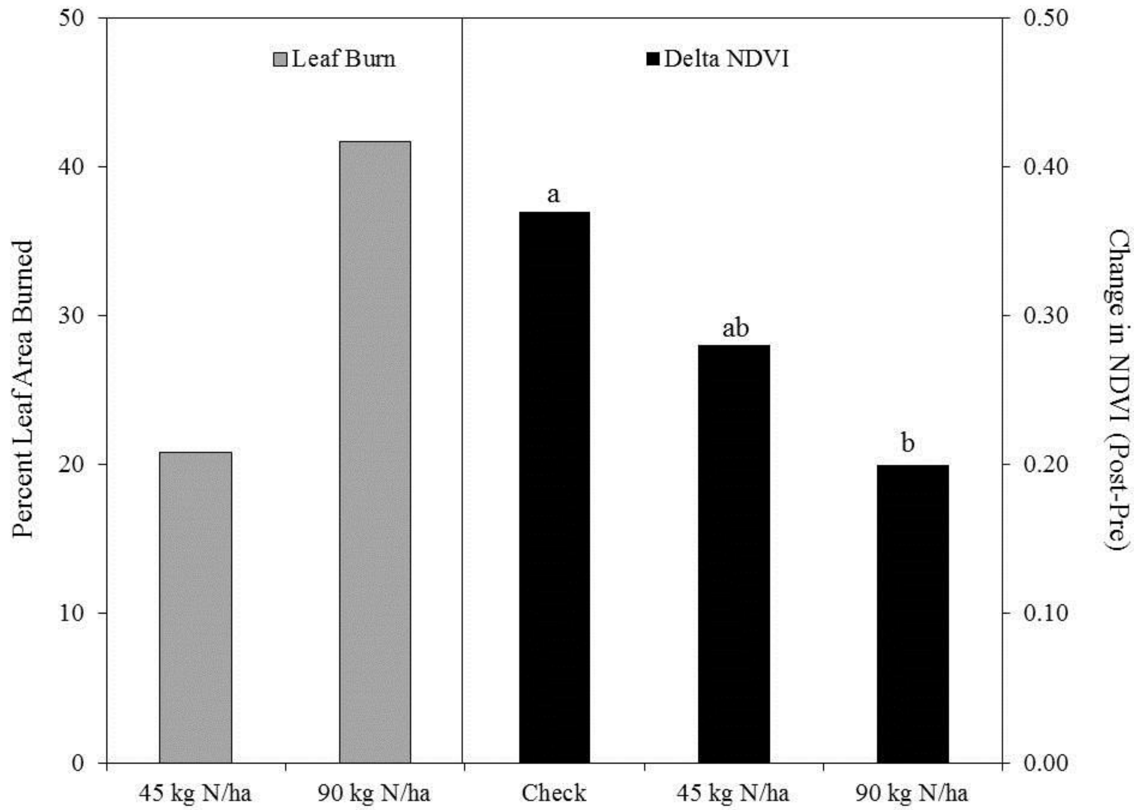

Figure 2.1-5. Stillwater, OK (2013) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 level.

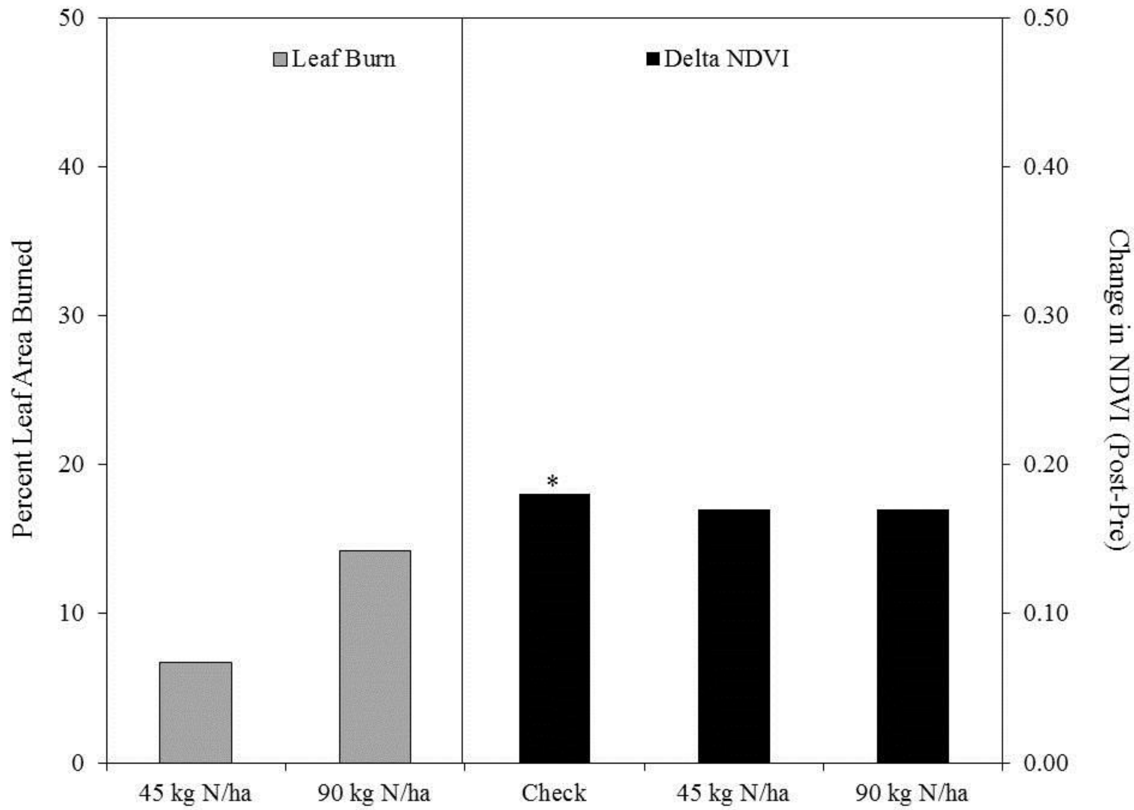

Figure 2.1-6. Lake Carl Blackwell (2013) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. (*) Denotes treatments were not significantly different at the 0.10 level.

