IMPACT OF DELAYED NITROGEN APPLICATION IN GRAIN SORGHUM

By

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IMPACT OF DELAYED NITROGEN APPLICATION IN

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Abstract:

A majority of grain sorghum production occurs in the central to north west portion of Oklahoma, where the average annual rainfall is at or below 900 mm and precipitation events become less frequent. The environment conditions associated with this region has resulted in yields being highly variable. This variability makes input management a challenge. One of the primary challenges is N fertilization, not only because it is one of the costliest inputs but determining optimum application rates in these conditions can be challenging. Being able to delay the investments of inputs such as N until crop status and final yield potential is better understood in-season could increase crop NUE. In 2006 Oklahoma State University released a Sensor Based Nitrogen Rate Calculator (SBRNC) for grain sorghum. The SBNRC uses in-season NDVI values from the crop and a N rich strip to predict final grain yield and optimum fertilizer N rate. This technique often requires the crop to experience some degree of N deficiency prior to N to application. The objective of this study is to determine the impact of delaying N application after the onset of N deficiencies and the crops ability to recover. In 2019 growing season this study was conducted at three locations in Oklahoma. Two trials were located at Lake Carl Blackwell Research Farm near Perry OK, and one trail at the Cimarron Valley Research Station near Perkins, OK. Three N rates were applied depending upon the yield potential at each location, LCB1 100 kg ha^{-1}, LCB2 134 kg ha^{-1}, Perkins 90 kg ha^{-1}. In 2020 all locations received 100 kg ha^{-1} N and included a fourth location on a privately own farm (KMF) near Alva, OK. Using ammonium nitrate as the source of nitrogen, only one treatment received pre-plant N all other treatments except for the un-fertilized check received all N in-season. In 2019 initial side dress application was to begin at first sight of visual difference, a difference between the pre-plant and non-fertilized (check) or 28 days after planting (DAP), while in 2020 first application was moved to 21 DAP. Once side-dressing was initiated one treatment received N every seven days until 70 days after the first application for a total of 10 side-dress application timings.

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CHAPTER I

INTRODUCTION

The state of Oklahoma has a diverse climate that creates several challenges for crop production. While moving westward across the state total precipitation decreases, precipitation events become more sporadic, humidity decrease, and daily temperatures increase. Such change creates semi-arid environments unsuitable for some crops leaving producers with limited cropping options. Producers choose to plant crops that are adapted to such environments to reduce potential production costs.

Sorghum bicolor (L.) commonly known as grain sorghum is predominantly produced in semi-arid climates. Through the development of cultivars sorghum has become well adapted to areas of low precipitation such as Oklahoma (Sanchez et al., 2002). In 2017, approximately 127,000 ha of grain sorghum were planted, with average yield of 3 Mg ha^{-1}. (Oklahoma Department of Agriculture, 2018). Predominate sorghum producing areas are located in the central to western portion of the state, with a majority of production in the north western region of the state known as the panhandle (Figure 1). In 2019, the total yearly rainfall received, ranged from 1,000-1,500, 609-935, and 356-670 mm for central, western, and panhandle regions, respectively (Figure 2) (McPherson et al., 2007). In areas similar to central, western, and panhandle Oklahoma, production of sorghum has become increasingly important as it is one of the few crops with the potential to produce in harsh environments.

Due to the increased temperature, above average wind speeds, low precipitation and decreased humidity of the region, proper N management is essential. Those environmental factors also influence N loss pathways such as ammonia volatilization, plant loss in the form of ammonia, and denitrification. Blackmer et al. (1989) found delaying N fertilization until mid-season in maize allowed for more accurate determination of crop need for N, thus minimizing N loss. To improve nitrogen fertilizer management, it is critical to understand the effects of delayed N application while determining the impact of prolonged nitrogen deficiency on grain yield.

CHAPTER II

REVIEW OF LITERATURE

Nitrogen in Plant Physiology

Nitrogen is considered an essential element needed for plant growth and development due to its role in amino acids and proteins (Novoa & Loomis, 1981). Amino acids are used as the building blocks for proteins that are responsible for metabolic reactions within the plant (Arnall, 2017). Brouwer (1962) proposed the idea of a functional balance between activities of shoots and roots, implying each organ be dependent upon the other to continue development. The balance interprets shoot and root growth as a ratio, and operates to restrict root or shoot growth depending upon which supplied factor is more limiting at the time (Novoa & Loomis, 1981). Edwards and Barber (1976), and C. David Raper et al. (1977) later reported that N would be included in functional balance relationships. Nitrogen follows a basic scheme of uptake, reduction, and protein formation (Figure.3). At uptake roots transform some NO3- into amino acids, but the majority of reduction occurs in the leaves. Amino acids formed in the leaves can then be transported to roots or other organs via phloem (Pate et al., 1979). Provided N follows similar movements as shoot: root ratio it can be an intricate part of the functional balance relationships previously observed in plant growth (Radin, 1978).

Plant growth stages have been shown to influence rate and demand of N (Novoa & Loomis, 1981). The following information unless stated otherwise was gathered from the Kansas State University sorghum development guide (Vanderlip, 1993b). Grain sorghum has a total of nine growth stages as the crop matures its demand for N increases (Figure.4). During vegetative growth stages zero (emergence) one (three-leaf stage), and two (five-leaf stage) sorghum will take up approximately 5% of sorghum total N requirement throughout the season. Emergence generally occurs within 3 to 10 days after planting (DAP). Time of emergence is depends on several factors including: soil temperature, moisture conditions, planting depth, and seed vigor. Emergence requires approximately 200 cumulative growing degree units (GDU's). Three-leaf stage will occur approximately 10 days after emergence requiring 500 cumulative GDU's. Around 21 days after emergence, 660 cumulative GDU's, stage two (five-leaf) occurs (Kelley, 2004). At stage three (growing point differentiation) the plant changes from vegetative leaf production to its reproductive (head producing) stages. An increase in growth and N uptake can be observed as approximately 25-30% of the crops total N has been taken up. Stage three transpires at roughly 30 days after emergence given the approximate 1365 cumulative GDU's(Kelley, 2004). As for stage four (flag leaf) this is the final leaf, by this stage all except the final 3-4 leaves should be fully expanded for maximum light interception, and head development is initiated. The nitrogen uptake is the same as for stage three, and occurs approximately 40 days after emergence needing 1470 cumulative GDU's (Kelley, 2004). Stage five (boot) potential head size is determined as it is nearly developed to full size in the flag leaf sheath. Elongation of the peduncle is beginning and will later result in the exertion of the head from the flag leaf sheath. This stage occurs approximately 50 days after emergence once obtaining around 1750 cumulative GDU's (Kelley, 2004). During this stage 70% of total N has been accounted for in uptake. Stage six (half bloom) 60 days following emergence and 1995 GDU's (Kelley, 2004), the peduncle is rapidly extending the head through the flag leaf sheath, and grain formation begins. At this time N uptake has reached 80% of the total requirement. At approximately 70 days after emergence and 2310 GDU's stage seven is reached (Kelley, 2004). Stage seven (soft dough) half of the plants dry weight is accumulated, and grain is formed rapidly. During this rapid formation of grain, the culm loses weight, lower leaves are still being lost with 8-12 remaining functional, and 90% of the total N has been taken up. Stage eight (hard dough) approximately three fourths of the grains dry weight has been accumulated, and nutrient uptake is complete. Stage eight occurs 85 days after emergence requiring 2765 GDU's (Kelley, 2004). Lastly stage nine (physiological maturity) maximum dry matter accumulation has occurred, and physiological maturity can be determined by the formation of the dark spot on the opposite side of the kernel from the embryo (Figure.5). This final stage occurring at approximately 95 days after emergence and 3360 GDU's (Kelley, 2004).

