Precision Nitrogen and Water Management for Enhancing Efficiency and Productivity in Irrigated Maize

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Abstract. *Nitrogen and water continue to be the most limiting factors for profitable maize production in the western Great Plains. The objective of this research was to determine the most productive and efficient nitrogen and water management strategies for irrigated maize. This study was conducted in 2016 at Colorado State University's Agricultural Research Development and Educational Center, in Fort Collins, Colorado. The experiment included a completely randomized block design with five treatments per block. The treatment strips were planted across the entire length of the field in the East to West direction such that the treatment strips traversed over each management zone (low, medium, and high zones). Five N rates of 0, 56, 112, 168, 224 kg ha^{-1} using 32% Urea Ammonium Nitrate were applied at the V8 crop growth stage. Three rates of irrigation applied at 80, 100, and 120 % of evapo-transpiration were applied throughout the crop growing season by employing weather and soil data that is readily available online, to model crop ET and plant available water in the soil. A significant ($P<0.1$) and positive grain yield response to increasing levels of N across all site-specific management zones was observed. Likewise, a significant effect of irrigation ($P<0.1$) was observed across the field and within zones. The four nitrogen management strategies evaluated in this study did have a significant effect on the mean grain yield and nitrogen use efficiency ($P<0.1$).*

Keywords. *Precision Agriculture, Nitrogen Management, Management Zones, Irrigation*

Introduction

Profitable maize (*Zea Mays* L.) production relies on efficient application of crop inputs such as: nitrogen fertilizer, water, and other inputs. Input use efficiency continues to improve through agronomic research and adoption of best management practices by growers. However, input use efficiency largely depends on managing spatial variability that exists in crop fields. Soil and crop scientists have successfully characterized spatial variability and have demonstrated that precision-farming practices enhances growers input use efficiency, productivity, mitigates environmental pollution, and maintains or increases profitability (Koch et al., 2004). The advent of precision-farming technologies such as precision planters, sprayers, and irrigation systems allow growers to vary the application rates of inputs at every location of a crop field. While researchers and growers have become more aware of the implications of spatial and temporal variability in crop fields, there is still significant necessity to develop an empirically proven strategy to optimize spatial management of fertilizer and water.

Nitrogen (N) is among the most limiting nutrient in maize production and must be applied in adequate amounts to achieve maximum yield potential. Over application of N has shown to be a significant and hazardous non-point source pollutant in surface and subsurface waterways. The consequences of inefficient application of N fertilizer in agriculture has been shown to be harmful to ecosystems including human health (Stewart & Lal, 2017).

Research has shown, site-specific management zones (SSMZ) for variable rate application of N is a simple and effective way to increase nitrogen use efficiency (NUE) and mitigate N pollution of the environment (Inman et al., 2004; Khosla et al., 2002; Delgado et al., 2005). The site-specific management zones are demarcated sub regions in a crop field that have similar and inherent yield limiting or promoting factors. Management zone creation and delineation employs many methods including: remotely sensed imagery, soil electrical conductivity, soil surveys, and yield data (Song et al., 2011; Flowers., et al 2001; Fleming et al., 2004). These methods allow characterization of soil macro-variability. Typically, management zones are generated to classify a sub region's productivity, into high, medium, and low productivity potential. With the SSMZ approach, N fertilizer is applied at a variable rate across a field but at a uniform rate within a management zone at rates determined to optimize and maximize yield.

More recently, commercially available proximal sensors have been used as a tool for deciding in-season variable rate N management. Proximal sensing based technique entails observing optical properties of a crop to detect biotic or abiotic stresses (Raun et al., 1998; Inman et al., 2005; Shaver et al., 2010). Effectively, proximal sensor monitors plant status (greenness) with percent reflection at wavebands in the photosynthetically active region of the electro-magnetic spectrum. Where, a darker green plant with higher chlorophyll content may require lower amounts of N relative to lighter green plants. Both the SSMZ and proximal sensing approaches aim to increase NUE and maximize yield by determining the optimal rate of N to apply. However, coupling the two techniques (proximal sensing and management zones) together has proved challenging because while SSMZ's are determined with soil characteristics, proximal sensing is based on crop canopy reflectance. The novel techniques and tools (i.e., SSMZs and proximal sensors, or a combination of the two) that are currently available to manage N in crops, it would be only logical to understand the efficacy of these techniques or "*N management strategies*" by comparing with traditional or uniform N management across the field.