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CHAPTER 2.2

EFFECT OF IRRIGATION AND PREPLANT NITROGEN FERTILIZER SOURCE ON MAIZE IN THE SOUTHERN GREAT PLAINS

Introduction

Over the last two decades the number of maize hectares planted and harvested in the Southern Great Plains of the United States has increased. While the number of irrigated hectares has remained fairly constant over this time span, the increase in hectares has more than doubled for rain-fed hectares (U.S. Department of Agriculture, 2014). This rise in area cultivated to maize is due to increased demand for maize for livestock feed exports and maize-based ethanol production (Wallander et al., 2011). With this increased production and an ever-growing concern for environmental implications, sustainable production practices that maximize the use of resources are being sought.

In some portions of the Southern Great Plains groundwater is available for irrigation of maize production. However, in areas such as the Ogallala Aquifer the amount of water extracted from the aquifer has been much greater than the amount recharged leading to drastic declines in the water table which can exceed 50 percent of the saturated thickness (Sophocleous, 2005). One method utilized to better maximize maize grain yield and water use efficiency (WUE) has been deficit irrigation. The most critical growth stage at which moisture stress has been observed to be most yield limiting is the two weeks prior and the two weeks following silking (Singh and Singh, 1995). Irrigation during the reproductive stages can still produce optimum grain yields and maximize WUE (Pandy et al., 2000; Shaozhong et al., 2000).

The inefficient use of N fertilizer has been one of the major focal points for environmental contamination. A considerable factor affecting maize grain yield and N use efficiency (NUE) is the chemical make-up of the N fertilizer source. The source of the N fertilizer can impact the potential rate of loss and/or availability of the fertilizer (Freeman et al., 2007). According to Tsai et al. (1992), utilizing ammoniacal-based N fertilizer sources may reduce potential losses via leaching and denitrification and may extend the availability of N for plant uptake throughout the growing season. Stevenson and Baldwin (1969) compared the effects of ammonium nitrate, urea, and anhydrous ammonia applied at different times in maize. Regardless of application time, anhydrous ammonia yielded 240 to 260 kg ha^{-1} more than both ammonium nitrate and urea. Power et al., (1972) evaluated the effects of ammonium sulfate (AS), ammonium nitrate, calcium nitrate, and urea on maize grain yield and dry matter production. They reported that maize dry matter increased significantly with fertilization, however grain yield differences among the different N sources was seldom significant. The ammoniacal sources typically displayed increased dry matter production with increasing N rates when compared to the calcium nitrate treatments and urea treatments were less than the other two ammoniacal sources. Olson et al. (1986) compared anhydrous ammonia to urea ammonium nitrate (UAN) that was applied at planting or sidedress. They reported that anhydrous ammonia yielded more than the UAN treatment. They attributed the decreased yields in the UAN treatments to the nitrate component, which has the potential for being lost through leaching or denitrification, and the urea component, which has greater potential for N losses via ammonia volatilization. Freeman et al. (2007) investigated the use of urea and anhydrous ammonia applied at different times with different soil incorporation procedures. They concluded that both grain yield and N uptake were improved when the N fertilizer source was urea, but only if the urea was applied and incorporated preplant or after harvest when residue incorporation is practiced.

The NUE and WUE of maize hybrids often coincide with one another (Eghball and Maranville, 1991) because of the greater response to N fertilizer with increases in added water (Martin et al., 1982; Eck, 1984). Because of this relationship, researchers have evaluated the effects of N fertilizer practices on WUE. For maize fields to be productive and resource-use efficient, numerous researchers have proposed a compromise of management practices that optimize grain yield and WUE. These practices include only applying N when water is adequate (Eck 1984; Di Paolo and Rinaldi), maintaining proper fertility based on tillage practices (Norwood, 2000), and applying proper amounts of irrigation at critical growth stages (Eck, 1984; Al-Kaisi and Yin, 2003; Mansouri-Far et al., 2010).

Objectives

The objectives of this study were to evaluate the interactive effects of two N fertilizer sources (UAN and AS), application rate, and deficit irrigation on maize early season vegetative growth, grain yield, NUE, and WUE.

Materials & Methods

The experiment was conducted at two locations (Stillwater, OK and Lake Carl Blackwell, OK) during the 2012 and 2013 growing seasons. Basic soil nutrient testing results and site soil mapping unit descriptions are provided in Table 2.2-1. If required, sites were fertilized prior to planting to 100 percent sufficient levels based upon soil test P and K results and the fertilizer recommendations described in Zhang and Raun (2006). This practice was conducted to insure that N was the only limiting nutrient.

A split-block experimental design with three replications per site-year was employed to evaluate the effects of irrigation and N fertilizer source in this experiment. Irrigated or rain-fed treatments served as the main plot, while five N fertilizer treatments based upon N source and N rate served as the sub-plot. Ammonium sulfate (AS, 21-0-0) and urea ammonium nitrate (UAN, 28-0-0) N fertilizer sources were evaluated in this experiment. Both fertilizer sources were applied at N rates of 90 and 180 kg N ha^{-1}. Fertilizer was broadcast applied and mechanically incorporated prior to planting. A complete list of the five N fertilizer treatments, which includes an unfertilized check, applied to both irrigated and rain-fed plots is provided in Table 2.2-2.