Physiological Response to Nitrogen Deficiency

Due to the N essential role in plant growth and development it is important to know and understand plant response's to low concentrations of N. Zhao et al. (2005) conducted an outdoor pot-culture study at Mississippi State using sorghum to determine the effects of N deficiency on plant processes and growth. Their research indicated N deficiency suppressed plant growth, dry matter accumulation, and allocation of N. A decrease in plant biomass production can be associated with smaller leaf area (LA), while contributing to reductions in both leaf photosynthetic (Pn) capacity, and chlorophyll concentrations (Sinclair, 1990). The decline in LA and Pn due to N deficiency have been determined to be the major causes of limiting plant growth and production (Novoa & Loomis, 1981; Sinclair, 1990). The decrease in LA and Pn can be explained by the functional balance of the plant system. When experiencing low concentrations of N shoot growth is restricted to promote root growth for further soil exploration, while high concentrations promote above ground growth (Novoa & Loomis, 1981; Schlüter et al., 2012). The promotion of root growth occurs by the reallocation of N, during this process N is transferred from the leaves (source) to the roots (sink) (Schlüter et al., 2012). C. David Raper et al. (1977) provided evidence supporting this role of nitrogen, as he observed the growth rate of cotton roots were increased in lower concentrations of nitrogen. More recently Bonifas and Lindquist (2009) preformed a study to determine effect of N deficiency on root development. In previous studies corn root morphology has responded significantly to decreasing levels of N (Bonifas et al., 2005). Corn roots are able to adapt to the low concentration of N through the use of their morphological characteristics. In the event of N deficiency root radius declines while length and density increases for soil exploration (Bonifas & Lindquist, 2006, 2009). The increase in root length and surface area improves the ability of nutrient uptake to alleviate plant stress (Bonifas & Lindquist, 2006, 2009). Therefore, root morphology is closely related with plant growth and development (Qi et al., 2019).

Nitrogen Use Efficiency

Nutrient use efficiency (NUE) is measured by a crops ability to efficiently utilize the nutrients from both soil and fertilization to produce grain. The world-wide NUE for most cereal crops is estimated at 33% (Raun & Johnson, 1999). Several factors contribute to a low NUE such as plant loss, volatilization, leaching, runoff, and denitrification. Past studies have indicated, the majority of N loss can be accounted for through plant loss (52 to 73% in corn) and volatilization (40% in wheat) (Raun et al., 2002).

A major factor contributing to such low NUE is the traditional N management of producers applying large amounts of N before a crop can effectively utilize it (Raun and Johnson, 1999). Most grain sorghum producers apply N fertilizer as a preplant and/or sidedress applications (Moges et al., 2007). Large preplant inputs have a greater risk of loss through environmental pathways lowering a crops NUE (Raun & Johnson, 1999). A low NUE is reflective of inefficient N management and could result in great economic loss to producers (Walsh et al., 2012). In previous research Raun and Johnson (1999) have shown NUE could be greatly increased by abstaining from early season inputs while leaning more towards mid-season applications of N that more accurately reflect crop needs. This reduces opportunity for loss due to plant establishment and ability of nutrient uptake (Keeney, 1982).

Environmental Influence on Nitrogen Use Efficiency

Nitrogen has multiple loss pathways including denitrification (9.5 to 10%), leaching (1 to 13%), runoff (1 to 13%); with its largest pathway being plant loss (52 to 73%), and ammonia volatilization (40%) (Raun et al., 2002). These losses can be significantly affected by the surrounding environment for instance areas of low moisture, precipitation intensity, high temperature, and high soil pH similar to the production areas of Oklahoma each contribute to N loss (Cossey et al., 2002; Kleinman et al., 2006). In these areas application methods such as surface application of N can be conducive to N loss (Turner et al., 2012). Correspondingly N source holds a crucial role in N loss, as ammonia based fertilizers like urea and anhydrous constitute a greater risk for ammonia volatilization (Arnall, 2017).

In 2019, sorghum production areas of Oklahoma received 356 to 1,500 mm of total rainfall for the year. In addition, soil temperatures in 2019 for these production areas ranged from 27°C to 38°C, and air temperatures ranging from 30°C to 35°C for the summer growing season (Mesonet, 2019). A climate containing these environmental factors poses challenges on producers as it creates an ideal framework for N loss. Due to its relative low cost many producers use urea as a source of N for applications. The source urea holds a greater risk for ammonia volatilization as it requires moisture to chemically transition from ammonia NH_3 to the plant available form ammonium NH_4^+.

Delaying N application until a point or growth stage that it could effectively uptake and utilize the given nutrient could decrease the risk of loss. As N is delayed the shoot:root ratio changes, focusing growth towards the roots for soil exploration to alleviate crop stress. Roots respond to deficiency by decreasing their diameter allowing for increased elongation and ease for exploration. This decrease in diameter allows roots to have a greater surface area by the increased concentration of roots to soil. Such increase in root concentration could allow for a greater ability for nutrient uptake and utilization as the requirement for N is dependent on growth stage.

Impact of Soil Characteristics on Nitrogen Loss

Soil parameters such as texture, topography, hydrological group greatly affect the movement of water and nutrients (Tremblay et al., 2011). Soil texture and topography are used to classify the hydrological soil group (HSG) a fundamental component for estimating rainfall runoff, and soil infiltration. The HSG's contain four standard classes (A,B,C,D), which correspond to a soils potential runoff and infiltration rate, risk of potential runoff increases from letter A to D, while infiltration rate has an inverse relationship (Ross et al., 2018).

The influence of these parameters has been well documented as they generally impact available N (Tremblay et al., 2012). The previously discussed soil parameters also effect the N loss pathway. For example, Sogbedji et al. (2001), found that fine-textured soils lost more NO_3 through denitrification, while coarser textured soils primarily lost NO_3 through leaching. Topography is reported to influence microclimate, soil properties, runoff, evaporation, and transpiration; which affect N mineralization, nitrification, and denitrification processes (Zhu et al., 2009). Previous research has indicated a significant effect of landscape position and N uptake. Dharmakeerthi et al. (2006) found N uptake was lowest at the backslope position, while the highest was observed at the toe/foot slope positions. Dharmakeerthi et al. (2005), attributed these differences to N availability, where N availability was lowest at the backslope, and highest at the toe/foot slope. The HSG effects the hydrological processes such as evapotranspiration, surface/subsurface water movement, soil water distribution, and water table, which in turn control soil N availability and crop growth by influencing water availability, N leaching, nitrification, denitrification, and volatilization (Zhu et al., 2009). Understanding the influence of these factors could lead to improved N management strategies.

Implications of Plant Nitrogen Loss

Plant loss has been documented as the largest N loss pathway ranging from 52 to 73% for corn (Raun et al., 2002). Although further research is necessary, plant physiologist found physiological processes, growth, and dynamics related to N loss. The initial plant N loss occurs at the roots during N acquisition, which is affected by root architecture, ammonium, and nitrate transporters (regulated by N from concentration), and temperature fluctuations. Thereafter begins the process of N assimilation, where N is reduced into ammonium for assimilation of amino acids. Nitrogen assimilation occurs in both above and below-ground portions, with a larger portion taking place in leaves. During the vegetative stage leaves are a sink for N and can attribute to N loss in the form of ammonia during leaf senescence (Figure.5; (Guohua Xu et al., 2012). Although leaf senescence is a naturally occurring deterioration of cellular tissue, the rate of deterioration can be influenced by drought, nutrient limitation, and extreme temperature (Lim et al., 2007; Masclaux-Daubresse et al., 2010). In an earlier study Farquhar et al. (1980), stated while there is a constant consumption and release of ammonia through leaves by the process of diffusion in regards to atmospheric particle pressure, suggesting that losses are greatest when temperatures are highest, stomatal conductance is increased, and ambient particle pressure is low. The process of photorespiration has been documented as a wasteful process requiring vast amount of energy and carbon, in which releases N in the form of ammonia. This process predominantly occurs in C_3 plants, while

C_4 plants possess a mechanism that minimizes photorespiration (Mallmann et al., 2014). Furthermore, the main contributing factor to N loss in the form of ammonia from aboveground parts is due to the imbalance between N accumulation and N assimilation within plants (Guohua Xu et al., 2012). Excluding plant loss pathways could in fact lead to overestimations of loss through volatilization, leaching, denitrification, and runoff. Understanding the implications between soil and plant systems could lead to improvements in N management and increases in plant NUE.

Delaying N application allowed for a variety of environmental and physiological parameters to be considered in the analysis. An analysis of this kind could contribute additional information on which parameters (soil, plant, environmental) have the greatest impact on applied N. This additional insight may potentially advance todays N management techniques by further understanding the magnitude of each implication, such as delaying N application until adequate environmental and physiological conditions exist. There is a lack of documentation on the recoverability of grain sorghum and its effects on grain yield, results from this study could allow for a reevaluation of how to increase the agronomical management of grain sorghum with the unpredictability of meteorological variables.