In 2016, growers in the US harvested roughly 35,100,000 ha of maize with an average yield of 11.7 Mg ha^{-1} (NASS USDA, 2016). Irrigated crop growers continually face many challenges related to water management notably: competition for water from increasing municipal demand and threats to the stability of water supply due to increasing severity and likelihood of drought. Precision irrigation management system has the potential to significantly reduce water consumption by crops, by applying the right amount of water, at the right place, and at the right time without impairing grain yields. While the technology and methods to implement precision irrigation have been available for over a decade, adoption and appreciation for precision irrigation is not yet wide spread. Research conducted at Colorado State University to quantify variability in soil water content has revealed that even a precision leveled field with the same soil type and textural class, show significant spatial variability in soil water content (Longchamps et al., 2015). More study is necessary to develop precision irrigation techniques to determine and apply optimal rates of water at every location in a crop field to maximize yield, water use efficiency and potentially conserve water.

The objective of this research was to determine the most productive and efficient nutrient and water management strategy for irrigated maize. The specific objectives of this research were:

i. To understand crop response to variable-rate nitrogen and water management across site specific management zones
ii. To compare four nitrogen management strategies that incorporates in-field macro-variability (soil based) and micro variability (based on proximal sensing of crop canopy).

Materials and Methods

Site Description

This study was conducted over the 2016 crop growing season on field 3100 at Colorado State University's Agricultural Research Development and Educational Center, in Fort Collins Colorado (40°40' 38.24'' N, 104° 58' 44.76'' W). The site has been under continuous maize cropping system with a center pivot irrigation system equipped with telemetry and drop nozzles for variable rate application of water. Soils at the site are classified as a fine-loamy, mixed, super active, mesic, Aridic Haplustalf (Soil Survey Staff, 1980). The two soil series at this site are a Kim loam and Nunn clay loam. The study site, field 3100 was tilled with vertical tillage implements in the fall of 2015 after harvest of the previous maize crop. In the Spring season prior to planting, starter fertilizer, Mono-Ammonium Phosphate (11-52-0) was applied at a uniform rate of 132 kg ha^{-1} across the field and incorporated into the soil with a Brillion mulcher (Landoll Corporation, Marysville, KS, USA).

Site specific management zones were previously delineated on the study field based on the methodology described by Khosla et al., 2002. Field was classified into productivity potential management zones of low , medium, and high and are referred to as zones 1, 2, and 3 respectively.

Experimental Design

For the purpose of objective (1) the experimental design consisted of a completely randomized block design with five treatments per block. The treatment strips were planted across the entire length of the field in the East to West direction such that the treatment strips traversed over each management zone. Using a six row John Deere precision vacuum planter (Deere & Company, Moline, IL, USA) with thirty-inch row spacing, DKC 46-20 (Dekalb) maize hybrid was planted on May 6th of 2016.

The Nitrogen fertilizer rates chosen in this study were intended to encompass rates such that the range of N rates were below and above the side dress N rates used by growers for irrigated maize cropping systems in the western Great Plains. Five N rates of 0, 56, 112, 168, 224 kg ha^{-1}using 32% Urea Ammonium Nitrate (UAN) were applied between the maize rows at the V8 crop growth stage (Ritchie, et al., 2005). A high clearance tractor equipped with a differentially corrected GPS unit was used to side dress UAN fertilizer. The tractor was equipped with a set of six drop tubes (one per maize row), and each drop tube had a gang of three nozzles that can be switched to provide a different N rate which was calibrated for the purpose of this study. As an additional precaution, prior to N application, each experimental strip was flagged with a unique color to indicate the level of N rate to be applied.