For all site-years, plot sizes were 3.1 m wide by 6.2 m long. Four rows spaced at 76 cm apart were planted per plot and all measured observations were collected on the middle two rows. Field activities including planting dates, hybrids, seeding rates, N fertilizer application dates, and harvest dates are provided in Table 2.2-3. Planting took place in the spring using maize hybrids that possesses a higher WUE. Seeding rates were based on best agronomic practices for the region. The type of irrigation used was surface drip irrigation. Two strips of drip tape were placed through each plot between the first and second rows and between the third and fourth rows. The amount of irrigation water (mm) distributed over each plot was determined by measuring the liters of water applied over the given area.

Potential differences in early vegetative growth/biomass accumulation were measured using the normalized difference vegetative index (NDVI) values collected with a Greenseeker (Trimble, Sunnyvale, CA, USA) ground based, optical sensor. Sensor readings were collected at the V6, V8, V10, and V12 growth stages (Abendroth et al., 2011) for all site-years.

Grain yield was determined by harvesting the center two rows of the four row plots with a Massey Ferguson 8XP self-propelled plot combine (Massey Ferguson, Duluth, GA, USA). Plot grain yields were adjusted for a standard moisture content of 15.5 percent. Grain sub-samples were oven-dried and processed to pass a 140 mesh screen and were analyzed for total N content using a dry combustion analyzer. The NUE was then calculated by employing the difference method described by Varvel and Peterson (1991).

The WUE (kg ha^{-1} mm^{-1}) was measured for both site locations only during the 2013 growing season. It was calculated as the ratio of dry grain yield (kg ha^{-1}) to the seasonal water use/evapotranspiration (ET). The ET was estimated using a modified water balance proposed by Heerman (1985) detailed in the following equation:

$$ET = \pm \Delta SWC + R + I$$

where ΔSWC is the change in soil profile (0 to 80 cm) volumetric soil water content from planting to harvest, *R* the rainfall, *I* the irrigation. It was assumed that water losses due to deep percolation or surface runoff were negligible. The ΔSWC was determined by collecting volumetric soil water samples from each plot with a 5 cm diameter probe long enough to encompass the 80 cm depth. The samples were collected using a hydraulic push probe (Giddings Machine Company, Windsor, CO, USA). Daily rainfall was measured from the adjacent Oklahoma Mesonet (Mesonet, 2014) climate monitoring station.

To understand the relationship of irrigation water applied to the daily potential evapotranspiration (PET) for the trial area, daily PET values were determined. The PET values were derived from the ASCE Standardized Reference Evapotranspiration Equation described by Walter et al. (2002). Data collected as inputs for the equation to determine PET and rainfall were downloaded from the adjacent Oklahoma Mesonet (Mesonet, 2014) climate-monitoring site. The percent of irrigation water applied compared to PET losses for each site-year is described in table 2.2-3.

Analysis of variance techniques were employed to detect significant differences for the main and interactive effects of treatments on early vegetative growth (NDVI), grain yield, NUE, and WUE. Single degree-of-freedom contrasts were used to partition statistical differences in treatment grouping means as well as detect any potential linear or quadratic trends based upon N fertilizer rate. All site-years were analyzed separately and thus the results are reported separately. For all analyses, an alpha level of 0.10 was used to determine statistical significance.

Results

Stillwater, OK (2012)

Vegetative growth. No significant differences were observed in either the irrigated or rain-fed NDVI values for any of the growth stages evaluated (Figure 2.2-1). Regardless of treatment the increase in NDVI appeared linear for the growth stages V6 through V10, and then plateaued between the V10 and V12 growth stages. One noticeable trend that was observed was that the 180 kg N ha^{-1} UAN treatments had the lowest NDVI values for the V6, V8, and V10 growth stages, but the opposite was observed for that specific treatment under rain-fed conditions (Figure 2.2-1).

Grain yield. Irrigated and rain-fed grain yield values ranged from 6381 to 12265 kg ha^{-1} and 2565 to 5980 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 2.2-4). On average, irrigated plots yielded about 4500 kg ha^{-1} more than rain-fed plots (Table 2.2-5). The interactive effect of irrigation and fertilizer treatment was significant, however the main effect of fertilizer treatment was not significant. Results from single degree-of-freedom contrasts could be used to explain the differences in treatments. Regardless of the fertilizer treatments being irrigated or rain-fed, AS treatments had higher grain yields compared to the UAN treatments, especially for the rain-fed plots (Table 2.2-6). Both the irrigated UAN and AS treatments displayed significant linear increases in grain yield (Table 2.2-6). For rain-fed treatments, the only significant N response trend was the quadratic trend for AS.

NUE. Irrigated and rain-fed NUE values ranged from 5.6 to 60.7 percent and nearly zero to 17.3 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 2.2-4). Though not statistically significant, irrigated plots improved

NUE by more than 20 percent (Table 2.2-5). The analysis of variance did not detect significant differences for fertilizer treatment and the interaction of irrigation and fertilizer treatments. Single degree-of-freedom contrasts did not reveal any statistical differences in NUE between UAN and AS (Table 2.2-6). However, NUE values were higher for the UAN irrigated treatments and NUE values were higher for the AS rain-fed treatments (Table 2.2-6). Because the check plots were used in the calculation of determining NUE, only linear trends could be observed. The only significant trend was a negative linear trend observed for the AS treatments in the irrigated plots (Table 2.2-6).

Lake Carl Blackwell, OK (2012)

Vegetative growth. No significant differences were observed in either the irrigated or rain-fed NDVI values for any of the growth stages evaluated (Figure 2.2-2). Regardless of treatment the increase in NDVI was linear for growth stages V6 through V10, and then increased linearly between V10 and V12. One noticeable trend that was observed was that the unfertilized check treatments had the lowest NDVI values for the V8, V10, and V12 growth stages, but the opposite was observed for that specific treatment when rain-fed (Figure 2.2-2).