CHAPTER III

METHODOLOGY

A trial was conducted at three locations in 2019 and four locations in 2020. In 2019, two trials were at Lake Carl Blackwell Research Farm (LCB) near Perry OK, and one trial at the Cimarron Valley Research Station (CVR) near Perkins, OK, while in 2020 only one trial was placed at LCB and locations were added at the Raymond Sidewell North Central Research Station (NCR) near Lahoma, OK, and on a privately owned farm (KMF) near Alva, Oklahoma. Description of location soil series, field classifications, and history is displayed in Table 1. Each trial consisted of 12 treatments in a random complete block design (RCBD) consisting of three to four replications, number of replications dependent upon availability of space, with plots that were 3 meters wide by 6 meters in length. Composite pre-plant soil samples, consisting of 15 cores per sample, were taken to a depth of 15 centimeters for each location (Table 3). In 2019 three rates of N were applied depending upon the yield potential of each location, LCB1 100 kg N ha^{-1}, LCB2 134 kg N ha^{-1}, Perkins 90 kg N ha^{-1}, while in 2020 all locations received 100 kg N ha^{-1}. Rates were chosen to be just below the optimal environmental N demands to allow for the evaluation of the impact of N timing on NUE. Biswas and Ma (2016) reported a decrease of NUE with increasing rates of N fertilization, while higher rates of N provided no statistical advantage to yield. An environment containing excess N would create similar results to Biswas and Ma (2016), thus generating unquantifiable differences in crop NUE and grain yield response to N timing (Muchow, 1998). Preplant N was applied for Trt1, Trt 2 was a non-fertilized check and Trt3-12 applications started at first sight of visual difference from the pre-plant and non-fertilized check. Onset of visual difference varied across location and site years, for 2019 CVR and LCB2 was documented at 22 DAP, and LCB1 at 28 DAP, while in 2020 locations CVR, and NCR reported 35 and 42 DAP, respectively. Both locations KMF and LCB20 indicated no sign of visual difference. The Trt3-Trt12 were applied as sidedress at 7 day intervals until 70 days after the first application for a total of 10 sidedress application timings. In 2019 if no visual difference was detected by 28 days after planting (DAP) the first side-dress application would be made to Trt3. This date was moved to 21 DAP for the 2020 trials (Table 4). The N source for all site years was ammonium nitrate (NH_4NO_3), which was spread by hand evenly between rows. Ammonium nitrate was used to limit environmental impact of application by removing the risk N loss through urea volatilization (Fenn & Hossner, 1985). In 2020 stand counts were taken at 21 days after planting (DAP), and a final head count prior to harvest. Plots were considered heading once 60% of the middle two rows main stem demonstrated panicle emergence of 3.8 cm or greater from the flag leaf sheath. Depending on the level of variability in physiological maturity between treatments the middle two rows were harvested using a Massey Ferguson 8XP plot combine, or individually hand harvested, which was then threshed using a plot combine. In 2019 due to the crop being delayed, the crops were individually hand harvested at black layer in an attempt to minimize bird damage during the dry-down period. In 2020, due to a timelier planting, the crop was predominantly harvested with a Massey Ferguson 8XP plot combine equipped with a Harvest Master Grain gauge. Two of the four sites were hand harvested, which were threshed using a Wintersteiger Delta plot combine equipped with a Harvest Master Grain gauge. Grain sub-samples were collected for nutrient and quality analysis. Post-harvest grain quality was analyzed using near infrared spectroscopy (NIR) Diode Array NIR analysis Systems model DA 7000 (Kungens Kurya Sweden) Statistical analysis of grain yield and N concentration were conducted using the statistical analysis software SAS using a Dunnett's procedure for multiple comparison analysis to determine treatment impacts of grain yield using the check and pre-plant as a control (SAS Institute Inc, Copyright © 2020). Linear model analysis was conducted to indicate the level or lack of significance of meteorological variables to determine if additional inspection was imperative (R Core Team, 2020).

CHAPTER IV

RESULTS AND DISCUSSION

Timing of Nitrogen Application

The purpose of the study was to evaluate grain sorghum's response to N deficiency and its ability to recover succeeding fertilization. In 2019 application of treatments began from 22 to 28 DAP. CVR-19 and LCB1-19 began at the 28 DAP, while the LCB2-19 began at 22 DAP. In the 2020 growing season, applications of treatments for all locations began at 21 DAP, while first sign of visual difference for CVR was documented at 35 DAP and 42 DAP for NCR, remaining locations KMR and LCB2-20 showed no visual difference during treatment applications. Dates of treatment application across site years can be found in Table 5. The delay in visual difference among site years could likely be reflective of the variation in residual N, mineralized N, and crop growth patterns.

Physiological Development Response to Nitrogen Timing

Across the majority of the sites a delay in sorghum heading and maturity were observed in relation to delayed N timing (Table 6). Heading for all 2019 locations was highly variable within treatments, which could be an influence of inadequate fertilizer distribution or field topography. Nitrogen application significantly impacted heading date at NCR and CVR in 2020 (Table 7). In both locations N deficiency resulted in a delay of heading by a two-week period. Early research conducted by Muchow and Carberry (1990); Muchow and Sinclair (1994) provided supporting evidence by reporting that N deficiency had a significant impact on timing of anthesis ad duration of the grain filling period, therefore influence flowering and maturity dates. Delays in maturity can also influence dry-down timing. Natural plant and grain dry-down will typically progress much slower the later into fall due to higher humidity and cooler temperatures. This can impact yields as later maturity or later maturity paired with slower dry-down can lead to prolonged animal predation, which led to a complete loss of LCB1 in 2019.

Grain Yield Response to Nitrogen Timing

Due to complications for grain storage the 2019 all samples were lost prior to threshing; therefore, the grain yield of 2019 trials will not be discussed. An ANOVA test was performed by trial for the 2020 crop in an effort to verify the effects of N timing, which indicated significant differences among treatments (p=0.05). A Dunnett's analysis was conducted to determine the impacts on grain yield. As this analysis only allows for comparison to a designated check treatment, all analysis was compared to the unfertilized check (Trt2) (Table 8). If a location had no treatment yielding significantly greater than the unfertilized check the location would be deemed non-responsive and would not be discussed further in this section. All locations indicated a significant response to applied N.

For the CVR and NCR locations all treatments except for 84 DAP showed a significant improvement in grain yield compared to the check. The LCB2-20 location followed a similar tread of increased grain yield for all treatments excluding 77 DAP and 84 DAP. At the KMF location only the 0 and 21 DAP treatments showed a significant increase over the unfertilized check.

To further evaluate the response of grain yield to N timing the un-fertilized check was removed from the analysis, and the pre-plant was used as the control for the multiple comparison Dunnett's procedure (Table 8). This analysis would provide evaluation on the effect that N timing had upon grain yield. Such analysis would provide insight on the optimum timing of N and at which point would it be too late to apply N and still achieve yields equivalent to pre-plant applications.

The Dunnett's analysis documented a significant yield differences at all locations. The only location to show a significant increase in grain yield was the CVR location at 49 DAP. Three of the four site years the point at which the delay of N application resulted in statistically reduced grain yield was determined. For the LCB20, NCR, and KMR locations the last application date at which grain yield was not significantly less than the pre-plant were 77 DAP, 70 DAP, and 35 DAP respectively. While CVR demonstrated a significant increase in grain yield, a point of no recovery could not be determined statistically as it showed no treatment significantly lower than the pre-plant application.

While statistical significance differed at each location there was a point in the application timing at which grain yield numerically declined over time, and this occurred well prior to the dates documented by the Dunnett's test. Statistical analysis provided by the ANOVA procedure determined numerical differences between pre-plant, statistical or numerically proven highest yielding treatment and delayed applications, these results are displayed in Table 9. A continuous numerical decline was observed at CVR between 49 and 56 DAP, while a significant decline occurred for the remaining treatments. Similarly, NCR decline occurred following 42 DAP, a numerical difference was detected in 56 and 63 DAP, while 49, 70, 77, and 84 DAP were statistically lower. From 21 to 42 DAP a numerical decline was indicated at LCB20, while remaining treatments were found to decrease significantly from 21 DAP. The KMR location provided equivalent results as a numerical decline was noticed following pre-plant to 35 DAP, whereas 42, 49, and 56 DAP denoted a significant decrease.