For the purpose of objective (2) the experimental design and project work were planned to allow comparisons of four unique N management strategies. These N management strategies were; (i) conventional uniform application of N, referred to as "Uniform"; (ii) a variable rate N management strategy that consisted of applying variable rate of N across management zones referred to as "MZ"; (iii) a proximal sensor based variable rate N management strategy referred as RS; and (iv) a variable rate N management strategy based on remote sensing within each management zone referred to as "MZRS". Beginning at the V6 crop growth stage proximal sensor readings were acquired until the crop reached V12 growth stage. The GreenSeeker (Trimble Navigation Limited, Sunnyvale California, USA) hand-held sensor was used to measure normalized vegetation index (NDVI). The NDVI readings were acquired continuously on the center row of every 6 row experimental strip, at a height of 0.8 m above the crop canopy in an east to west or west to east direction. The starting and ending point of each experimental strip was the same for every sensor reading date. NDVI readings were averaged over 10 second time intervals to create a geocoded NDVI measurement point.

Three rates of irrigation calculated as 80, 100, and 120 % of evapo-transpiration (ET) were applied throughout the crop growing season. Experimental layout was designed such that some or all of the levels of irrigation rates were randomly applied to clusters of experimental plots within each strip to achieve combinations of every factor level (i.e., N rate, Management Zone, and Irrigation rate). At each irrigation event, the 100% of ET irrigation rate was used as the base application rate and the other two rates varied accordingly. To schedule and determine the quantity of water applied for irrigation events the online irrigation water management tool, Water Irrigation Scheduling for Efficient Application (WISE) (Andales et al., 2014) was used. The W.I.S.E tool uses a soil water balance approach by employing weather and soil data that is readily available online, to model crop ET and plant available water in the soil. Irrigation was triggered and the amount of irrigation was applied such that the soil water content level stayed at or near maximum allowable depletion as determined by the WISE model.

Grain was harvested in the Fall on October 21st, with a combine equipped with yield monitoring system. The yield data was corrected for errors using the protocols described by Khosla and Flynn, 2008 for subsequent statistical analysis.

Statistical Analysis

For objective 1, least squares (LS) regression analysis was performed on the entire grain yield data set to study the main effects of water, nitrogen, and their interaction. For objective 2, the entire grain yield data set was sampled to a smaller subset for each N management strategy and further statistical analysis was performed to compare four N management strategies.

Nitrogen and Water Effects

The factors and their levels are defined as Irrigation Rate (80, 100, 120 % of evapotranspiration), Nitrogen Rate (0, 56, 112, 168, and 224 kg ha^{-1}), and predetermined Management Zones (1, 2, and 3). The response variable was the harvested maize grain yield (Mg ha^{-1}). A 2-level linear mixed model was fit to grain yield data where the study factors were assigned as fixed main and two-way interaction effects in the model. In addition, UTM coordinates were standardized and included in the model as covariates. Random effects were included in the model by experimental strip and by strip, irrigation rate, and management zone combinations to account for the design structure. All random effects were assumed to be independent and normally distributed with an expectation of 0 and some variance component. Using restricted maximum likelihood and Kenward-Roger degrees of freedom, F-tests were generated for the fixed effects. Post-hoc analysis included estimation of marginalized means, contrasts, and simple effect comparisons. Standard residual diagnostic plots were used to check the assumptions of the model. Data analysis was done using SAS for Windows software, Version 9.4.