Grain yield. Irrigated and rain-fed grain yield values ranged from 4490 to 7351 kg ha^{-1} and 1322 to 6461 kg ha^{-1}, respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 2.2-4). On average, irrigated plots yielded 1000 kg ha^{-1} more than rain-fed plots (Table 2.2-5). No significant differences were observed for fertilizer treatments and the interaction of irrigation and fertilizer treatments (Table 2.2-4). Regardless of the fertilizer treatments being irrigated or rain-fed, AS treatments had higher grain yields compared to the UAN treatments (Table 2.2-7). No significant trends were observed for the response to UAN fertilizer (Table 2.2-7). A significant linear response was observed for AS in the irrigated plots and a quadratic response was observed for the rain-fed plots (Table 2.2-7).

NUE. Irrigated and rain-fed NUE values ranged from 10.5 to 44.2 percent and nearly zero to 78.3 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 2.2-4). When comparing irrigated versus rain-fed plots, no noticeable trend was observed in the differences between NUE values (Table 2.2-5). The analysis of variance did reveal significant differences for fertilizer treatment and the interaction of irrigation and fertilizer treatments. Regardless of fertilizer treatments being irrigated or rain-fed, AS treatments displayed higher NUE values (Table 2.2-7). This was especially true for the rain-fed plots in which the difference between UAN and AS was as much as 10 percent and was statistically different (Table 2.2-7). Across irrigated and rain-fed treatments, significant, negatively linear responses were observed for both UAN and AS (Table 2.2-7). However, the linear response was only significant for UAN in the irrigated plots and AS in the rain-fed plots (Table 2.2-7).

Stillwater, OK (2013)

Vegetative growth. Because irrigation did not commence until approximately the V12 or later growth stages, NDVI values were averaged across the irrigated and rain-fed treatments. No differences were observed for the V6, V10, and V12 growth stages; however at the V8 growth stage the NDVI value of the check treatment was significantly higher than the fertilized treatments (Figure 2.2-3). No distinct linear or quadratic trend was observed for the vegetative growth over time. The slopes of the lines between growth stages appeared to all be different, with the slope flattening out between the V10 and V12 growth stages (Figure 2.2-3).

Grain yield. Irrigated and rain-fed grain yield values ranged from 6020 to 11583 kg ha^{-1} and 1345 to 3651 kg ha^{-1}, respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 2.2-4). On average, irrigated plots yielded 6000 kg ha^{-1} more than rain-fed plots (Table 2.2-5). No significant difference was observed for irrigation by fertilizer treatments interaction, but the effect of fertilizer treatments was observed to be significant (Table

2.2-4). Regardless of the fertilizer treatments applied to irrigated or rain-fed conditions, single degree-of-freedom contrasts revealed the response to UAN to be a linear response, whereas the response to AS was a quadratic response (Table 2.2-6). Overall, the UAN treatments yielded more compared to AS fertilizer treatments. This was also true when fertilizer treatments were partitioned by irrigated and rain-fed treatments (Table 2.2-6).

NUE. Irrigated and rain-fed NUE values ranged from 6.5 to 83.7 percent and less than one to 25.4 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE, even though the average differences were greater than 20 percent (Table 2.2-4). The analysis of variance did reveal significant differences for fertilizer treatments, but not the interaction of irrigation and fertilizer treatments (Table 2.2-4). Single degree-of-freedom contrasts did not reveal any significant differences in NUE values between UAN and AS; however, the trend was that UAN gave higher NUE values regardless if irrigated or rain-fed (Table 2.2-6). No significant linear trend was observed for the UAN fertilizer treatments, but the AS treatments displayed a negative linear trend, especially for the irrigated treatments (Table 2.2-6).

WUE. Irrigated and rain-fed WUE values ranged from 10.5 to 19.7 kg ha^{-1} mm^{-1} and 2.3 to 6.9 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 2.2-4). On average, irrigated plots yielded about 10 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 2.2-5). The interactive effect of irrigation and fertilizer treatments was insignificant; however, the main effect of fertilizer treatment on WUE values was significant (Table 2.2-4). Single degree-of-freedom contrasts revealed UAN fertilizer treatments to be higher than AS treatments, which was significant regardless of irrigation treatment and for the irrigated treatments (Table 2.2-6). Overall, the response to UAN tended to follow a linear trend, but the response to AS was a quadratic trend (Table 2.2-6).

Lake Carl Blackwell, OK (2013)

Vegetative growth. As previously stated, since irrigation did not commence until approximately the V12 or later growth stages, NDVI values were averaged across the irrigated and rain-fed treatments. No significant differences in NDVI were observed between fertilizer treatments at any of the growth stages. Regardless of fertilizer treatment, the NDVI values tended to follow a quadratic pattern over time. One noticeable trend observed was the check fertilizer plot had the lowest NDVI values for the V8, V10, and V12 growth stages (Figure 2.2-3).

Grain yield. Irrigated and rain-fed grain yield values ranged from 4675 to 12227 kg ha^{-1} and 1327 to 6440 kg ha^{-1}, respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 2.2-4). On average, irrigated plots yielded 4500 kg ha^{-1} more than rain-fed plots (Table 2.2-5). No significant difference was observed for the irrigation by fertilizer treatments interaction, but the effect of fertilizer treatment was observed to be significant (Table 2.2-4). Even though it was not observed to be significant, AS treatments yielded higher than UAN treatments, whether it was under irrigated or rain-fed conditions (Table 2.2-7). No observable trend was observed for the UAN treatments, but for the AS treatments the response to fertilizer was linear for the irrigated plots and quadratic for the rain-fed plots (Table 2.2-7).