Grain Protein Response to Nitrogen Timing

Similar statistical analysis as conducted for yield was used to detect significant, if any, differences in protein dry weight basis (DWB%) in the effect of N timing. Complications in grain storage resulted in the loss of sub-samples from NCR, thus it will not be discussed in this analysis. Of the three locations CVR, and LCB20 showed a significant effect of nitrogen timing to protein DWB%, while KMR indicated a response to nitrogen application it was unresponsive to timing (p=0.31).

Multiple comparison Dunnett's procedure indicated a significant increase in protein DBW% for CVR at 77, and 84 DAP, while 70 to 84 DAP for LCB20 showed a significant increase when compared to the pre-plant application (Table 10). Furthermore, LCB20 showed numerical differences between previously listed treatments when comparing them to the numerically highest protein DWB% 84 DAP, these results are shown in Table 11.

Environmental Implications on Nitrogen Application

In an attempt to explain some of the variation in yield between treatments and locations, further analysis of weather variables such as precipitation, precipitation intensity, temperature and soil moisture were included to identify a correlation between N application and grain yield response. Meteorological data was collected using Mesonet Daily data retrieval, and transferred to Microsoft Excel where maximum precipitation (PMAX), intensity (PI), precipitation (P), average maximum and minimum temperature (TMAX, TMIN) , and soil moisture at day one at 5 cm (SMD1), average soil moisture at 5 cm (AvgSM), and delta soil moisture at 5 cm (DeltaSM) were observed on a 7 day interval (Brock et al., 1995; McPherson et al., 2007). In this discussion, each location will be independently discussed in an effort to efficiently convey possible explanations or factors that may have impacted treatments.

The analysis of LCB20 indicated a significant relationship between PI ($p = 0.1$), TMAX/TMIN ($p = 0.001$)), and SMD1 at 5 cm ($p = 0.1$). It is possible these parameters could have had a slight impact on N application and final grain yield. Although not significant a numerical difference of 839 kg ha^{-1} was observed between the pre-plant and 21 DAP treatment. Weather data from the week of pre-plant application reported a total of 4 precipitation events totaling to 13 mm. Maximum precipitation received from a singular event occurred 6 days after application equating to 11 mm, while consisting of a PI of 24 mm hr^{-1}. Weather data also indicated a decline of 2 in daily soil moisture ranging from day 5 to 7. In result of a decline in soil moisture following an 11 mm precipitation event, it could be hypothesized that the pre-plant N application was subject to runoff thus causing a decline in final grain yield. The same hypothesis could be considered for treatment 35 DAP, which consisted of 5 precipitation events totaling to 33 mm. Maximum precipitation event of 19 mm with a PI of 30 mm hr^{-1} occurred 1 day after application. A similar decline in soil moisture was observed on the day of maximum precipitation continuing to day 7.

Treatment 49 DAP received 0 precipitation events; thus, the N application was not effectively incorporated into the soil profile for crop uptake. Treatment 56 DAP experienced similar limitations in precipitation, where 0 precipitation events occurred until the following application 63 DAP consisting of 3 precipitation events totaling to 58 mm with a PI of 46 mm at 2 mm hr^{-1}. Timing of precipitation event could account for the difference of treatment 49 DAP grain yield from treatments 56 and 63 DAP, while its P and PI could account for the difference in yield between treatments 63 and 70 DAP.

In the analysis of the CVR location there were significant relationships between PI ($p = 0.02$), P ($p = 0.02$), and SMD1 at 25 cm ($p = 0.03$) and grain yield. As previously mentioned, it is likely these parameters contributed to the difference observed among treatments. For instance, statistical analysis indicated a significant increase of 823 kg ha^{-1} between the pre-plant and 49 DAP applications. This increase could be reflective of the precipitation events and their intensities. Weather data for the week of the pre-plant application showed 5 precipitation events totaling to 24 mm, with a maximum intensity of 58 mm hr. The shear small size of the crop and total precipitation could have led to inadequate N uptake and N loss via leaching. Although treatments 42 to 56 DAP were without precipitation until the week of treatment 63 DAP, due the excess amount received and relatively high soil moisture the same assumption can be made for the decline noticed following treatment 49 to 84 DAP. An increase of 2 in soil moisture was observed between treatments 42 to 56 DAP, this increase in soil moisture through capillary action could have alleviated a fraction of N stress, while the lack of precipitation contributed to no N loss through leaching. The increase of these treatments from the pre-plant could also be an effect of crop requirement, size, and ability to effectively uptake nutrients. 63 to 84 DAP received excess amounts of precipitation at relatively high intensities contributing to N loss through leaching thus causing a decrease in grain yield.

The environmental analysis of NCR provided peculiar information, which indicated a significant relationship involving maximum temperature (TMAX) ($p = 0.1$), SMD1 a 5 cm ($p = 0.001$), and AvgSM ($p = 0.05$) to grain yield. Although not significant a slight numerical increase observed from the pre-plant in treatments 21 and 42 DAP. Soil moisture data showed a decrease in SMD1 of 0.10 from the pre-plant and 21 DAP, and 0.31 for 42 DAP. The weekly AvgSM for the previously discussed treatments were recorded at 2.3 (pre-plant), 2.4 (21 DAP), and 2.2 (42 DAP), while TMAX data ranged from 19.2 °C (21 DAP), 22°C (pre-plant), to 33°C (42 DAP). A second numerical increase of 422 kg ha^{-1} was reported between treatments 49 and 63 DAP. The AvgSM for treatment 63 DAP could not be obtained due to sensor failure during the week of application, AvgSM for treatment 49 DAP was recorded as 2. Soil moisture data showed an increase of 0.3 in SMD1 from treatment 49 to 42 DAP, while TMAX decrease from treatment 49 DAP to 63 DAP equating to a difference of 15 °C. Due to an insufficient amount of meteorological and yield data an accurate determination of the level of influence these parameters had in final grain yield is unobtainable.

The results of the meteorological analysis indicated significant correlations between TMAX /TMIN model ($p = 0.01$), SMD1 at 5 and 25 cm ($p = 0.1$, 0.02 respectively), AvgSM at 25 cm ($p = 0.02$) and grain yield for KMF. A numerical decrease in grain yield among pre-plant and treatments 21 and 28 DAP, while a significant decline in yield was reported for treatments 35 to 56 DAP. A complete comparison of SMD1 and AvgSM for treatments 35 DAP to 56 DAP is unattainable due to a failure involving the station soil moisture sensor. Perhaps the numerical decline in yield could be the effect of fluctuations between TMAX and TMIN. For treatments 1 to 4 the average TMAX was 34 °C with an average TMIN of 22 °C. In the week of treatment 1, soil moisture data reported the highest AvgSM (3), and SMD1 (3) for the location.

Following pre-plant a decline in soil moisture was observed among 21 and 28 DAP, both treatments reported an AvgSM of 1, and SMD1 of 1. Although the relationship involving total precipitation was not found significant it is possible to have influenced grain yield. The decrease in grain yield between 28 DAP and pervious treatments could be an effect of total precipitation of 118 mm received by 28 DAP, whereas prior treatment pre-plant received 0.3 mm and 29 mm for 21 DAP. Precipitation of this caliber could have influenced N incorporation efficiency resulting in N loss through runoff, leaching, or denitrification. Remaining treatments 35 to 56 DAP, further inspection of yield differentiation involving soil moisture data will not occur, while the assumption of TMAX and TMIN fluctuations and total precipitation could be considered as contributing factors of yield differences among treatments. Average TMAX across remaining treatments equated to 32°C and 19°C average TMIN. In contrast to prior discussion of earlier treatments total precipitation received decreased with each treatment, initial decrease began following treatment 35 DAP with a total precipitation of 28 mm, 42 DAP totaled to 23 mm, 49 DAP totaled to 5 mm, while 56 DAP experience 0 precipitation events until the early portion of September totaling to 33 mm.

Soil Characteristics Influence on Nitrogen Application

Soil properties and qualities data from each trail locations were gathered using web soil survey, interpreted data included soil texture, hydrological soil group (HSG) and hydraulic conductivity (Ks) (Soil Survey Staff). Hydrological conditions were determined by evaluating tillage, and planting practices. All locations followed no-till management practices consisting of cover crop accounting for at least 5% of the surface area, except for CVR, which cover crop did not meet the surface area requirement. These parameters are essential when implementing the Curve Number Methods (CN) and estimating potential runoff (Boughton, 1989).