Four N Management Strategies

From the entire grain yield data set (n>1000) recorded for objective 1 of this study, the yield data set was sampled to a smaller subset (n=135) for each N management strategy for objective 2 of this study as described here:

(i) For the "uniform" N management strategy, yield observations were sub-sampled corresponding to uniform N rate of 168 kg ha^{-1} independent of management zones.
(ii) For the management zone based N strategy (MZ), yield observations were subsampled based on their location corresponding to management zones 1, 2, and 3. Where for zone 1 yield observations corresponded to a lower level of N application and vice versa for zone 3.
(iii) For proximal sensor based N strategy (RS), a multi-step process was employed to prepare the yield dataset as follows: (a) Measured NDVI values were assigned to each yield pixel. (b) The NDVI dataset was then classified using k-means clustering algorithm (R Development Core Team, 2012) leading to five NDVI classes, and (c) Each NDVI class was grouped with a level of N rate such that, low NDVI classes were paired with a high level of N and vice versa for high NDVI classes.
(iv) For the fourth N management strategy, remote sensing within Zones (MZRS), steps (a) and (b) of strategy (iii) were preformed within management zones leading to three NDVI classes per zone. These three NDVI classes within each management zone were grouped with corresponding levels of N such that, low levels of N rate were grouped in Zone 1 and vice versa for zone 3. Corresponding yield observations were also recorded.

The four N management strategies were then statistically analyzed to compare yield levels and NUE using ANOVA and Tukey's HSD statistics. This was accomplished with the "aov" and "TukeyHSD" functions in R statistical software (R Development Core Team, 2012).

Results and Discussion

Weather

Northeastern Colorado is a semi-arid environment and the study site (field 3100) is located in the rain shadow of the Front Range of northeastern Colorado. The 2016 crop growing season experienced an unusual hot and dry weather. The 100% of ET treatments received 635 mm in total water through precipitation and irrigation. However, a majority 84% (i.e., 533mm) of the water applied to crop came from irrigation. The maize hybrid (DKC 46-20) used in this study is a short-season maize variety that was planted on May 6th and harvested on October 21st 2016. From planting to harvest 2503 growing degree units (Bauder et al., 2003) were accrued.

Nitrogen

The findings of the N rate study treatments were logical. As expected, there was a significant ($P<0.1$) and positive grain yield response to increasing levels of N across all site-specific management zones (Table. 1). Mean grain yield varied from a low, 5.8 to a high, 9.2 Mg ha^{-1} across all N treatments.

Table 1. Mean grain yield and standard errors of the means for the corresponding five rates of Nitrogen applied in this study.

N rate	Mean Grain Yield	Standard Error
---------Kg ha^{-1}------------	----------------------------Mg ha^{-1}--------------------------	
0	5.8^{a1}	0.41
56	7.4^{b}	0.40
112	8.4^{c}	0.44
168	9.0^{c}	0.43
224	9.2^{c}	0.45

1. Different letters (a, b and c) indicate significant differences at alpha = 0.10

Statistical comparison using Least Squares Means pursuant to objective (i) for grain yield across all levels of N treatments, show significant differences between 0 and all higher rates of N. These differences range from 1.6 Mg ha^{-1} between 0 and 56 kg N ha^{-1} N rate treatment to 3.4 Mg ha^{-1} between 0 and 224 kg ha^{-1} N rate treatment. Likewise, a significant mean grain yield increase of 1.6 Mg ha^{-1} or more was observed for N rates of 168 and 224 kg ha^{-1} when compared to the 56 kg ha^{-1} N treatment. No significant difference was detected in grain yield among N rates of 112, 168, and, 225 kg ha^{-1}.