NUE. Irrigated and rain-fed NUE values ranged from 6.4 to 79.7 percent and 2.7 to 70.7 percent, respectively. Analysis of variance determined the effect of irrigation to be significant for NUE values (Table 2.2-4). On average, irrigated plots yielded 20 percent more than rain-fed plots (Table 2.2-5). The analysis of variance did not reveal significant differences for fertilizer treatment, as well as the interaction of irrigation and fertilizer treatment (Table 2.2-4). Single degree-of-freedom contrasts did not reveal much in the way of response trends or differences between fertilizer sources. In irrigated treatments, UAN had slightly higher NUE values compared to AS; however, the opposite was observed for rain-fed conditions (Table 2.2-7).

WUE. Irrigated and rain-fed WUE values ranged from 5.5 to 15.7 kg ha^{-1} mm^{-1} and 1.7 to 8.6 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 2.2-4). On average, irrigated plots yielded about 5 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 2.2-5). The interactive effect of irrigation and fertilizer treatments was insignificant; however, the main effect of fertilizer treatment on WUE values was significant (Table 2.2-4). No observable trends or differences were observed for either fertilizer sources in the rain-fed areas (Table 2.2-7). No difference was observed in the WUE values between the UAN and AS treatments for the irrigated plots (Table 2.2-7). A significant quadratic response was observed for the UAN treatments, however the highest ordered significant response for the AS treatments was a linear trend (Table 2.2-7).

Discussion

The deficit irrigation applied in the later vegetative and reproductive maize growth stages significantly increased grain yield and WUE. These results are what were to be expected. Applying irrigation at times that have been deemed critical for optimum grain yield (Singh and Singh, 1995), have aided in optimizing yield (Pandy et al., 2000; Shaozhong et al., 2000). Though only statistically significant for one of four site-years, deficit irrigation also increased the NUE of the maize crop. Increases in NUE were likely due to greater N uptake and grain yield response to N fertilization. These results are similar to what has been observed by other researchers (Martin et al., 1982; Eck, 1984; Al-Kaisi and Yin, 2003; Di Paolo and Rinaldi, 2008).

For three of the four site-years, rain-fed treatments had a greater yield response and increase in NUE for the AS treatments compared to the UAN treatments. This may be because of the more expansive root growth in the maize plant's attempt to acquire more soil moisture. The expansive root system would then have the ability to take up more of the immobile ammonium in the soil. Another desirable trait of ammoniacal N fertilizer sources in maize, is that maize is able to take up ammonium during reproductive growth, whereas, nitrate uptake is inhibited (Pan et al., 1984; Tsai et al., 1992). UAN can be an effective N fertilizer source if the potential loss mechanisms (leaching, volatilization, denitrification) are minimized (Olson et al, 1986). The UAN treatments did outperform the AS treatments for the 2013 irrigated trials, but not the 2012 irrigated trials. This could be due to the fact that both 2013 sites had above average rainfall for the region and with adequate moisture early in the growing season, expansive root systems were not developed, which would have reduced ammonium acquisition from the soil. The lower increases in yield using UAN as an N source at the Lake Carl Blackwell, OK site in 2013 could be due to potential N losses from the UAN. This site received the most rainfall of any site-year and we observed the topsoil to be saturated for a substantial amount of time prior to reproductive growth, thus leading to potential N losses via leaching and/or denitrification.

Little to no observable differences or trends in early season vegetative growth, as determined by collecting NDVI values, were present. However, with differences observed in grain yield and NUE between fertilizer treatments, there is the possibility that the inorganic N form (nitrate or ammonium) present in the soil later in the growing season affected grain yield and NUE.

To better optimize grain yield and NUE the proper N fertilizer rate should be applied. The decrease in NUE values when the N fertilizer rate was increased from 90 to 180 kg N ha^{-1} is typical for maize production and has been observed by others (Freeman et al., 2007; Walsh et al., 2012). For irrigated treatments, linear relationships with grain yield and N fertilizer rate were usually observed for both the UAN and AS. However, a few of the rain-fed and irrigated site-years displayed statistically significant quadratic trends. These trends in which there is either a decrease or no increase in grain yield with added N above 90 kg N ha^{-1} point towards excess N being applied and producers should adjust N application rates accordingly. With only two fertilizer rates along with a check treatment being employed, accurately determining an agronomic optimum preplant N fertilizer rate with the data from this trial would not be accurate. However, producers should attempt to utilize some form of a grain yield approach in making a N fertilizer rate recommendation or use regional N response trials from similar soil types.

Irrigated maize WUE values reportedly range from approximately 2 to 40 kg ha^{-1} mm^{-1} (Zwart and Bastiaanssen, 2004. Irrigated WUE values observed in this experiment fell within this range. Variability in WUE values among treatments and growing seasons is to be expected. Zwart and Bastiaanssen (2004) reported climate, water management, and soil fertility, all of which were evaluated in this trial, have the potential to give rise to the variability of WUE in maize. The main and interactive effects determined significant from the analysis of variance and single degree-of-freedom contrast results were similar for grain yield and WUE. This likely could be due to the manner in which WUE was calculated for this experiment, which involves the ratio of grain yield to measured ET. One variable employed for deriving the ET was to measure the change in profile soil moisture prior to planting and immediately after harvest. Pre- and post-harvest soil profile samples revealed no differences in the soil profile content between samples (data not reported). The July and August months in the Southern Great Plains can be extremely hot and dry and likely much of the soil profile moisture was lost to evaporation and some transpiration during the grain dry-down period after irrigation had ceased. If no differences were observed in ET between fertilizer treatments within irrigated or rain-fed plots then one can conclude differences in WUE would be dictated by the differences in grain yield.