All locations for the 2020 growing season consisted of an HSG B except for LCB20, due to the Port-Oscar complex this location contained two HSG's B (Port) and C (Oscar). Based on field management and planting practices the CN's for each location are as follows KMF 80, NCR 80, LCB20 83, and 75 for CVR. With the relatively high CN's noticed across KMF, NCR, and LCB20 we hypothesized that there was potential for an effect of yield influenced by N application runoff, while CVR could reflect N leaching.

CHAPTER V

CONCLUSION

The purpose of this study was to develop an enhanced level of understanding on the effects of N fertilized timing and prolonged N deficiency on grain yield and N concentration. This approach could lead to the identification of optimum N timing and pinpoint the growth stage at which recovery from N stress was no longer possible. In the analysis N timing had a significant effect on grain yield and N concentration. Three of the four locations documented the delaying of N was possible without yield penalties and also identified the point where recovery of yield was not possible, NCR and LCB20 indicated a lack of recovery initiating at 77 to 84 DAP respectively, while KMF the double crop location denoted 28 DAP as the point of irreversible yield loss. All locations apart from KMF demonstrated the ability to maintain grain yield, while CVR significantly increase grain yield as a result of delayed N application. In a similar study conducted in maize Binder et al. (2000), reported supportive evidence that maximum grain yield could be obtained with N delayed until 71 days after emergence (DAE), while attributing irreversible yield loss to be dependent on the level of N deficiency and crop demand.

An objective of this study was to determine the ability of grain sorghums to recover after the onset of nitrogen deficiency, and to what cost of grain yield.

Scharf et al. (2002), reported evidence that a continuous decrease in yield was observed with the increased delay in nitrogen application in maize yield. Results from CVR contradict Scharf et al. (2002) as yield was significantly increased by 1395.4 kg ha^{-1} compared to the pre-plant application. This could be reflective of crop requirement and effect of environment, as the pre-plant application was subject to loss through inadequate uptake via plant and leaching from heavy precipitation events. Results from all locations except the double crop KMF, provide evidence that suggest the possibility of delaying nitrogen application until precipitation chances increase.

These results are noteworthy for the grain sorghum production areas of the southern Great Plains regarding N management. The data collected from this study suggests the ability to delay N application and maintain grain yield, while increasing protein concentration. Such results could lead to advancements in nitrogen management thus decreasing potential nitrogen loss due to environmental factors while increasing economic returns for producers of Oklahoma.

REFERENCES

Arnall, B. H. Z. a. B. R. (2017). *Oklahoma Soil Fertility Handbook* (B. H. Arnall, Gayle, Ed.). Oklahoma State University.

Binder, D. L., Sander, D. H., & Walters, D. T. (2000). Maize Response to Time of Nitrogen Application as Affected by Level of Nitrogen Deficiency. *Agronomy Journal*, *92*(6), 1228-1236. https://doi.org/10.2134/agronj2000.9261228x

Biswas, D. K., & Ma, B.-L. (2016). Effect of nitrogen rate and fertilizer nitrogen source on physiology, yield, grain quality, and nitrogen use efficiency in corn. *Canadian Journal of Plant Science*, *96*(3), 392-403. https://doi.org/10.1139/cjps-2015-0186

Blackmer, A. M., Pottker, D., Cerrato, M. E., & Webb, J. (1989). Correlations between Soil Nitrate Concentrations in Late Spring and Corn Yields in Iowa. *Journal of Production Agriculture*, *2*(2), 103-109. https://doi.org/10.2134/jpa1989.0103

Bonifas, K. D., & Lindquist, J. L. (2006). Predicting biomass partitioning to root versus shoot in corn and velvetleaf (Abutilon theophrasti). *Weed Science*, *54*(1), 133-137. https://doi.org/10.1614/WS-05-079R1.1

Bonifas, K. D., & Lindquist, J. L. (2009). Effects of Nitrogen Supply on the Root Morphology of Corn and Velvetleaf. *Journal of Plant Nutrition*, *32*(8), 1371-1382. https://doi.org/10.1080/01904160903007893

Bonifas, K. D., Walters, D. T., Cassman, K. G., & Lindquist, J. L. (2005). Nitrogen supply affects root:shoot ratio in corn and velvetleaf (Abutilon theophrasti). *Weed Science*, *53*(5), 670-675. https://doi.org/10.1614/WS-05-002R.1

Boughton, W. (1989). A review of the USDA SCS curve number method. *Soil Research*, *27*(3), 511-523.

Brock, F. V., Crawford, K. C., Elliott, R. L., Cuperus, G. W., Stadler, S. J., Johnson, H. L., & Eilts, M. D. (1995). The Oklahoma Mesonet: a technical overview. *Journal of Atmospheric and Oceanic Technology*, *12*(1), 5-19.

Brouwer, R. (1962). *Nutritive Influences on the Distribution of Dry Matter*.

C. David Raper, J., Parsons, L. R., Patterson, D. T., & Kramer, P. J. (1977). Relationship between Growth and Nitrogen Accumulation for Vegetative Cotton and Soybean Plants. *Botanical Gazette*, *138*(2), 129-137. https://doi.org/10.1086/336907

Cossey, D. A., Thomason, W. E., Mullen, R. W., Wynn, K. J., Woolfolk, C. W., Johnson, G. V., & Raun, W. R. (2002). RELATIONSHIP BETWEEN AMMONIUM AND NITRATE IN WHEAT PLANT TISSUE AND ESTIMATED NITROGEN LOSS. *Journal of Plant Nutrition*, *25*(7), 1429-1442. https://doi.org/10.1081/PLN-120005400

Dharmakeerthi, R., Kay, B., & Beauchamp, E. (2005). Factors contributing to changes in plant available nitrogen across a variable landscape. *Soil Science Society of America Journal*, *69*(2), 453-462.

Dharmakeerthi, R. S., Kay, B. D., & Beauchamp, E. G. (2006). Spatial Variability of In-Season Nitrogen Uptake by Corn Across a Variable Landscape as Affected by Management. *Agronomy Journal*, *98*(2), 255-264. https://doi.org/https://doi.org/10.2134/agronj2005.0028

Edwards, J. H., & Barber, S. A. (1976). Nitrogen Flux into Corn Roots as Influenced by Shoot Requirement1. *Agronomy Journal*, *68*(3), 471-473. https://doi.org/10.2134/agronj1976.00021962006800030009x

Farquhar, G. D., Firth, P. M., Wetselaar, R., & Weir, B. (1980). On the Gaseous Exchange of Ammonia between Leaves and the Environment: Determination of the Ammonia Compensation Point. *Plant Physiology*, *66*(4), 710-714. https://doi.org/10.1104/pp.66.4.710

Fenn, L., & Hossner, L. (1985). Ammonia volatilization from ammonium or ammonium-forming nitrogen fertilizers. In *Advances in soil science* (pp. 123-169). Springer.

Keeney, D. R. (1982). Nitrogen Management for Maximum Efficiency and Minimum Pollution. In F. J. Stevenson (Ed.), *Nitrogen in Agricultural Soils* (Vol. 22, pp. 605-649). https://doi.org/10.2134/agronmonogr22.c16

Kelley, J. (2004). Growth and Development In L. E. J. Kelly (Ed.), *Grain Sorghum Production Handbook* (pp. 3-5). Cooperative Extension Service, University of Arkansas

Kleinman, P. J. A., Srinivasan, M. S., Dell, C. J., Schmidt, J. P., Sharpley, A. N., & Bryant, R. B. (2006). Role of Rainfall Intensity and Hydrology in Nutrient Transport via Surface Runoff. *Journal of environmental quality*, *35*(4), 1248-1259. https://doi.org/https://doi.org/10.2134/jeq2006.0015

Lim, P. O., Kim, H. J., & Nam, H. G. (2007). Leaf Senescence. *Annual review of plant biology*, *58*(1), 115-136. https://doi.org/10.1146/annurev.arplant.57.032905.105316

Mallmann, J., Heckmann, D., Bräutigam, A., Lercher, M. J., Weber, A. P. M., Westhoff, P., & Gowik, U. (2014). The role of photorespiration during the evolution of C4 photosynthesis in the genus Flaveria. *eLife*, *3*, e02478-e02478. https://doi.org/10.7554/eLife.02478

Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L., & Suzuki, A. (2010). Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. *Annals of Botany*, *105*(7), 1141-1157. https://doi.org/10.1093/aob/mcq028

McPherson, R. A., Fiebrich, C. A., Crawford, K. C., Kilby, J. R., Grimsley, D. L., Martinez, J. E., Basara, J. B., Illston, B. G., Morris, D. A., Kloesel, K. A., Melvin, A. D., Shrivastava, H., Wolfinbarger, J. M., Bostic, J. P., Demko, D. B., Elliott, R. L., Stadler, S. J., Carlson, J. D., & Sutherland, A. J. (2007). Statewide Monitoring of the Mesoscale Environment: A Technical Update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, *24*(3), 301-321. https://doi.org/10.1175/jtech1976.1

Moges, S. M., Girma, K., Teal, R. K., Freeman, K. W., Zhang, H., Arnall, D. B., Holtz, S. L., Tubaña, B. S., Walsh, O., Chung, B., & Raun, W. R. (2007). In-season estimation of grain sorghum yield potential using a hand-held optical sensor.