Statistical analysis performed on grain yield for N treatments within each management zone also display a positive yield response to increasing levels of N. For Zone 1 mean grain yield varied from a low, 5.7 to a high, 9.3 Mg ha^{-1}; for Zone 2 mean grain yield varied from a low, 5.8 to a high, 9.3 Mg ha^{-1}; and for Zone 3 mean grain yield varied from a low, 5.8 to a high, 9.0 Mg ha^{-1}. As expected, the lowest mean grain yield occurred at 0 kg ha^{-1} N treatment for all zones. The maximum mean grain yield in zones 1 and 3 occurred at the 224 kg ha^{-1} N treatment. While zone 2 attained highest yield at the 168 kg ha^{-1} N treatment. However, no significant interaction (P>0.1) between zone and N treatments were observed. Results from this study, conducted over one crop growing season and one study site, indicate that the farmer could have achieved the optimum grain yield by an application of a single, uniform N rate of 112 kg ha^{-1}, across the management zones (Figure 1). Such a finding from this study appears to be anomalous, because long-term research at this location has documented that the N fertilizer must be applied variably to maximize yield across management zones (Inman et al., 2005; Khosla et al., 2002; Koch et al., 2004; Hornung et al., 2006). There are multiple reasons that could be attributed to this anomalous observation. (i) The year 2016 was an unusually dry year, where only 16% percent of the crop water needs was met by precipitation. Though this study site had a sprinkler pivot irrigation system, field observations made during the season indicate periods of crop water stress in between irrigation cycles. (ii) The study site, field 3100 underwent significant change in 2012 when it was precision leveled from a previous field-gradient of 3% to a gentle slope of <1% to accommodate a transition from furrow irrigated system to a precision irrigated center pivot system. The management zones currently employed on this study site were delineated prior to 2012 under furrow irrigation system. Under the furrow irrigation, water moved from West to East direction of the field. This was also reflected in the productivity potential of management zones delineated on the field as they followed a West to East gradient, where East part of the field was the most productive or designated as high management zone. It is postulated that the management zones may have shifted both, spatially and temporally due to the change in irrigation methodology. To date, minimal research has been conducted to determine how and if zones shift spatially overtime and if there exists a necessity to reclassify fields as these shifts may occur. More research is need to reclassify this field and similar other fields for most efficiency maize production systems.

Water

There was a significant effect of irrigation treatment (P<0.1). The irrigation rates of 80, 100, and 120 % of ET resulted in mean grain yield of 7.8, 7.8, and 8.2 Mg ha^{-1} respectively.

Table 2. Irrigation rates for each management zone, and corresponding mean grain yield along with standard error of the means observed in this study.

Irrigation Rate	Zone	Mean Grain Yield	Standard Error
------------ET %----------	-------------------------------------Mg ha^{-1}	---------------------------------	
	1	7.8[a1]	0.30
80	2	7.8[a]	0.27
	3	7.7[a]	0.34
	1	8.6[a]	0.28
100	2	8.0[a]	0.24
	3	7.1[b]	0.31
	1	7.7[a]	0.24
120	2	8.2[b]	0.23
	3	8.7[b]	0.52

1. Different letters (a and b) indicate significant differences at alpha level of 0.01 across management zones by irrigation rate.

Additionally, zone and irrigation interaction was found to be significant (P<0.1) as presented in Table 2. At the 100% of ET rate, a grain yield advantage of up to 1.5 Mg ha^{-1} was observed when comparing zones 1 and 2 to zone 3. When irrigation application rate was increased to 120% of ET, zones 2 and 3 outperformed zone 1 by up to 1 Mg ha^{-1}. The results seem to indicate that applying excess water led to increasing grain yield responses across zones 2 and 3. However, previous research has shown that over applying irrigation water typically leads to decreasing levels of grain yield as a result of reduced oxygen exchange between soil and the atmosphere, reductions in root growth, and reduced transport of nutrients and water from roots to aboveground biomass (Kanwar et al., 1988). As indicated previously, the 2016 growing season was hot and dry even for the semi-arid conditions of north eastern Colorado. Cumulative irrigation water applied at the 100% of ET treatment was 533 mm. It has been documented that the ASCE Penman Monteith equation for calculating reference ET, used by WISE to estimate crop ET, can result in underestimations of ET in hot advective environments (Gowda et al., 2008). Thus, the irrigation applied could have been misappropriated such that the 120% ET rate was in effect the 100% of the ET rate. Clearly more research is needed to evaluate such aspects of irrigation. However, variable rate irrigation systems show promise in maximizing grain yield and water use within and across management zones.