Conclusions

In conclusion, deficit irrigation during late vegetative and reproductive growth stages increased grain yield, NUE, and WUE. With three of the four rain-fed site years reporting increases in grain yield and NUE, we would recommend that a pure ammoniacal N fertilizer source be applied if a preplant only N fertilizer application is to be utilized. If irrigation water is available, the N source is not as critical. However, the producer should be cognizant of the potential N loss mechanisms (leaching, volatilization, denitrification) of N fertilizer sources like UAN. Lastly, if producers are going to utilize a preplant only fertilizer N application for maize cultivated on the Southern Great Plains they should accordingly adjust N fertilizer rates based on a reasonable yield goal or regional N response trials.

Table 2.2-1. Initial surface (0-15cm) chemical characteristics and soil classification of sites utilized in this study.

Location[a]	Year	Soil Mapping Unit	Major Component Soil Taxonomic Classification	pH[b]	NH_4-N[c]	NO_3-N[c]	P[d]	K[d]	Total N[e]	Organic C[e]
					----------------mg kg^{-1}			----------------	-----g kg^{-1}	-----
STW	2012	Easpur loam, 0 to 1 percent slopes, occasionally flooded	Easpur: Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls	6.2	11	4	30	119	0.8	9.4
LCB	2012	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastustalfs	5.6	8	3	22	111	0.6	7.8
STW	2013	Norge loam, 3 to 5 percent slopes	Norge: Fine-silty, mixed, active, thermic Udic Paleustolls	5.0	16	11	87	117	1.2	10.5
LCB	2013	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastustalfs	6.1	6	5	24	139	1.1	9.5

[a]STW, Oklahoma State University Agriculture Experiment Station near Stillwater, OK; LCB, Oklahoma State University Agriculture Experiment Station near Lake Carl Blackwell, OK.
[b]1:1 water.
[c]2 *M* KCl extract (Mulvaney, 1996).
[d]Mehlich III extract (Mehlich, 1984).
[e]Dry combustion (Nelson and Sommers, 1996).

Table 2.2-2. Nitrogen fertilizer treatment structure applied to both irrigated and rain-fed plots in this study.

Treatment no.	Pre-Plant N Rate ---kg N ha^{-1}---	Pre-Plant N Source [a]
1	0	---
2	90	UAN
3	90	AS
4	180	UAN
5	180	AS

[a] UAN, urea ammonium nitrate (28-0-0); AS, ammonium sulfate (21-0-0); applied prior to planting and mechanically incorporated.

Table 2.2-3. Field activities for the four site-years utilized in this study.

	--------------------2012--------------------		--------------------2013--------------------	
Field Activity	---STW[a]---	---LCB[a]---	---STW---	---LCB---
Pre-plant N fertilization date	April 2	April 5	March 18	March 18
Planting date	April 9	April 10	March 20	March 20
Cultivar	Pioneer P1498HR	Pioneer P0876HR	Pioneer P1498HR	Dekalb 63-55
Seeding rate (seeds ha^{-1})	49,000	49,000	54,000	54,000
Start irrigation	May 16	May 17	June 13	June 14
Cease irrigation	July 11	July 9	July 9	July 9
Irrigation percent of PET[b]	38	21	28	13
Number of irrigations	22	14	9	5
Amount of irrigation (mm)	173	89	55	27
Amount of rainfall (mm)	233	201	621	834
Harvest Date	August 6	July 26	September 9	September 4

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

[b] PET, potential evapotranspiration.

Table 2.2-4. P value results from analysis of variance for the main and interactive effects of irrigation (Irr.) and preplant fertilizer treatment (Tmt.) on grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain Yield	NUE	WUE
STW[a] 2012			
Irrigation	0.0150	0.2258	---
Treatment	0.2241	0.6263	---
Irr. X Tmt.	0.0544	0.1089	---
LCB[a] 2012			
Irrigation	0.0118	0.9156	---
Treatment	0.1355	0.0145	---
Irr. X Tmt.	0.3038	0.0394	---
STW 2013			
Irrigation	0.0034	0.2243	0.0037
Treatment	0.0221	0.0381	0.0283
Irr. X Tmt.	0.1036	0.3306	0.1190
LCB 2013			
Irrigation	0.0440	0.0415	0.0498
Treatment	0.0370	0.2215	0.0319
Irr. X Tmt.	0.5533	0.7275	0.4957

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 2.2-5. Irrigated and rain-fed treatment means for grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain Yield ---kg ha^{-1}---	NUE ---%---	WUE ---kg ha^{-1} mm^{-1}---
STW[a] 2012			
Irrigated	8598	29.0	---
Rain-fed	4017	6.4	---
P value	0.0150	0.2258	---
LCB[a] 2012			
Irrigated	6047	21.4	---
Rain-fed	4835	19.8	---
P value	0.0118	0.9156	---
STW 2013			
Irrigated	9120	31.1	15.6
Rain-fed	2361	6.2	4.4
P value	0.0034	0.2243	0.0037
LCB 2013			
Irrigated	8662	43.2	10.8
Rain-fed	4022	25.0	5.3
P value	0.0440	0.0415	0.0498

[a] STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 2.2-6. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Stillwater, OK (STW) in 2012 and 2013.

	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
Contrast	--------Grain Yield--------			----------NUE----------			-----WUE-----		
STW 2012									
UAN vs. AS (difference)	ns[a] (-792)	ns (-241)	*[b] (-1343)	ns (0.4)	ns (4.8)	ns (-5.7)	---	---	---
UAN Linear	ns	**	ns	ns	ns	ns	---	---	---
UAN Quadratic	ns	ns	ns	---	---	---	---	---	---
AS Linear	**	**	ns	ns	*	ns	---	---	---
AS Quadratic	ns	ns	*	---	---	---	---	---	---
STW 2013									
UAN vs. AS (difference)	*(924)	**(1463)	ns (385)	ns (4.8)	ns (8.4)	ns (1.3)	*(1.4)	*(2.1)	ns (0.7)
UAN Linear	**	***	ns	ns	ns	ns	**	***	ns
UAN Quadratic	ns	ns	ns	---	---	---	ns	ns	ns
AS Linear	ns	ns	ns	**	**	ns	ns	ns	ns
AS Quadratic	**	**	ns	---	---	---	**	**	ns

[a] ns, not significant at the 0.10 level.