Archives of Agronomy and Soil Science, *53*(6), 617-628. https://doi.org/10.1080/03650340701597251
Muchow, R. C. (1998). Nitrogen utilization efficiency in maize and grain sorghum. *Field Crops Research*, *56*(1), 209-216. https://doi.org/https://doi.org/10.1016/S0378-4290(97)00132-9
Muchow, R. C., & Carberry, P. S. (1990). Phenology and leaf-area development in a tropical grain sorghum. *Field Crops Research*, *23*(3), 221-237. https://doi.org/https://doi.org/10.1016/0378-4290(90)90056-H
Muchow, R. C., & Sinclair, T. R. (1994). Nitrogen Response of Leaf Photosynthesis and Canopy Radiation Use Efficiency in Field-Grown Maize and Sorghum. *Crop Science*, *34*(3), cropsci1994.0011183X003400030022x. https://doi.org/https://doi.org/10.2135/cropsci1994.0011183X003400030022x
Novoa, R., & Loomis, R. S. (1981). Nitrogen and plant production. *Plant and Soil*, *58*(1), 177-204. https://doi.org/10.1007/BF02180053
Oklahoma Department of Agriculture, F. a. F., National Agriculture Statistics Service. (2018). *Oklahoma Agriculture Statistics*. USDA-NASS, Oklahoma Field Office
Pate, J. S., Layzell, D. B., & McNeil, D. L. (1979). Modeling the Transport and Utilization of Carbon and Nitrogen in a Nodulated Legume. *Plant Physiology*, *63*(4), 730-737. https://doi.org/10.1104/pp.63.4.730
Qi, D., Hu, T., Song, X., & Zhang, M. (2019). Effect of nitrogen supply method on root growth and grain yield of maize under alternate partial root-zone irrigation. *Scientific Reports*, *9*(1), 8191. https://doi.org/10.1038/s41598-019-44759-2
R Core Team. (2020). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.
Radin, J. W. (1978). A physiological basis for the division of nitrate assimilation between roots and leaves. *Plant Science Letters*, *13*(1), 21-25. https://doi.org/https://doi.org/10.1016/0304-4211(78)90060-3
Raun, W. R., & Johnson, G. V. (1999). Improving Nitrogen Use Efficiency for Cereal Production. *Agronomy Journal*, *91*(3), 357-363. https://doi.org/10.2134/agronj1999.00021962009100030001x
Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W. E., & Lukina, E. V. (2002). Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application. *Agronomy Journal*, *94*(4), 815-820. https://doi.org/10.2134/agronj2002.8150
Ross, C. W., Prihodko, L., Anchang, J., Kumar, S., Ji, W., & Hanan, N. P. (2018). HYSOGs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling. *Scientific Data*, *5*(1), 180091. https://doi.org/10.1038/sdata.2018.91
Sanchez, A. C., Subudhi, P. K., Rosenow, D. T., & Nguyen, H. T. (2002). Mapping QTLs associated with drought resistance in sorghum (Sorghum bicolor L. Moench). *Plant Molecular Biology*, *48*(5), 713-726. https://doi.org/10.1023/A:1014894130270
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Scharf, P. C., Wiebold, W. J., & Lory, J. A. (2002). Corn Yield Response to Nitrogen Fertilizer Timing and Deficiency Level. *Agronomy Journal*, *94*(3), 435-441. https://doi.org/https://doi.org/10.2134/agronj2002.4350

Schlüter, U., Mascher, M., Colmsee, C., Scholz, U., Bräutigam, A., Fahnenstich, H., & Sonnewald, U. (2012). Maize Source Leaf Adaptation to Nitrogen Deficiency Affects Not Only Nitrogen and Carbon Metabolism But Also Control of Phosphate Homeostasis. *Plant Physiology*, *160*(3), 1384-1406. https://doi.org/10.1104/pp.112.204420

Sinclair, T. (1990). Nitrogen influence on the physiology of crop yield. *Theoretical production ecology: Reflections and prospects*, *181*.

Sogbedji, J., Van Es, H., Klausner, S., Bouldin, D., & Cox, W. (2001). Spatial and temporal processes affecting nitrogen availability at the landscape scale. *Soil and Tillage Research*, *58*(3-4), 233-244.

Soil Survey Staff, N. R. C. S., United States Department of Agriculture. *Web Soil Survey* Retrieved 1/20/2021 from http://websoilsurvey.sc.egov.usda.gov/

Tremblay, N., Bouroubi, M. Y., Vigneault, P., & Bélec, C. (2011). Guidelines for in-season nitrogen application for maize (Zea mays L.) based on soil and terrain properties. *Field Crops Research*, *122*(3), 273-283. https://doi.org/https://doi.org/10.1016/j.fcr.2011.04.008

Tremblay, N., Bouroubi, Y. M., Bélec, C., Mullen, R. W., Kitchen, N. R., Thomason, W. E., Ebelhar, S., Mengel, D. B., Raun, W. R., Francis, D. D., Vories, E. D., & Ortiz-Monasterio, I. (2012). Corn Response to Nitrogen is Influenced by Soil Texture and Weather. *Agronomy Journal*, *104*(6), 1658-1671. https://doi.org/10.2134/agronj2012.0184

Turner, D. A., Edis, R. E., Chen, D., Freney, J. R., & Denmead, O. T. (2012). Ammonia volatilization from nitrogen fertilizers applied to cereals in two cropping areas of southern Australia. *Nutrient Cycling in Agroecosystems*, *93*(2), 113-126. https://doi.org/10.1007/s10705-012-9504-2

Vanderlip, R. L. (1993a). How a Sorghum Plant Develops. *Kansas State University*.

Vanderlip, R. L. (1993b). How a Sorghum Plant Develops. *Kansas State University*.

Walsh, O., Raun, W., Klatt, A., & Solie, J. (2012). EFFECT OF DELAYED NITROGEN FERTILIZATION ON MAIZE (ZEA MAYS L.) GRAIN YIELDS AND NITROGEN USE EFFICIENCY. *Journal of Plant Nutrition*, *35*(4), 538-555. https://doi.org/10.1080/01904167.2012.644373

Xu, G., Fan, X., & Miller, A. J. (2012). Plant nitrogen assimilation and use efficiency. *Annual review of plant biology*, *63*, 153-182.

Xu, G., Fan, X., & Miller, A. J. (2012). Plant nitrogen assimilation and use efficiency. *Annu Rev Plant Biol*, *63*, 153-182. https://doi.org/10.1146/annurev-arplant-042811-105532

Zhao, D., Reddy, K. R., Kakani, V. G., & Reddy, V. R. (2005). Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy*, *22*(4), 391-403. https://doi.org/https://doi.org/10.1016/j.eja.2004.06.005

Zhu, Q., Schmidt, J. P., Lin, H. S., & Sripada, R. P. (2009). Hydropedological processes and their implications for nitrogen availability to corn. *Geoderma*, *154*(1), 111-122. https://doi.org/https://doi.org/10.1016/j.geoderma.2009.10.004

TABLES

Table 1. Soil Series and classification description for all locations of the delayed N study 2019-2020.

Location	Year	Soil Series and Description	Hydrological Soil Group	Crop residue
LCB1	2019	Port (silt loam)	B	Wheat
LCB2	2019/2020	Port -Oscar Complex (silt clay loam)	B/C	Wheat
CVR	2019/2020	Teller (loam) Konawa (fine sandy loam)	B	Wheat (2019) Cotton (2020)
NCR	2020	Grant (silt loam)	B	Wheat
KMF	2020	Waynoka (fine sandy loam)	B	Wheat

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva.