Nitrogen Management Strategies

The four nitrogen management strategies evaluated in this study did have a significant effect on the mean grain yield (Figure 1). In comparison to the uniform N management strategy where 168 kg of N ha^{-1} was applied uniformly, the MZ strategy did not result in higher mean grain yield that was significantly different than that of the uniform N management strategy. This observation is similar to previous research where fields managed uniformly achieved yield equivalent to or less than that of the fields that were managed variably (Koch et al., 2004). However, the aspect that distinguishes the two N management strategies is often the NUE as was observed in this study. The other two N management strategies (RS or MZRS) had a significant difference in grain yield of at least 1.3 Mg ha^{-1} compared with the Uniform strategy. This may be attributed to less N on average being applied to both RS and MZRS management strategies. There was no significant difference in grain yield when compared between the RS and the MZRS strategies. The MZRS management strategy is not yet well studied however, previous research has suggested increases in grain yield are possible when compared to a uniform N fertilizer application (Roberts et al., 2012).

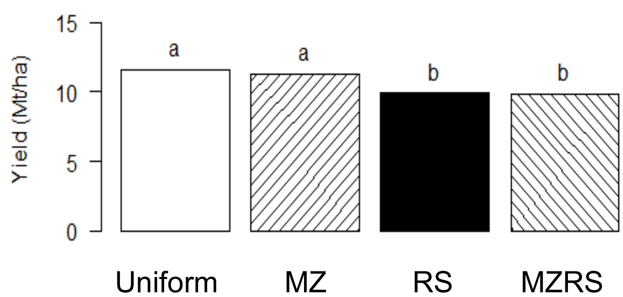

Figure 1. Bar plots of mean grain yield for different nitrogen management strategies. Management Strategies include: uniform N application rate, variable-rate N based on management zone (MZ), variable-rate N based on proximal remote sensing (RS), and variable-rate N based on remote sensing within management Zones (MZRS). Significant differences (P<0.1) are indicated by different letters (a and b).

As presented in Figure 2., all three N management strategies that employed a variable rate N fertilizer application resulted in improved NUE compared to the uniform strategy. The two strategies that included proximal remote sensing resulted in the largest NUE increase compared to the uniform. On average, the N fertilizer rate that was applied for the RS and MZRS strategies was less than the Uniform and MZ strategies.

These results clearly indicate that a variable-rate N fertilizer application could be employed for both, to maintain yield and increase NUE, relative to the uniform N management strategy.

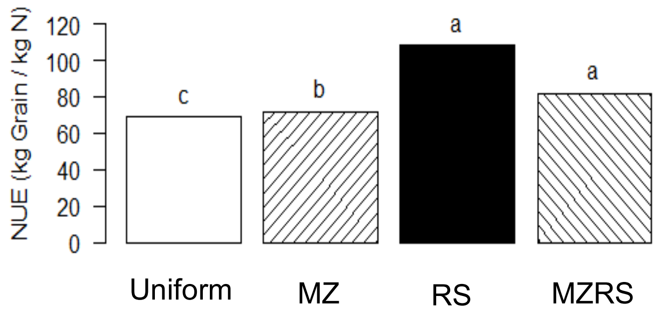

Figure 2. Bar plots of average nitrogen use efficiency (NUE) for different Management Strategies. Management Strategies include: uniform application rate, variable-rate based on management zone (MZ), variable-rate based on proximal remote sensing (RS), and variable-rate based on remote sensing within management Zones (MZRS). Significant differences ($P<0.1$) are indicated by different letters (a, b and c).

Conclusion

The research objectives for this study were to study the interaction of nitrogen and water as well as to compare four Nitrogen management strategies. An increasing mean grain yield response was observed for increasing levels of N fertilizer applied across the field but not within management zones. Mean grain yield was also found to increase with increasing levels of irrigation water applied, both, across the field and within management zones. The comparisons of the four Nitrogen management strategies showed potential to increase nitrogen use efficiency with the employment of the three variable rate N management strategies (MZ, RS, and MZRS) as well as maintain or improve grain yield.

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