[b] *, **, ***, significant at the 0.10, 0.05, and 0.01 level, respectively.

Table 2.2-7. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Lake Carl Blackwell, OK (LCB) in 2012 and 2013.

	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
Contrast	--------Grain Yield--------			----------NUE----------			-----WUE-----		
LCB 2012									
UAN vs. AS (difference)	ns (-303)	ns (-767)	ns (-569)	ns (-4.5)	ns (1.0)	**(-10.0)	---	---	---
UAN Linear	ns	ns	ns	**	**	ns	---	---	---
UAN Quadratic	ns	ns	ns	---	---	---	---	---	---
AS Linear	*	*	ns	**	ns	***	---	---	---
AS Quadratic	*	ns	**	---	---	---	---	---	---
LCB 2013									
UAN vs. AS (difference)	ns (230)	ns (691)	ns (-232)	ns (2.2)	ns (6.0)	ns (-1.6)	ns (0.4)	ns (1.1)	ns (-0.4)
UAN Linear	**	**	ns	*	ns	ns	**	**	ns
UAN Quadratic	ns	*	ns	---	---	---	*	**	ns
AS Linear	**	**	ns	ns	ns	ns	**	**	ns
AS Quadratic	**	ns	ns	---	---	---	ns	ns	ns

[a] ns, not significant at the 0.10 level.
[b] *, **, ***, significant at the 0.10, 0.05, and 0.01 level, respectively.

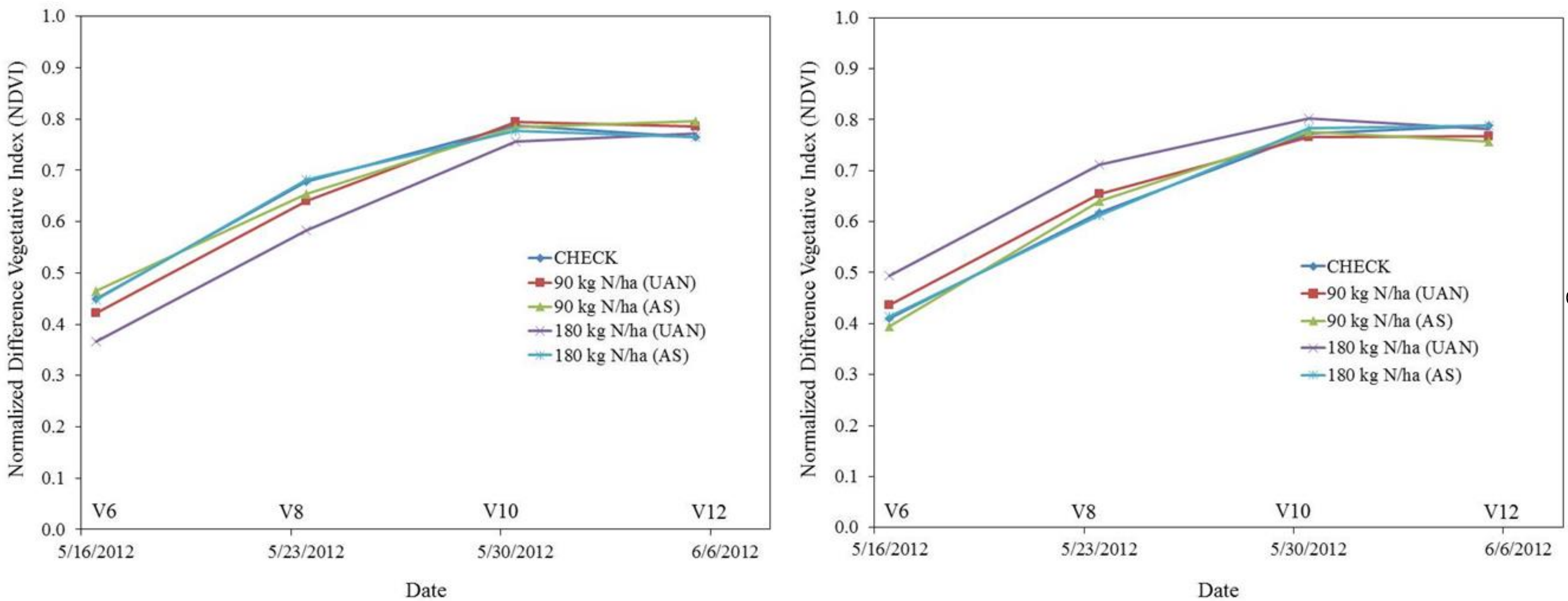

Figure 2.2-1. Normalized difference vegetative index (NDVI) values by maize growth stage for irrigated (left) and rain-fed (right) fertilizer treatments at Stillwater, OK (2012).