Table 2. Location, year, and hybrid for delayed N study conducted in northwest to central Oklahoma over the 2019 and 2020 growing seasons.

Location	Year	Planting Date	Hybrid
CVR	2019	5/13/2019	SP73B12
LCB1	2019	6/3/2019	SP73B12
LCB2	2019	6/3/2019	SP73B12
CVR	2020	4/17/2020	SP73B12
LCB20	2020	4/17/2020	SP73B12
NCR	2020	4/16/2020	P86G32
KMF	2020	6/27/2020	SP43M80

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. SP73B12 and SP43M80 are products of Sorghum Partners, and P86G32 is a product of pioneer.

Table 3. Average composite soil sample analysis for all locations of the delayed N study conducted over the 2019 and 2020 growing seasons.

Location	Year	pH	BI	N kg ha^{-1}	P mg kg	K mg kg	OM %
CVR	2019	7	NA	6	12	106	NA
LCB1	2019	6.2	6.8	6	18	125	NA
LCB2	2019	5.5	6.9	43	8	73	NA
CVR	2020	6.2	7.2	4	18	120	0.71
NCR	2020	5.2	6.4	6	15	181	1.61
KMF	2020	6	7.3	15	16	199	1.05
LCB2	2020	6.3	NA	5	7	87	0.78

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. Organic matter (OM) was not included in the 2019 soil sample analysis as indicated by the NA. N is Nitrogen, P is Phosphorus, K is Potassium.

Table 4. Treatment structure for the delayed N study conducted in 2019 and 2020 growing seasons.

2019				2020			
TRT	**Timing**	**If No N Response**	**kg ha^{-1}**	**TRT**	**Timing**	**If No N Response**	**kg ha^{-1}**
1	Pre-Plant	Pre		1	Pre-Plant	Pre	100
CHECK	CHECK	CHECK		CHECK	CHECK	CHECK	
3	0 DAVD	28 DAP		3	0 DAVD	21 DAP	100
4	7 DAVD	35 DAP		4	7 DAVD	28 DAP	100
5	14 DAVD	42 DAP		5	14 DAVD	35 DAP	100
6	21 DAVD	49 DAP		6	21 DAVD	42 DAP	100
7	28 DAVD	56 DAP		7	28 DAVD	49 DAP	100
8	35 DAVD	63 DAP		8	35 DAVD	56 DAP	100
9	42 DAVD	70 DAP		9	42 DAVD	63 DAP	100
10	49 DAVD	77 DAP		10	49 DAVD	70 DAP	100
11	56 DAVD	84 DAP		11	56 DAVD	77 DAP	100
12	63 DAVD	91 DAP		12	63 DAVD	84 DAP	100

N rate was dependent upon location in 2019 which was determined by the environmental and soil conditions as well as access to irrigation. In 2020 N was applied at a flat rate across all locations. CHECK represents the non-fertilized treatment, while DAVD is days after visual difference and DAP is days after planting. In the event of no N response from the pre-plant and CHECK applications would begin on 28 DAP in 2019 and 21 DAP in 2020. The timing of applications were moved to an earlier date in 2020 due to time constraints in the fall

Table 5. N application dates for all locations of delayed N study for 2019 and 2020 growing seasons.

Location	Pre-Plant	Date of Treatment Application										
		21	28	35	42	49	56	63	70	77	84	91
CVR-19	12-May	-	10-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	4-Aug	12-Aug
LCB1-19	5-Jun	25-Jun	-	1-Jul	8-Jul	22-Jul	22-Jul	29-Jul	4-Aug	12-Aug	20-Aug	26-Aug
LCB2-19	5-Jun	-	1-Jul	8-Jul	15-Jul	29-Jul	29-Jul	4-Aug	12-Aug	20-Aug	26-Aug	3-Sep
CVR-20	17-Apr	8-May	14-May	21-May	29-May	4-Jun	12-Jun	18-Jun	26-Jun	3-Jul	9-Jul	-
LCB2-20	17-Apr	8-May	14-May	21-May	29-May	4-Jun	12-Jun	18-Jun	25-Jun	3-Jul	9-Jul	-
NCR-20	17-Apr	8-May	14-May	21-May	29-May	4-Jun	12-Jun	18-Jun	25-Jun	3-Jul	9-Jul	-
KMF-20	3-Jul	17-Jul	24-Jul	3-Aug	10-Aug	17-Aug	24-Aug	-	-	-	-	-

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. The green highlight indicates the first day of visual difference, while red dashes denote applications that were not applied, weather that be due to differences in time of visual difference or a change in application timing.

Table 6. This table contains heading dates for the LCB1 location of the delayed N study over the 2019 growing season which experienced a delay in physiological development.

TRT	Heading Date		
	8/9/2019	8/20/2019	8/26/2019
1	SF		
2		SF	
3	SF		
4	SF		
5	S	F	
6	SF		
7		SF	
8		SF	
9		S	F
10		S	F
11		S	F
12		S	F

Lake Carl Blackwell Research Farm (LCB) near Perry OK, S indicates the start of heading while F represents the finishing, columns that contain both SF denote treatments that began and finished heading within the same week. TRT indicates the treatment and the timing of application

Table 7. This table consists of the locations (CVR,NCR) in the 2020 growing season which experienced a delay in physiological development in the delayed N study.

Location	CVR			NCR		
TRT	Heading Date			Heading Date		
	7/3/2020	7/9/2020	7/17/2020	7/3/2020	7/9/2020	7/17/2020
1	S	F		SF		
CHECK		S	F		SF	
3	SF			SF		
4	S	F		SF		
5		SF		S		F
6		SF			SF	
7		SF			SF	
8		SF			SF	
9		SF			SF	
10		S	F	S		F
11			SF		SF	
12			SF		SF	

Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma, OK,. S indicates the start of heading while F represents the finishing, columns that contain both SF denote treatments that began and finished heading within the same week.

Table 8. Multiple comparison Dunnett's procedure (p=0.05) for grain yield Mg ha^{-1} of the 2020 delayed N study, with Check (trt2) (no application of N) as control. Colors denote significance.

Location	Pre - Plant	Days After Planting (DAP)									
		21	28	35	42	49	56	63	70	77	84
CVR	2.98^{bc}	3.06^{bc}	3.37^{bc}	3.31^{bc}	3.68^{abc}	4.38^{a}	3.74^{ab}	3.17^{bc}	2.97^{bc}	2.81^{c}	1.82^{d}
LCB20	3.65^{abcde}	4.49^{a}	3.89^{abcd}	4.35^{ab}	4.10^{abc}	3.22^{cdef}	3.51^{bcde}	3.15^{def}	3.95^{abcd}	2.91^{efg}	2.19^{g}
NCR	5.17^{abc}	5.63^{ab}	4.42^{cd}	4.67^{bcd}	5.78^{a}	4.72^{bcd}	5.34^{abc}	5.39^{ab}	3.87^{de}	3.33^{ef}	2.76^{f}
KMF	4.97^{a}	4.31^{ab}	3.51^{bc}	3.10^{bc}	3.11^{bc}	2.93^{bc}	3.46^{c}	-	-	-	-

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. Green signifies significantly greater than check, while yellow indicates no significant difference from check. Gray highlight and red dashes represent applications which were not made, due to crop stage. Letter's denote significance of treatment, treatments containing the same letter are not significantly different

Table 9. Multiple comparison Dunnett's procedure (p=0.05) for grain yield of the 2020 delayed N study, with pre-plant application as control. Letters L, E and G indicate significance for each comparison.

Location	Days After Planting (DAP)									
	21	28	35	42	49	56	63	70	77	84
CVR	E	E	E	E	G	E	E	E	E	E
LCB20	E	E	E	E	E	E	E	E	E	L
NCR	E	E	E	E	E	E	E	E	L	L
KMF	E	E	E	L	L	L	-	-	-	-

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. Letters L, E and G indicate significance for each comparison, E signifies no significant difference, while L denotes significantly less than, and G indicates significantly greater than the control. Gray highlight and red dashes represent applications which were not made, due to crop stage

Table 10. Multiple comparison Dunnett's procedure for grain N concentration of the 2020 delayed N study, using pre-plant as control. Colors indicate significance.