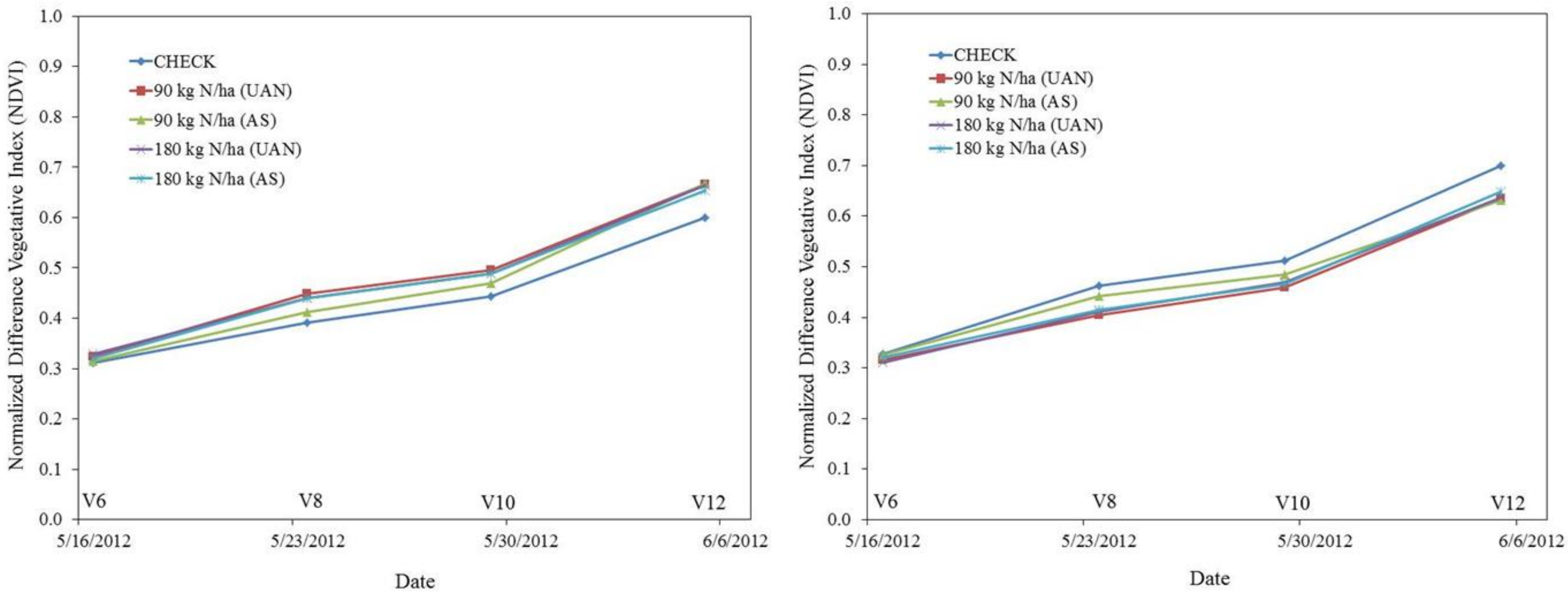

Figure 2.2-2. Normalized difference vegetative index (NDVI) values by maize growth stage for irrigated (left) and rain-fed (right) fertilizer treatments at Lake Carl Blackwell, OK (2012).

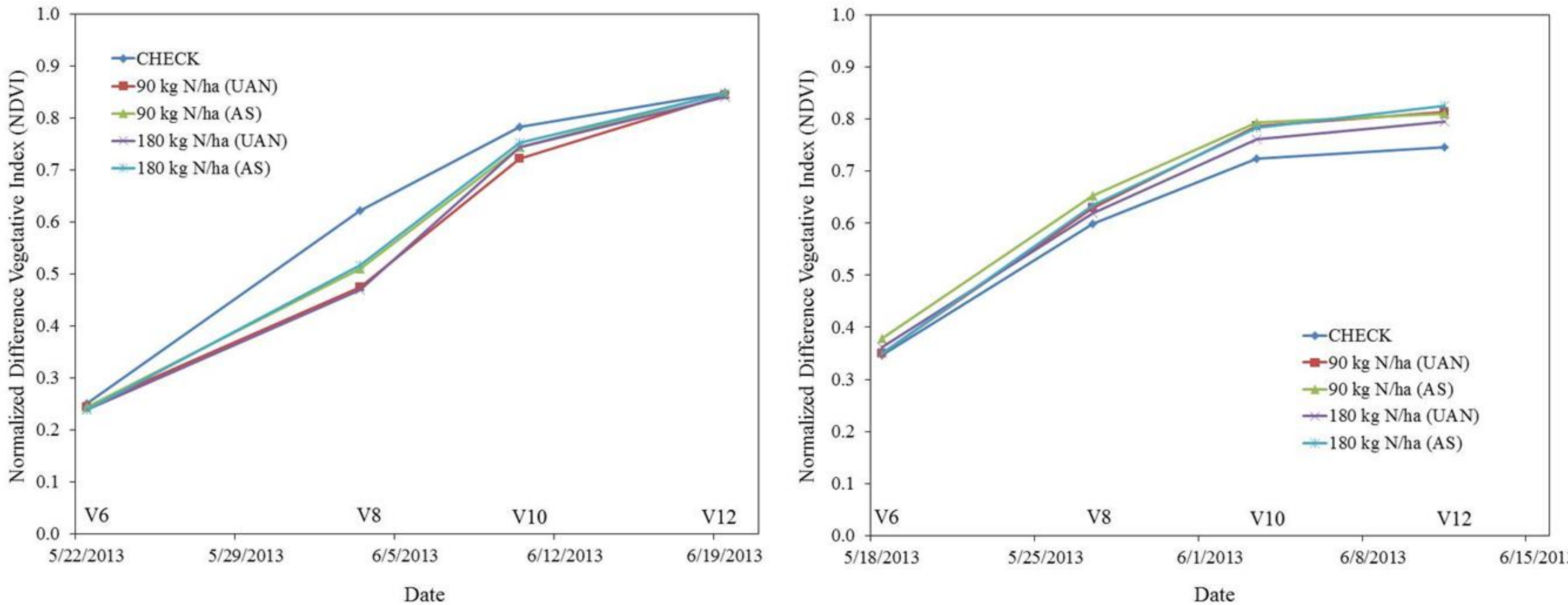

Figure 2.2-3. Normalized difference vegetative index (NDVI) values by maize growth stage for Stillwater, OK (left) and Lake Carl Blackwell, OK (right) fertilizer treatments for the 2013 growing season.

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