Location	Days After Planting (DAP)									
	21	28	35	42	49	56	63	70	77	84
CVR	9.08	8.66	9.14	8.67	8.46	8.98	8.99	10.08	10.57	12.18
LCB20	8.67	9.24	9.32	10.42	10.40	9.52	10.10	11.30	11.07	11.62
KMF	11.12	10.57	10.62	9.82	9.81	9.10	-	-	-	-

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, Raymond Sidewell North Central Research Station (NCR) near Lahoma OK, and on a privately owned farm (KMF) near Alva. Yellow indicated no significant difference from pre-plant, while green denotes significantly greater than pre-plant, Gray highlight and red dashes represent applications which were not made, due to crop stage.

Table 11. This table contains grain N concentration for grain sorghum in regard to all locations of the delayed N study conducted in the 2020 growing season.

Location	Pre - Plant	Days After Planting (DAP)									
		21	28	35	42	49	56	63	70	77	84
CVR	9.10[c]	9.08[c]	8.66[c]	9.14[c]	8.67[c]	8.46[c]	8.98[c]	8.99[c]	10.08[b]	10.57[b]	12.18[a]
LCB20	9.45[de]	8.67[f]	9.24[ef]	9.32[bc]	10.42[bc]	10.40[bc]	9.52[de]	10.10[cd]	11.30[a]	11.07[ab]	11.62[a]
KMF	10.68[ab]	11.12[a]	10.57[ab]	10.62[ab]	9.82[ab]	9.81[ab]	9.10[b]	-	-	-	-

Lake Carl Blackwell Research Farm (LCB) near Perry OK, Cimarron Valley Research Station (CVR) near Perkins, OK, and on a privately owned farm (KMF) near Alva. Letters indicate statistical significance difference, treatments consisting of the same letter are not significantly different. The red dashes represent applications which were not made, due to crop stage.

FIGURES

Figure 1. Grain sorghum production acres for Oklahoma (Oklahoma Department of Agriculture, 2018).

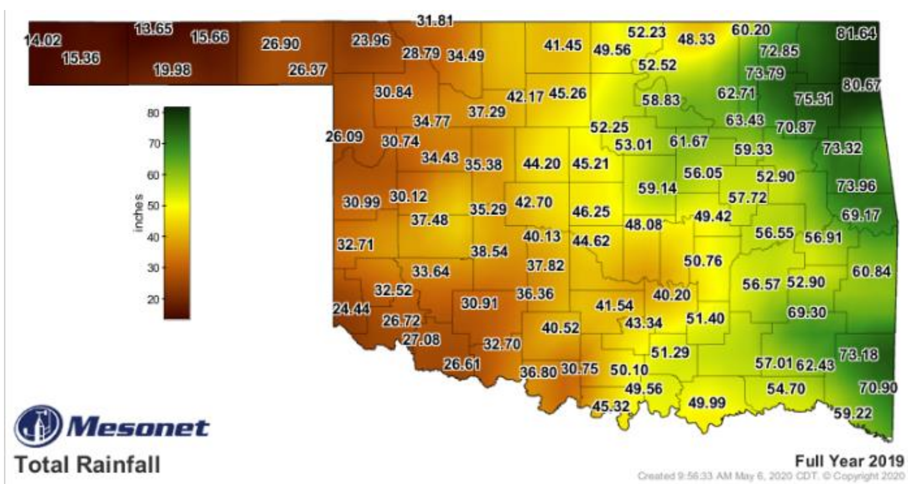

Figure 2. Total annual precipitation for Oklahoma (McPherson et al., 2007)

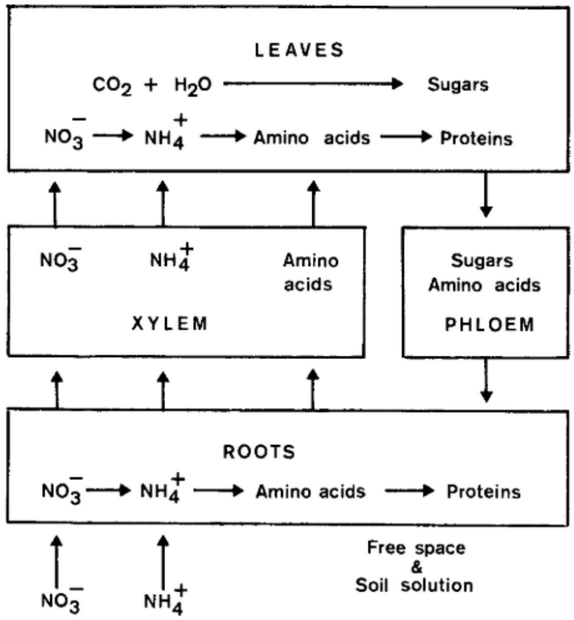

Figure 3. In plant Nitrogen balance method (Novoa & Loomis, 1981).

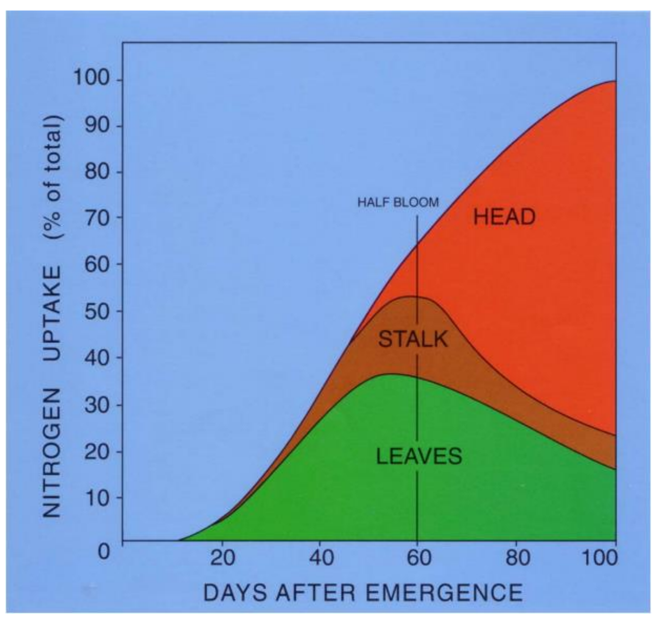

Figure 4. Grain sorghum nitrogen uptake curve (Vanderlip, 1993b)

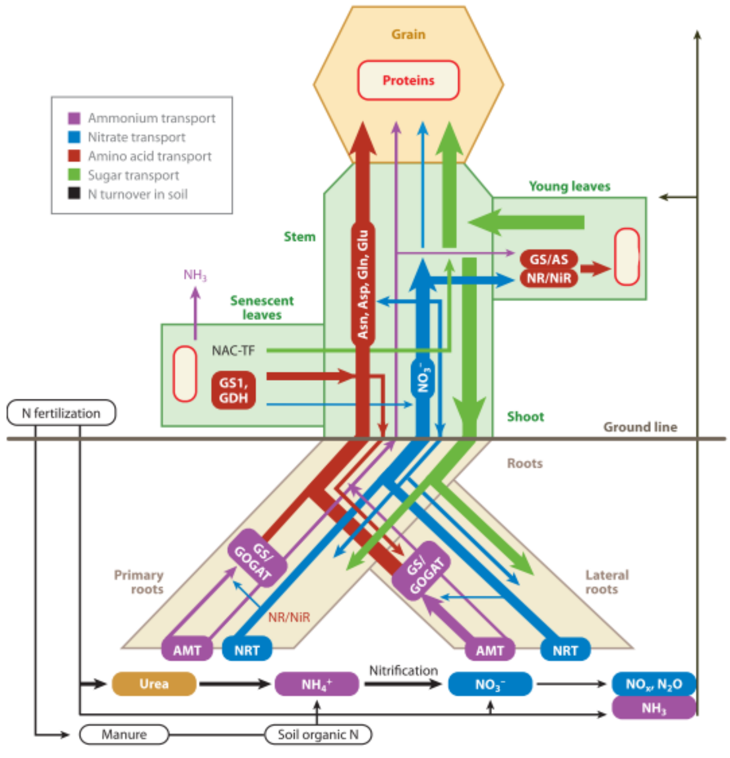

Figure 5. Nitrogen movement, uptake and reduction within plant (Guohua Xu et al., 2012)

VITA

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